

AN ANALYSIS OF THE STRENGTH OF WELDING JOINT BETWEEN HSLA STEEL &
CHROMIUM - MOLYBDENUM STEEL USING MECHANICAL TEST AND FINITE
ELEMENT METHOD



Presented in Partial Fulfillment of the Requirements for the
Master of Engineering Degree in Mechanical Engineering
at Srinakharinwirot University

November 2017

AN ANALYSIS OF THE STRENGTH OF WELDING JOINT BETWEEN HSLA STEEL &
CHROMIUM - MOLYBDENUM STEEL USING MECHANICAL TEST AND FINITE
ELEMENT METHOD



Presented in Partial Fulfillment of the Requirements for the
Master of Engineering Degree in Mechanical Engineering
at Srinakharinwirot University

November 2017

Nuttaporn Bungmek (2017). *An Analysis of the Strength of Welding Joint between HSLA Steel and Chromium – Molybdenum Steel using Mechanical Test and Finite Element Method*, M.Eng (Mechanical Engineering). Bangkok: Graduate School, Srinakharinwirot University.
Advisor Committee; Assoc. Prof. Dr. Ganwarich Pluphrach, Prof. Dr. Hadi Sutanto.

The welding process by Shielded Metal Arc Welding (SMAW) was used to join High-Strength Low-Alloy steel (HSLA) and chromium-molybdenum steel with AWS E7016 electrodes. The ABS EH36 steel was part HSLA grade and AISI: 4140 was a part of chromium-molybdenum steel. The testing forms of weld ability were used to predict mechanical properties and microstructures. An investigation was carried out to determine the mechanical properties in a hardness test (Vickers hardness tester) and a tensile test. The base zone of 4140 has a maximum value of hardness test and the weakness point (the fracture point) is the central area between the base zone and HAZ of EH36 for the tensile test. Microstructures were examined for chemical composition analysis with a spectrometer, an EDS analysis on the SEM with a scanning electron microscope and predicted the strength as the optical microscope (OM) that used the figure to find the grain size number by the intercept method and applied to use the value to find the yield stress with the Hall-Petch relationship. The element found by EDS analysis on SEM had similar values with the composition, standard and the yield stress at the base zone of 4140 at a maximum value of 476 MPa and more than another zone. The minimum value of the yield stress was 368 MPa at the base zone of EH36. The results from those methods can identify that Chromium-molybdenum steel has a higher strength than High-Strength Low-Carbon Microalloyed Steel (HSLA) and from the base zone of 4140 to the base zone of EH36 respectively. The simulations performed showed good agreement the analytical and experimental results by Finite Element Method. After comparisons with mechanical testing, it was found that the results were in a similar direction of the results for the strength. They were confirmed with the computational simulations and can be considered to confirm the strength of material, with a specimen at the welding joint.

การวิเคราะห์ความแข็งแรงของแนวเชื่อมต่อระหว่างเหล็กกล้าคาร์บอนต่ำ และเหล็กโครเมียม-
โมลิบดีนัม โดยใช้วิธีทดสอบ สมบัติทางกล และระเบียบวิธีไฟไนต์เอลิเมนต์



บทคัดย่อ
ของ
ว่าที่ รต. ณัฐภรณ์ บังเมฆ

เสนอต่อบัณฑิตวิทยาลัย มหาวิทยาลัยศรีนครินทรวิโรฒ เพื่อเป็นส่วนหนึ่งของการศึกษา
ตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต สาขาวิชาวิศวกรรมเครื่องกล
พฤษภาคม 2560

ณัฐภรณ์ บังเมฆ (2560). การวิเคราะห์ความแข็งแรงของแนวเชื่อมต่อระหว่างเหล็กกล้าคาร์บอนต่ำ และเหล็กโครเมียม-โมลิบดีนัม โดยใช้วิธีทดสอบ สมบัติทางกล และระเบียบวิธีไฟไนต์เอลิเมนต์, ปรินญาณพนธ์ วศ.ม.(วิศวกรรมเครื่องกล). กรุงเทพฯ: บัณฑิตวิทยาลัย มหาวิทยาลัยศรีนครินทรวิโรฒ. อาจารย์ที่ปรึกษาปรินญาณพนธ์: อาจารย์ รศ.ดร.กัณวรัช พลุปราชญ์, อาจารย์ที่ปรึกษาร่วม: อาจารย์ ศ.ดร.ฮาดี ชูตันโต

กระบวนการเชื่อมโดย การเชื่อมอาร์ค ลวดหุ้มฟลักซ์ (SMAW) ใช้เชื่อมเหล็กกล้าคาร์บอนต่ำ (HSLA) และเหล็กโครเมียม-โมลิบดีนัมด้วยลวดเชื่อม AWS E7016. เหล็กเกรด ABS EH36 เป็นส่วนหนึ่งของเหล็กกล้าคาร์บอนต่ำ และเหล็กเกรด AISI: 4140 เป็นส่วนหนึ่งของเหล็กโครเมียม-โมลิบดีนัม ซึ่งรูปแบบการทดสอบความสามารถในการเชื่อม ใช้เพื่อทำนายสมบัติทางกลและโครงสร้างจุลภาค การตรวจสอบสมบัติทางกล ใช้การทดสอบความแข็งโดยวิธีของวิกเกอร์ส (Vickers hardness tester) และการทดสอบแรงดึง (Tensile Test) ซึ่งสรุปว่า ในการทดสอบความแข็งของเหล็ก พบว่า พื้นที่บริเวณฐานของเหล็กเกรด 4140 มีค่าความแข็งสูงสุด และในการทดสอบแรงดึงพบว่าจุดที่อ่อนที่สุด (จุดแตกหัก) เป็นพื้นที่ระหว่างบริเวณกระพุ้งร้อนและพื้นที่ฐานในฝั่งของเหล็กเกรด EH36 การวิเคราะห์โครงสร้างทางจุลภาคที่ใช้เครื่องสเปกโทรมิเตอร์ โดยการวิเคราะห์ธาตุ (EDS) ด้วยกล้องจุลทรรศน์อิเล็กตรอนแบบส่องกราด (SEM) และการทำนายความแข็งแรงของเหล็กโดยกล้องจุลทรรศน์แสง (OM) ที่นำรูปไปใช้เพื่อหาจำนวนขนาดเกรนของโครงสร้างเหล็กโดยวิธี Intercept method และนำมาประยุกต์ใช้ เพื่อคำนวณหาความความเค้นครากโดยวิธี Hall-Petch relationship ซึ่งพบว่า การวิเคราะห์โครงสร้างทางจุลภาคโดยใช้เครื่องสเปกโทรมิเตอร์ โดยการวิเคราะห์ธาตุ (EDS) ด้วยกล้องจุลทรรศน์อิเล็กตรอนแบบส่องกราด (SEM) มีค่าใกล้เคียงกับมาตรฐานของเหล็กทั้งสอง และการคำนวณหาความเค้นครากพบว่าที่บริเวณฐานของฝั่งเหล็กเกรด 4140 มีค่าเท่ากับ 476 MPa และค่าสูงสุดที่มากกว่าอีกบริเวณอื่นของชิ้นงานทดลอง ค่าต่ำสุดคือ 368 MPa ที่ฐานของฝั่งเหล็กเกรด EH36 ซึ่งจากผลดังกล่าว สรุปได้ว่า เหล็กโครเมียม-โมลิบดีนัม มีความแข็งแรงกว่าเหล็กกล้าคาร์บอนต่ำ โดยเรียงจากพื้นที่ฐานของเหล็กเกรด 4140 ข้ามไปจนถึงด้านพื้นที่ฐานของเหล็กเกรด EH36 ตามลำดับ ในส่วนของการทดสอบด้วยจำลองโดยระเบียบวิธีไฟไนต์เอลิเมนต์ ได้ผลที่ดีและอยู่ในเกณฑ์ที่ใกล้เคียงกับมาตรฐานของเหล็ก โดยใช้ในการเปรียบกับการคำนวณหาความเค้นคราก ซึ่งยืนยันความแข็งแรงของเหล็กก่อนนำไปใช้งานจริงได้ทั้งสองวิธี

The thesis titled
“An analysis of the strength of welding joint between HSLA steel & Chromium – Molybdenum steel
using mechanical test and finite element method”

By
Act Sub LT. Nuttaporn Bungmek

Has been approved by the Graduate School as partial fulfillment of the requirement for the
Master of Engineering degree in Mechanical Engineering of Srinakharinwirot University

..... Dean of Graduate School
(Asst. Prof. Dr. Chatchai Ekpanyaskul, MD.)

November....., 2017

Thesis Committee

..... Major-advisor

(Assoc. Prof. Dr. Ganwarich Pluphrach)

..... Co-advisor

(Prof. Dr. Hadi Sutanto)

Oral Defense Committee

..... Chair

(Asst. Prof. Dr. Siriporn Rojananan)

..... Committee

(Assoc. Prof. Dr. Ganwarich pluphrach)

..... Committee

(Prof. Dr. Hadi Sutanto)

..... Committee

(Asst. Prof. Dr. Pracha Bunyawanichakul)

ACKNOWLEDGEMENTS

I would like to express sincere thanks to my advisor, Assoc. Prof. Dr .Ganwarich Phulphrach and Prof. Dr. Hadi Sutanto, for their valuable suggestions, attentive interest. I would like to express sincere thanks to Asst. Prof. Charnont Moolwan kind recommendations in my present study and I would like to express sincere thanks to Mr. Anuprong Pronpijit, Mr. Nirut Bunchoo, National metal and materials technology center (M-Tech), for their help and guidance during my study and another recommendations. Lastly, I would like to thank my family for always helping me to remember what is important in life, their always supporting me in my good and bad times and for giving right suggestions to me, encouragement, endless love and understanding throughout my study program.

Nuttaporn Bungmek

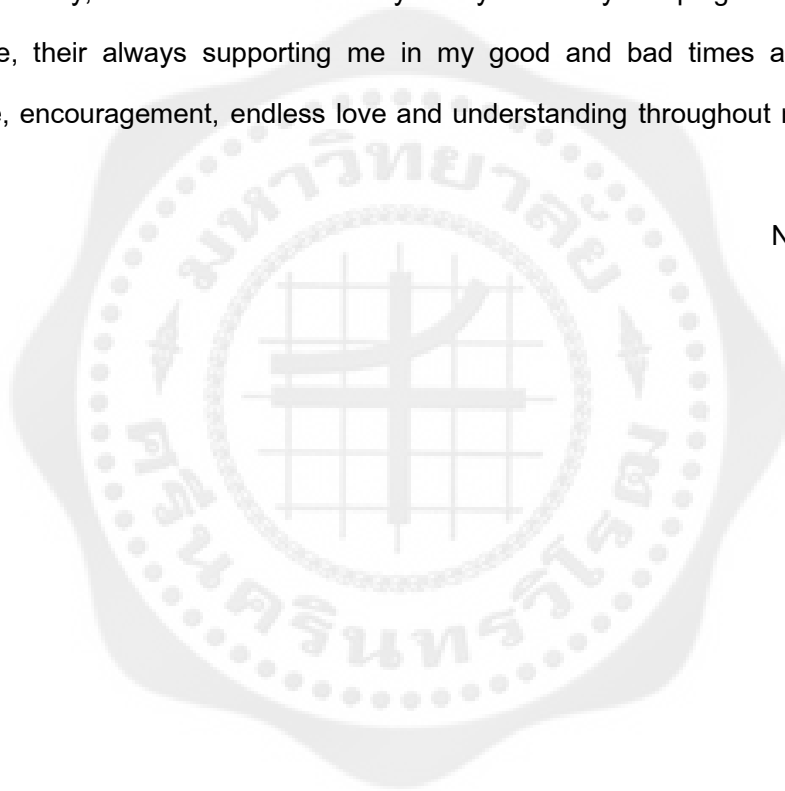


TABLE OF CONTENTS

Chapter	Page
1 INTRODUCTION	1
Overview	1
Assumption	1
Objective	2
Scopes	2
2 LITERATURE REVIEW AND THEORY	3
Literature Review	3
Theory	6
HSLA Steel	7
Chromium - Molybdenum steel	9
Welding Electrodes	16
Welding of HSLA Steel method & Weld ability of HSLA Steel	23
Welding method & Weld ability of Chromium-Molybdenum steel	25
Fusion Welding	29
Mechanical Tests	39
Grain Size	55
Finite element method	62
3 EXPERIMENTAL METHOD	83
Materials Used	83
Chemical composition analysis	84
Weld Setup	85
Weld joint	86
Mechanical Tests	87
Microstructure examination	88
Finite element method	91

TABLE OF CONTENTS (Continued)

Chapter	Page
4 RESULTS AND DISCUSSION	92
Chemical composition.....	92
Mechanical Tests.....	92
Hardness Tests.....	92
Tensile Tests.....	94
Microstructure	96
OM (Optical Microscope).....	96
SEM and EDS.....	106
Finite element method.....	111
Comparisons between Mechanical Tests and Finite element method...	113
Discussion.....	115
5 CONCLUSION AND SUGGESTION	116
Conclusions.....	116
Suggestion.....	116
REFERENCES	118
APPENDIX	121
Appendix A List of symbols.....	122
Appendix B Properties of selected engineering material.....	126
Appendix C Kasem Bundit engineering journal	131
VITAE	151

LIST OF TABLES

Table	Page
1 Samples & welding joint.....	2
2 Chemical composition of ABS EH36 for steel plate, angle steel bar, bulb flat bar, L section steel bar.....	9
3 Chemical composition of AISI 4140.....	12
4 Mechanical Properties of AISI 4140.....	12
5 Electrode Classification Number.....	18
6 Carbon and Low-Alloy Steel Welding Consumables for SMAW Process...	21
7 Chemical Composition of Deposited Metal (%).....	22
8 Mechanical Properties of Deposited Metal.....	22
9 Reference Current (AC, DC+).....	22
10 Nominal percentages for the P-91 type chart.....	26
11 Chemical composition of ABS EH36 and AISI: 4140.....	92
12 The results of Vickers hardness tester.....	92
13 The results of tensile test.....	94
14 The result of OM (Optical Microscope).....	106
15 Comparisons between Mechanical Tests and Finite element method.....	114

LIST OF FIGURES

Figures	Page
1 Metals chart.....	6
2 Line pipe strip and plate, automotive hot & cold-rolled strip, structural plate	8
3 AISI 4140 Chrome - Molybdenum high tensile steel.....	11
4 Oxyfuel gas welding operation.....	30
5 The basic configuration of an arc welding operation.....	30
6 Shielded metal arc welding operation.....	32
7 Submerged arc welding operation.....	32
8 Gas metal arc welding operation.....	33
9 Gas tungsten arc welding operation.....	34
10 Plasma Arc Welding.....	35
11 Transverse and longitudinal residual stress pattern (Left) and likely distortion in the welded assembly (Right).....	36
12 Steps in a spot welding cycle: (1) parts inserted between open electrodes, (2) electrodes close and force is applied, (3) weld time (Current is switched), (4) current is turned off but force is maintained, and (5) electrodes are opened, and the welded assembly is removed....	37
13 Resistance seam welding operation.....	38
14 Different types of seam welding (from left to right) conventional seam welding, roll spot welding, continuous resistance seam welding.....	39
15 Typical tensile testing machine.....	39
16 Standard shape tensile specimens.....	40
17 Stress/strain curve.....	41
18 Calculation of percentage elongation (a), Calculation of percentage reduction of area (b).....	42
19 Determination of proof (offset yield) strength.....	43
20 Square or rectangular cross joint tensile test piece.....	44
21 Flat cross joint tensile specimen machined from tube.....	45

LIST OF FIGURES (Continued)

Figures	Page
22 Multiple cross joint specimens machined from thick plate.....	45
23 Effect of speed of testing on strength and ductility.....	47
24 Brinell Hardness Test.....	48
25 Schematic principles of operation of Vickers hardness machine.....	49
26 Vickers hardness test.....	50
27 Micro-hardness test.....	52
28 Equotip test.....	53
29 Ultrasonic testing using a Microdur unit.....	54
30 Image of Grains in Steel at 100x Magnification.....	56
31 Example of a microscope eyepiece reticle used to compare against a live image.....	56
32 Grain Analysis via the Intercept method.....	60
33 Grain Analysis via the Planimetric method.....	61
34 Illustrates the microscope magnification.....	61
35 Various types of simple lowest-order finite elements with corner nodes only and higher-order elements with intermediate nodes.....	64
36 Discretized railroad control tower (28 nodes, 48 beam elements) with typical degrees of freedom shown at node 1.....	69
37 Two-dimensional analysis of a hydraulic cylinder rod end (120 nodes, 297 plane strain triangular elements).....	70
38 Finite element model of a spur gear.....	70
39 (a) wheel rim; (b) engine block ((a) Courtesy of Mark Blair; (b) courtesy of Mark Guard).....	70
40 Three-dimensional stresses on an element.....	71
41 Tetrahedral solid element.....	73
42 HSLA Steel (ABS EH36).....	83
43 Chromium-molybdenum steel (AISI: 4140).....	84
44 Spectrophotometer test machine (THERMO model ARL 3460).....	84

LIST OF FIGURES (Continued)

Figures	Page
45 1.Welding Power Source, 2.Insulated electrode holder, 3.Work piece, 4.Work Clamp.....	84
46 Shielded metal arc welding (SMAW).....	85
47 Joint Design.....	86
48 Typical tensile testing machine.....	87
49 Standard shape for tensile testing.....	87
50 Specimens shape for tensile testing (Welding joint).....	88
51 Micro-Vickers hardness testing machines (MITUTOYO: HM-210A)....	88
52 Metallography examination process.....	89
53 Mounting small a sample specimens in a synthetic resin a) EH36-EH36, b) 4140-4140, c) 4140-EH36.....	89
54 Optical microscope (Olympus laser microscopes model OLS 4000)...	90
55 HITACHI S-3400N-II Scanning Electron Microscope (SEM).....	90
56 Example for analysis of tensile test by ANSYS.....	91
57 The results of Vickers hardness tester for EH36 & EH36.....	93
58 The results of Vickers hardness tester for 4140 & 4140.....	93
59 The results of Vickers hardness tester for 4140 & EH36.....	94
60 The results of tensile testing for EH36 & EH36.....	95
61 The results of tensile testing for 4140 & 4140.....	95
62 The results of tensile testing for 4140 & 4140.....	96
63 Optical micrographs of EH36 & EH36 and apply to find the grain size number.....	96
64 Variety of grain sizes at Base zone (EH36 & EH36).....	97
65 Variety of grain sizes at HAZ (EH36 & EH36).....	97
66 Variety of grain sizes at Welding zone (EH36 & EH36).....	98
67 Optical micrographs of 4140 & 4140 and apply to find the grain size number.....	99
68 Variety of grain sizes at Base zone (4140 & 4140).....	99

LIST OF FIGURES (Continued)

Figures	Page
69 Variety of grain sizes at HAZ (4140 & 4140).....	100
70 Variety of grain sizes at Welding zone (4140 & 4140).....	100
71 Optical micrographs of 4140 & EH36 and apply to find the grain size number.....	101
72 Variety of grain sizes at Base zone1 (4140 & EH36).....	102
73 Variety of grain sizes at HAZ1 (4140 & EH36).....	102
74 Variety of grain sizes at Welding zone (4140 & EH36).....	103
75 Variety of grain sizes at HAZ2 (4140 & EH36).....	103
76 Variety of grain sizes at Base zone2 (4140 & EH36).....	104
77 The EDS (analysis on the SEM) spectrum analysis at Base zone (EH36 & EH36).....	106
78 The EDS (analysis on the SEM) spectrum analysis at HAZ (EH36 & EH36).....	107
79 The EDS (analysis on the SEM) spectrum analysis at Weld zone (EH36 & EH36).....	107
80 The EDS (analysis on the SEM) spectrum analysis at Base zone (4140 & 4140).....	108
81 The EDS (analysis on the SEM) spectrum analysis at HAZ (4140 & 4140).....	108
82 The EDS (analysis on the SEM) spectrum analysis at Weld zone (4140 & 4140).....	109
83 The EDS (analysis on the SEM) spectrum analysis at Base zone1 (4140 & EH36).....	109
84 The EDS (analysis on the SEM) spectrum analysis at HAZ1 (4140 & EH36).....	110
85 The EDS (analysis on the SEM) spectrum analysis at Welding zone (4140 & EH36).....	110

LIST OF FIGURES (Continued)

Figures	Page
86 The EDS (analysis on the SEM) spectrum analysis at HAZ2 (4140 & EH36).....	110
87 The EDS (analysis on the SEM) spectrum analysis at Base zone2 (4140 & EH36).....	111
88 The result in ANSYS simulation (EH36 & EH36).....	112
89 The result in ANSYS simulation (4140 & 4140).....	112
90 The result in ANSYS simulation (4140 & EH36).....	113
91 Comparisons between Mechanical Tests and Finite element method by tensile strength.....	114

CHAPTER 1

INTRODUCTION

1. Overview

Since, humans have discovered the steel production process and used in various industries. It was developed to the standards (shape & size) and quality that are appropriate to use and include joining together using many methods. One of them is the weld method.

The weld method has developed continuously for the high efficiency in coalescing materials. There are several different methods to weld the steel and the steel products that are commonly used in production with the welding techniques.

Other elements of welding have been steadily improving as well, such as electrode welding, weld inspection methods, including the program to analyze and predict the result of an advance. Accordingly, simulation of the welding process is to be more important for the welding industry.

One typical benefit from the steel is the grain refinement of ferrite. It is an important fundamental physical property of steel. When the steels are fusion welded, it is also of interest and significance to study the ferrite grain size and further phase transformation at the welding joint. Therefore, it should be studied for strength from the manner and general use to be certain before applying them.

Nowadays, in the steel industries remain a problems to solve of welding two dissimilar materials, especially when two types of materials have differences in the chemical properties and thermal properties. The effect in the welding processes is not easy to understand, like dissimilar welding between High strength low alloy steel (HSLA Steel) and Chromium-Molybdenum steel.

2. Assumption

Able to analyze the strength of the welding joint that will be changed at the welding joint between high strength low alloy steel (HSLA Steel) and Chromium-Molybdenum steel using mechanical properties and finite element method

3. Objective

3.1. To study the effect of mechanical properties at the welding joint (Base zone, HAZ, Welding zone) between high strength low alloy steel (HSLA Steel) and Chromium-Molybdenum steel using a mechanical test.

3.2. To analyze any stresses of the welding joint between high strength low alloy steel (HSLA Steel) and Chromium-Molybdenum steel using microstructure and finite element method.

3.3. To compare the results between mechanical test and finite element method.

4. Scope

This research aims to study the welding joint of dissimilar welds between High strength low alloy steel (ABS EH36 in 4 mm thickness of steel plate) and chromium-molybdenum steel (AISI: 4140 in 4 mm thickness of steel plate) in detail as follows:

4.1. To study the effect of mechanical properties at the welding joint between High strength low alloy steel (HSLA Steel) and Chromium-Molybdenum steel using mechanical tests (Tensile test and Vickers hardness test).

4.2. To analyze any stresses at the welding joint between high strength low alloy steel (HSLA Steel) and Chromium-Molybdenum steel using microstructure (OM and EDS analysis on the SEM) and finite element method (Ansys).

4.3. Comparisons between mechanical Tests and finite element method.

4.4. Welding process by Shielded Metal Arc Welding (SMAW).

4.5. Welding electrodes standards AWS-A 5.1 E7016

4.6. The sample has the single V groove and welding joint process at table 1

Table 1 Samples & welding joint

Material	But joint
HSLA steel& HSLA steel (EH36 & EH36)	●
Chromium-molybdenum steel & Chromium-molybdenum steel (4140 & 4140)	●
Chromium-molybdenum steel & HSLA steel (4140 & EH36)	●

CHAPTER 2

LITERATURE REVIEW AND THEORY

1. Literature Review

S.D. Bhole (2005) *“Effect of nickel and molybdenum additions on weld metal toughness in submerged arc welded HSLA line-pipe steel”* The effects of alloy additions of nickel (Ni), molybdenum (Mo), and Ni and Mo together on the impact toughness of an API HSLA-70 steel by submerged arc welding in the laboratory were investigated and micro-structural factors which affect the impact toughness were discussed. Ni additions resulted in low impact toughness and an increased fracture appearance transition temperature (FATT) in weld metal (WM). The above influences of Ni should be attributed to the formation of acicular ferrite (AF) suppressed by increasing the Ni content. Conversely, the combined presence of Ni and Mo in the WM decreased the volume fractions of grain-boundary ferrite (GBF) and promoted formation of high toughness of AF. The increase of Mo content created an acicular ferrite-predominant weld metal microstructure with impressively improved toughness. Mo addition of 0.881 wt. % in the WM gave the optimal impact toughness at -45 °C with a microstructure of 77% AF and 20% granular bainite (GB).

Bravo Ivan Mendoza; Zepeda Cuauhtemoc Maldonado; Hernandez Apolinar Albiter; Piedras Eduardo Robles (2010) *“Dissimilar Welding of Super duplex Stainless Steel/HSLA Steel for Offshore Applications Joined by GTAW”* The dissimilar metal weld is demanding as well as the similar weld, however, dissimilar weld is more complex than similar weld due to the necessity of being applied in zones where a requirement is to improve some properties. In this work the main purpose is to know the mechanical behavior of a dissimilar weld between HSLA Steel and Super duplex Stainless Steel (SDSS) to establish if the joint is feasible or not. The alloys were welded with GTAW process using a 60-deg and 90-deg single-V groove test specimens in order to observe the effect of the weld pass. The filler metal was chosen with the aid of Schaeffer diagram. It was found that the ER 25.10.4L filler metal provided the best equilibrium between ferrite and austenite phase in the Super duplex Stainless Steel final microstructure and a band of martensite in the HSLA steel final microstructure. The dissimilar joint presented acceptable mechanical properties which are superior to the HSLA in the as-received condition, but lower than the SDSS in the as-received condition, proving that the filler metal was the adequate.

S. Ravi, V. Balasubramanian; S. Babu; S. Nemat Nasser (2003) *“Assessment of some factors influencing the fatigue life of strength mis-matched HSLA steel weldments”* Welding of high strength low alloy steels (HSLA) involve usage of low, even and high strength filler materials (electrodes) than the parent material depending on the application of the welded structures and the availability of the filler material. In this investigation an attempt has been made to assess the influences of mis-match ratio (MMR), post-weld heat treatment (PWHT) and notch location on fatigue life of HSLA steel welds. Shielded metal arc welding (SMAW) process has been used to fabricate the butt joints. Centre cracked tension (CCT) specimen has been used to evaluate the fatigue life of welded joints. Fatigue experiments have been conducted using servo hydraulic controlled fatigue testing machine at constant amplitude loading ($R=0$). Design of experiments (full factorial design) concept has been used to optimize the number of experimental conditions. A procedure has been developed to assess and optimize the above chosen factors to attain a maximum fatigue life value by incorporating (i) response table and response graph, (ii) normal probability plot and (iii) analysis of variance (ANOVA) techniques.

Shu Xu (2011) *“Thermal Stress Analysis of dissimilar welding joints by Finite Element Method”* This paper relates to the dissimilar welding joints of 45, 0Cr18Ni9 and 1Cr9Mo steel using the different welding metal A302 or Inconel182. The thermal stress numerical simulation is carried out to the dissimilar welding joints. The thermal stresses of dissimilar welding joints generated in the heating to 450 °C from the ambient temperature for 45/1Cr9Mo and 45/0Cr18Ni9 and 500 °C for 1Cr9Mo/0Cr18Ni9 are calculated by finite element method. It is shown that large tensile stress is generated in the weld metal, fusion line and heat affected zone (HAZ) when the welding metal is A302, while the compressive or low tensile stress is shown in the HAZ and fusion line of 1Cr9Mo or 45 steel. The maximum circumferential stress is presented in 1Cr9Mo or 45 steel, while the large compressive or low tensile stress is shown in 0Cr18Ni9. The stress is decreased when the A302 is changed to Inconel182. It is concluded that the replacement of A302 by Inconel182 can decrease the thermal stress and increase the life of the welding joint.

Yashar Javadi; Mehdi Ahmadi Najafabadi (2013) *“Comparison between contact and immersion ultrasonic method to evaluate welding residual stresses of dissimilar joints”* This paper presents a comparison of contact and immersion waves used to measure residual stresses. The residual stresses are produced due to a dissimilar welding of stainless steel (304) to carbon steel (A106). Longitudinal critically refracted (LCR) wave propagated by 2 MHz contact

and immersion ultrasonic transducers is employed to measure the residual stresses. A Finite Element (FE) model of welding process, which is validated by hole-drilling method, is used to verify the ultrasonic results while an acceptable agreement is achieved. The best agreement is observed in the parent material while the maximum difference is measured in the heat affected zone (HAZ). The results show no considerable difference between using contact and immersion transducers in ultrasonic stress measurement of dissimilar joints.

Lei Zhang; Thomas Kannengiesser; (2014) *“Austenite grain growth and microstructure control in simulated heat affected zones of microalloyed HSLA steel”* The roles of microalloying niobium, titanium and vanadium for controlling austenite grain growth microstructure evolution and hardness were investigated at different simulated heat affected zones (HAZ) for high strength low alloy (HSLA) S690QL steel. High resolution FEG-SEM has been used to characterize fine bainitic ferrite, martensite and nanosized second phases at simulated coarse and fine grain HAZs. It was found that for Ti bearing steel (Ti/N ratio is 2) austenite grain had the slowest growth rate due to the presence of most stable TiN. The fine cuboidal particles promoted intragranular acicular ferrite (IGF) formation. Nb bearing steel exhibited relatively weaker grain growth retardation compared with titanium bearing steels and a mixed microstructure of bainite and martensite was present for all simulated HAZs. IGF existed at coarse grain HAZ of Ti + V bearing steel but it was totally replaced by bainite at fine grain HAZs. Hardness result was closely related to the morphology of bainitic ferrite, intragranular ferrite and second phases within ferrite. The microstructure and hardness results of different simulated HAZs were in good agreement with welded experimental results.

M.Kazerminezhad, A. Karimi Taheri (2004) 106 – 110 *“Prediction of ferrite grain size and tensile properties of a low carbon steel”* A relationship between ferrite grain size, cooling rate from austenitising temperature, austenitising time, and austenitising temperature is developed to predict the ferrite grain size of a low carbon steel. The coefficients of that relationship are determined experimentally. A Hall - Petch relationship is used to predict the yield stress and fracture stress from the predicted ferrite grain size. Considering the experimental results, maximum errors of 12.5% and 6.5% were found in the prediction of ferrite grain size and strengths, respectively.

Pauli Lehto, Heikki Remes, Tapio Saukkonen, Hannu Hänninen, Jani Romanoff (2013) *“Influence of grain size distribution on the Hall - Petch relationship of weld structural steel”* The strength of polycrystalline metals increases with a decrease in grain size according to the Hall – Petch relationship. However, heterogeneous microstructures deviate from this relationship

depending on the distribution of grain sizes. This paper introduces a rule of mixtures based approach for determining the characteristic length of the microstructure for heterogeneous weld metal. The proposed grain size parameter, the volume – weighted average grain size, is measured experimentally for nine structural steel weld metals and two base materials. The weld metals are found to have a large variety of grain size distributions that are noticeably broader than those of the base material due to differences in phase contents. The results show that the volume – weighted average grain size is able to capture the influence of grain size distribution on the strength of welded structural steel. Based on the experimental results, a modified Hall – Petch relationship is formulated for the strength prediction of heterogeneous micro - structures. The modified relationship is also found to be applicable to data from the literature.

2. Theory

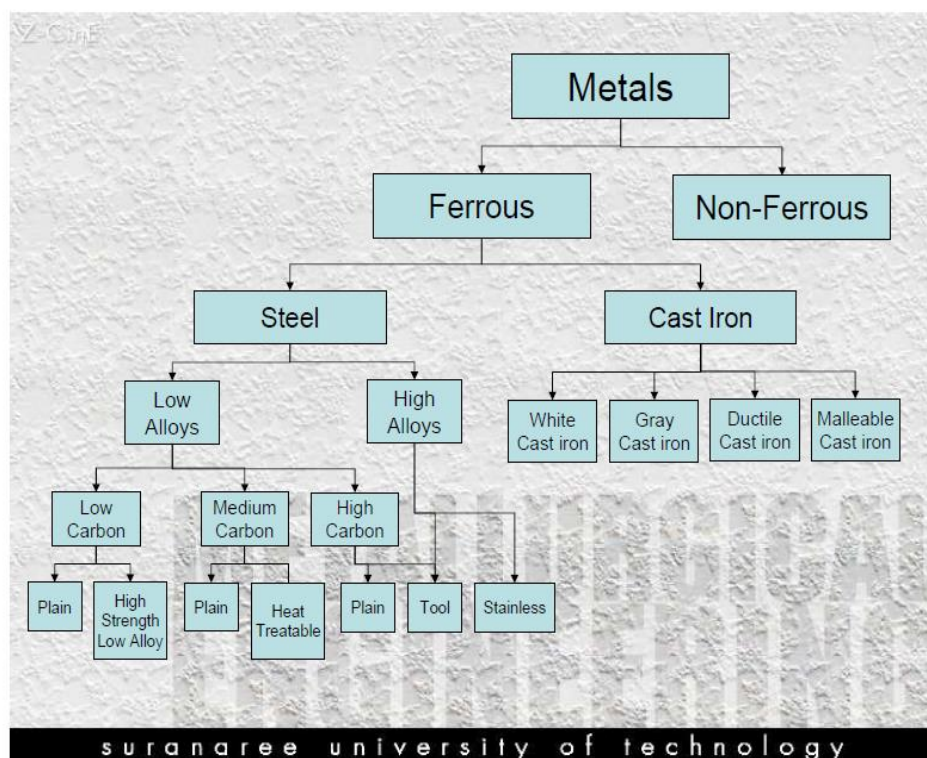


Figure 1 Metals chart

In the metals chart (Figure 1) the steel is an alloy of iron and carbon that is widely used in construction and other applications because of its high tensile strength and low cost. Carbon,

other elements, and inclusions within iron act as hardening agents that prevent the movement of dislocations that naturally exist in the iron atom crystal lattices.

The carbon in typical steel alloys may contribute up to 2.1% of its weight. Varying the amount of alloying elements, their formation in the steel either as solute elements, or as precipitated phases, retards the movement of those dislocations that make iron so ductile and weak, and thus controls qualities such as the hardness, ductility, and tensile strength of the resulting steel. Steel's strength compared to pure iron is only possible at the expense of ductility, of which iron has an excess.

Low alloy steels are one that possesses similar microstructure to, and requires similar heat treatment to, plain carbon steels. These generally contain up to 3.4% of one or more alloying elements for purpose of increasing strength, toughness and hardenability such as Chromium-Molybdenum steel (AISI 4140) or HSLA steel (A572). The applications of low alloy steels are similar to those of plain carbon steels of similar carbon contents. Low alloy steels containing nickel are particularly suitable for applications requiring resistance to fatigue.

High alloy steels. There is a distinction between the low-alloy steels described above and the higher alloy steels (usually containing over 8% alloying elements). The higher alloy steels include stainless steels, tool steels, heat-resistant steels, wear-resistant steels, and ultrahigh-strength steels.

2.1. HSLA steel

High Strength Low Alloy (HSLA) steels were originally developed in the 1960s for large-diameter oil and gas pipelines. The line pipe used in these projects required higher strength and toughness than mild carbon steel, and good weldability provided by a low carbon equivalent. The oil & gas sector is still market where the most important applications for HSLA steels are found, but the automotive and the offshore & onshore structural engineering sectors now consume significant quantities of these alloys. HSLA steels are available today with traditional ferritic - pearlitic, bainitic, martensitic and multiphase microstructures, each available in hot- or cold - rolled steels. The yield strength of contemporary HSLA steels ranges from 260 MPa to over 1000 MPa.

Typically, Mo is used in HSLA steel when the yield strength must be above 550 MPa, or a particular microstructure is demanded. Mo is particularly beneficial for producing bainite (and more specifically for its acicular ferrite variant) and the multiphase microstructures that appear in dual phase, complex phase or TRIP steels.

HSLA steel (high strength low alloy steel) is a type of steel alloy that provides many benefits over regular steel alloys. In general, HSLA alloys are much stronger and tougher than ordinary plain carbon steels. They are used in cars, trucks, cranes, bridges and other structures that are designed to handle a lot of stress, often at very low temperatures.



Figure 2 Line pipe strip and plate, automotive hot & cold-rolled strip, structural plate

HSLA steels are so called because they only contain a very small percentage of carbon. Typical HSLA steel may contain 0.15% carbon, 1.65% manganese and low levels (under 0.035%) of phosphorous and sulfur. It may also contain small amounts of copper, nickel, niobium, nitrogen, vanadium, chromium, molybdenum, silicon or zirconium. HSLA are therefore also referred to as 'micro alloyed', as they are indeed alloyed in extremely small amounts by comparison to other main commercial alloy steels. As little as 0.10% niobium and vanadium can have profound effects on the mechanical properties of 0.1% C, 1.3% Mn steel. These added elements are intended to utterly alter the microstructure of plain carbon steels, which is usually a ferrite - pearlite aggregate, to produce a very fine dispersion of alloy carbides in an almost pure ferrite. This eliminates the toughness-reducing effect of a pearlitic volume fraction, yet maintains and even increases the material's strength by precipitation strengthening and by refining the grain size, which in the case of ferrite increases yield strength by 50% for every halving of the mean grain diameter. Its yield strength can be anywhere between 250-590 MPa (35000-85000 psi).

HSLA steels are also more resistant to rust than most carbon steels. Although the material quickly becomes covered with surface rust, this is superficial and rust takes a long time to threaten the integrity of a structure made from the material. The Angel of the North at Gateshead, England is a well-known example of an unpainted HSLA structure (the actual alloy used

is called COR-TEN and includes a small amount of copper). HSLA steels usually have densities of around $7800 \frac{kg}{m^3}$

All ABS steels are standard carbon steels. All of these steels have been engineered to be optimal long-lived shipbuilding steels. As with other grades of steel, they have a specific gravity of 7.8. Higher-strength ABS shipbuilding steel comes in six grades of two strengths, The ABS EH36 grades have yield strength of 51,000 psi (355 MPa), and ultimate tensile strength of 71,000 - 90,000 psi (490-620 MPa). They are suitable for container and bulk cargo vessels as well as cruise ships, ferries and yachts.

ABS EH36 is a part of HSLA and the chemical composition of specimen and standard property details. One of them is ABS EH36 steel and it is popular less than other steel grade such as SCM440 etc. It is difficult find to buy in local and the best price (cheap).

Table 2 Chemical composition of ABS EH36 for steel plate, angle steel bar, bulb flat bar, L section steel bar.

C	Si	Mn	P	S	Cr	Mo	Ni	V	Al	Cu	Ti	Nb	Fe
	Max		Max	Max	Max	Max	Max		Min	Max	Max		
0.18	0.50	0.9-1.6	0.035	0.035	0.2	0.08	0.40	0.05-0.10	0.015	0.35	0.02	0.02-0.05	Balance

2.2. Chromium - Molybdenum steel

Chromium molybdenum alloys have characteristics that make them good choices for many products used in construction and manufacturing. This article discusses some applications for these materials and the processes and equipment necessary to complete them.

Chromium-molybdenum alloys often are grouped in a single category. The names for this category are nearly as numerous as their uses. Some of the names are chrome moly, croalloy, Chromalloy, and CrMo. These alloys' characteristics make them desirable in many areas of construction and manufacturing. The main characteristics are strength (creep strength and room temperature), rigidity, harden ability, wear resistance, corrosion resistance, fairly good impact resistance (toughness), relative ease of fabrication, and the ability to be alloyed in various ways that create "fitness for use" in some applications.

Instruction: Often unnoticed by the general engineering populace, the value of these alloys in building construction has been brought to the forefront by the 9/11 event. Some innovative engineers realized that this material possibly could have saved hundreds of lives had the towers been constructed with the alloy in some form—most likely A387 Grade 11 or Grade 22. The theory is that the CrMo would have retained approximately 50 percent of its strength at 1,000 degrees F and, therefore, would not have collapsed so quickly. It's possible that the material could be used in constructing skyscrapers and other buildings in the future. Hopefully, a tragedy such as 9/11 will never occur again, but fires that produce similar results are likely to occur.

Automotive and heavy equipment: These alloys have many more uses than once was believed. For a young car racer, a chrome-moly crankshaft was a must-have if he wanted to be a winner. Some drivers had no idea why it was important to have such an alloy in that part of the engine. It was just thought to be the “thing” to have.

Cast-iron crankshafts served automobiles well for many years when the RPMs were relatively low and the highways did not stretch from coast to coast. The horsepower was not great enough to cause crankshaft failure in most cases. Heat didn't build up under the hood the way it does today with modern engines. The crankshaft is a very good example of the benefits of chrome moly in that wear, heat resistance, and strength are all needed properties for an efficient and long-lasting engine.

Modern diesel engines also need very strong crankshafts. Earthmoving machinery has higher horsepower and torque that enable the equipment to move massive amounts of earthen materials (rock, coal, and sand) very rapidly.

The hydraulic systems in this equipment also require good tensile strength and wear resistance to lift the large buckets and shovels that were unheard of just a few years ago. Most of the hydraulic shaft material is CrMo. Axles and roller pins on track machines (bulldozers) are nearly always made of this material in some formula.

One of the major benefits of using this material for heavy-duty machinery is its ability to surface-harden (case-harden) or through-harden. Case hardening allows the surface to be wear-resistant and the interior to be relatively ductile and less brittle.

The tensional strength inherent in CrMo alloys is extremely important in modern high-performance engines. Some of today's street automobiles now have more than 300 HP and torque that were unimaginable some years ago.

Today's race cars have even much more horsepower. Their frames are not built by the automotive manufacturers; they are custom-built to meet the requirements of NASCAR® and other racing affiliates. Most of the frames (nearly all) are fabricated from CrMo tubing. This allows the frames to be made from thinner materials because the strength is greater than that of regular low-carbon steel. Because of its ductility, 4130 CrMo is the most popular for race car frames. Although it is stronger, higher-carbon 4140 is not as ductile. Brittle material renders race cars unsafe.

AISI 4140 Chrome-Molybdenum High Tensile Steel is a chromium-molybdenum alloy steel. The chromium content provides good hardness penetration, and the molybdenum content ensures uniform hardness and high strength. AISI 4140 chrome-molybdenum steel can be oil hardened to a relatively high level of hardness. The desirable properties of the AISI 4140 include superior toughness, good ductility and good wear resistance in the quenched and tempered condition.



Figure 3 AISI 4140 Chrome - Molybdenum high tensile steel.

The AISI 4140 cold finished annealed chromium - molybdenum alloy steel can be heated using various methods to yield a wide range of properties, hence it is often used as stock for forging as it has self-scaling properties. AISI 4140 is capable of resisting creep in temperatures up to 538°C (1000°F) and maintaining its properties even after long exposure at comparatively high working temperatures. The AISI 4140 cold rolled rounds are available in the 41L40 variant that contains 0.15-0.35 lead. The lead content improves machinability, but has significant effect on other desirable properties.

AISI 4140 is versatile because of its simple chemistry and has the following composition: 0.40 % carbon and 0.85 % manganese which offers toughness and can be heat

treated and hardened 0.1 % chromium adds to overall toughness but is not enough to be made into stainless steel and 0.25 % molybdenum, small amounts of sulfur, silicon and phosphorous. The density of AISI 4140 is 7.7 to 8.03 kg/m³ and mechanical properties for AISI 4140 in the annealed state.

Table 3 Chemical composition of AISI 4140

Element	Content
Carbon, C	0.380 - 0.430 %
Chromium, Cr	0.80 - 1.10 %
Iron, Fe	96.785 - 97.77 % (As remainder)
Manganese, Mn	0.75 - 1.0 %
Molybdenum, Mo	0.15 - 0.25 %
Phosphorous, P	≤ 0.035 %
Silicon, Si	0.15 - 0.30 %
Sulfur, S	≤ 0.040 %

Table 4 Mechanical Properties of AISI 4140

Mechanical Properties	Metric	Imperial
Hardness, Brinell	197	197
Hardness, Knoop (Converted from Brinell hardness)	219	219
Hardness, Rockwell B (Converted from Brinell hardness)	92	92
Hardness, Rockwell C (Converted from Brinell hardness. Value below normal HRC range, for comparison purposes only)	13.0	13.0
Hardness, Vickers (Converted from Brinell hardness)	207	207
Tensile Strength, Ultimate	655 MPa	95000 psi
Tensile Strength, Yield	415 MPa	60200 psi
Elongation at Break (in 50 mm)	25.7 %	25.7 %
Modulus of Elasticity (Typical for steel)	205 GPa	29700 ksi
Shear Modulus	80.0 GPa	11600 ksi

Machining: AISI 4140 has good machinability. Operations such as turning, hobbling, drilling, sawing, broaching, tapping and milling can be easily performed using the recommendations provided by the machine's manufacturer for ideal tool type-feeds and speeds. AISI 4140 has the following properties: Machinability rating at 66% of B1112, Average cutting speed of 110 ft/min.

Weld ability: AISI 4140 is difficult to weld, but welding can be performed using any of the common welding practices. Welding can be done by preheating the section and ensuring that stress relieving takes place after welding. It is basically recommended that welding of AISI 4140 steel in the hardened and tempered condition should be avoided as it changes the mechanical properties within the weld heat affected zone. Likewise welding in the nitrided, flame or induction hardened condition is not recommended. However welding of AISI 4140 chrome-molybdenum steel in the annealed condition is widely preferred. In case welding in the hardened and tempered condition is required, the work piece must be cooled instantly and the stress is relieved at 15°C below the original tempering temperature. When welding AISI 4140 steel (in any condition) only low hydrogen electrodes should be used. Following welding, the maximum cooling rate that should be employed is 95°C /hr down to 95°C. This should be followed by cooling in still air. The cooling rate can be slowed by wrapping the work piece in a heat resistant blanket or burying it in sand.

Heat Treatment: There are various heat treatments of the AISI 4140 Chrome-Molybdenum High Tensile Steel which are

Forging:

1. Can be heated to 1150°C and maintained until uniform
2. Minimum forging temperature 850°C
3. Can be cooled slowly in sand or ash

Stress Relieving

1. Hardened: Heat to 500°C – 550°C
2. Annealed: Heat to 600°C – 650°C
3. Cool in still air

Annealing

1. Heat to 830°C – 850°C
2. Furnace cool

Normalizing

1. Heat to 870°C – 900°C
2. Cool in still air

Nitriding

1. Heat to 500°C – 530°C and hold for sufficient time to develop the depth of case required
2. Parts should be pre-hardened and tempered as required and also pre-machined leaving a small grinding allowance only.

Tempering

1. Heat to 450°C – 700°C cool in still air
2. Tempering in the range of 200°C – 420°C causes temper brittleness and should be avoided

Flame and Induction Hardening

All materials consisting of de-carburized surfaces should be removed to ensure best results.

1. Heat quickly to the required case depth at 860°C – 890°C and soak instantly in water or oil
2. Tempering at 150°C – 200°C helps reduce stresses in the case with marginal effect on its hardness

Hardening

1. Hardening
2. Heat to 830°C – 880°C
3. Soak in oil or polymer

AISI 4140 is used extensively in most industry sectors for a wide range of applications such as:

Strippers	bolts	axle shafts
tool bodies	bolsters	holder blocks
stubs	crankshafts	tool holders
machinery parts and components	mold bases	couplings
connecting rods	tie rods	conveyor parts
ejectors	reamer bodies	chuck bodies
boring bars	crow bars	back up and support tooling
axles	collets	guides
logging parts	fixtures	piston rods
conveyor pins & rolls	tracks	shafts
jigs	rams	ejector pins
ways	sprockets	molds
hydraulic machinery shafts	forks	slides
studs	cams	gears
guide rods	wear strips or parts	pump shafts
drill collars	sprockets	torsion bars
forming dies	ring gears	gear racks
chain links	lathe spindles	brake dies
adapters	valves	spindles
logging parts	trim dies	arbors
milling spindles	motor shafts	pinch bars
pins	pinions	nuts
pump shafts	tool holders	sockets

2.3. Welding Electrodes

An electrode is a metal wire that is coated. It is made out of materials with a similar composition to the metal being welded. There are a variety of factors that go into choosing the right electrode for each project. SMAW or stick electrodes are consumable, meaning they become part of the weld, while TIG electrodes are non-consumable as they do not melt and become part of the weld, requiring the use of a welding rod. The MIG welding electrode is a continuously fed wire referred to as wire. Electrode selection is critical to ease of cleanup, weld strength, bead quality and for minimizing any spatter. Electrodes need to be stored in a moisture free environment and carefully removed from any package (follow the directions to avoid damage).

Covered Welding Electrodes

When molten metal is exposed to air, it absorbs oxygen and nitrogen, and becomes brittle or is otherwise adversely affected. A slag cover is needed to protect molten or solidifying weld metal from the atmosphere. This cover can be obtained from the electrode coating. The composition of the welding electrode coating determines its usability, as well as the composition of the deposited weld metal and the electrode specification. The formulation of Welding electrode coatings is based on well-established principles of metallurgy, chemistry, and physics. The coating protects the metal from damage, stabilizes the arc, and improves the weld in other ways, which include:

1. Smooth weld metal surface with even edges.
2. Minimum spatter adjacent to the weld.
3. A stable welding arc.
4. Penetration control.
5. A strong, tough coating.
6. Easier slag removal.
7. Improved deposition rate.

The metal-arc electrodes may be grouped and classified as bare or thinly coated electrodes, and shielded arc or heavy coated electrodes. The covered electrode is the most popular type of filler metal used in arc welding. The composition of the electrode covering determines the usability of the electrode, the composition of the deposited weld metal, and the specification of the electrode. The type of electrode used depends on the specific properties required in the weld deposited. These include corrosion resistance, ductility, high tensile

strength, the type of base metal to be welded, the position of the weld (flat, horizontal, vertical, or overhead); and the type of current and polarity required.

Classification

The American Welding Society's classification number series for welding electrodes has been adopted by the welding industry. The electrode identification system for steel arc welding is set up as follows:

1. E indicates electrode for arc welding.
2. The first two (or three) digits indicate tensile strength (the resistance of the material to forces trying to pull it apart) in thousands of pounds per square inch of the deposited metal.
3. The third (or fourth) digit indicates the position of the weld. 0 indicates the classification is not used; 1 is for all positions; 2 are for flat and horizontal positions only; 3 are for flat position only.
4. The fourth (or fifth) digit indicates the type of electrode coating and the type of power supply used; alternating or direct current, straight or reverse polarity.
5. The types of coating, welding current, and polarity position designated by the fourth (or fifth) identifying digit of the electrode classification are as listed in table 2.3
6. The number E6010 indicates an arc welding electrode with a minimum stress relieved tensile strength of 60,000 psi; is used in all positions; and reverse polarity direct current is required.

Coating, Current and Polarity types Designated by the Fourth Digit in the Electrode Classification Number. When the fourth (or last) digit is 0, the type of coating and current to be used is determined by the third digit. The welding electrode identification system for stainless steel arc welding is set up as follows:

1. E indicates electrode for arc welding.
2. The first three digits indicated the American Iron and Steel type of stainless steel.
3. The last two digits indicate the current and position used.
4. The number E-308-16 by this system indicates stainless steel Institute type 308; used in all positions; with alternating or reverse polarity direct current.

Table 5 Electrode Classification Number

Digit	Coating	Weld Current
0	*	*
1	Cellulose Potassium	ac, dcrp, dcsp
2	Titania sodium	ac, dcsp
3	Titania potassium	ac, dcsp, dcrp
4	Iron Powder Titania	ac, dcsp, dcrp
5	Low hydrogen sodium	dcrp
6	Low hydrogen potassium	ac, dcrp
7	Iron powder iron oxide	ac, dcsp
8	Iron powder low hydrogen	ac, dcrp, dcsp

The principal types of welding electrode coatings for mild steel and are described below.

1. Cellulose-sodium (EXX10): Electrodes of this type cellulosic material in the form of wood flour or reprocessed low alloy electrodes have up to 30 percent paper. The gas shield contains carbon dioxide and hydrogen, which are reducing agents. These gases tend to produce a digging arc that provides deep penetration. The weld deposit is somewhat rough, and the spatter is at a higher level than other electrodes. It does provide extremely good mechanical properties, particularly after aging. This is one of the earliest types of electrodes developed, and is widely used for cross country pipe lines using the downhill welding technique. It is normally used with direct current with the electrode positive (reverse polarity).

2. Cellulose-potassium (EXX11): This electrode is very similar to the cellulose-sodium electrode, except more potassium is used than sodium. This provides ionization of the arc and makes the electrode suitable for welding with alternating current. The arc action, the penetration, and the weld results are very similar. In both E6010 and E6011 electrodes, small amounts of iron powder may be added. This assists in arc stabilization and will slightly increase the deposition rate.

3. Rutile-sodium (EXX12): When rutile or titanium dioxide content is relatively high with respect to the other components, the electrode will be especially appealing to the welder. Electrodes with this coating have a quiet arc, an easily controlled slag, and a low level of spatter. The weld deposit will have a smooth surface and the penetration will be less

than with the cellulose electrode. The weld metal properties will be slightly lower than the cellulosic types. This type of electrode provides a fairly high rate of deposition. It has a relatively low arc voltage, and can be used with alternating current or with direct current with electrode negative (straight polarity).

4. Rutile-potassium (EXX13): This electrode coating is very similar to the rutile-sodium type, except that potassium is used to provide for arc ionization. This makes it more suitable for welding with alternating current. It can also be used with direct current with either polarity. It produces a very quiet, smooth running arc.

5. Rutile-iron powder (EXXX4): This coating is very similar to the rutile coatings mentioned above, except that iron powder is added. If iron content is 25 to 40 percent, the electrode is EXX14. If iron content is 50 percent or more, the electrode is EXX24. With the lower percentage of iron powder, the electrode can be used in all positions. With the higher percentage of iron powder, it can only be used in the flat position or for making horizontal fillet welds. In both cases, the deposition rate is increased, based on the amount of iron powder in the coating.

6. Low hydrogen-sodium (EXXX5): Coatings that contain a high proportion of calcium carbonate or calcium fluoride are called low hydrogen, lime ferritic, or basic type electrodes. In this class of coating, cellulose, clays, asbestos, and other minerals that contain combined water are not used. This is to ensure the lowest possible hydrogen content in the arc atmosphere. These electrode coatings are baked at a higher temperature. The low hydrogen electrode family has superior weld metal properties. They provide the highest ductility of any of the deposits. These electrodes have a medium arc with medium or moderate penetration. They have a medium speed of deposition, but require special welding techniques for best results. Low hydrogen electrodes must be stored under controlled conditions. This type is normally used with direct current with electrode positive (reverse polarity).

7. Low hydrogen-potassium (EXXX6): This type of coating is similar to the low hydrogen-sodium, except for the substitution of potassium for sodium to provide arc ionization. This electrode is used with alternating current and can be used with direct current, electrode positive (reverse polarity). The arc action is smothering, but the penetration of the two electrodes is similar.

8. Low hydrogen-potassium (EXXX6): The coatings in this class of electrodes are similar to the low-hydrogen type mentioned above. However, iron powder is

added to the electrode, and if the content is higher than 35 to 40 percent, the electrode is classified as an EXX18.

9. Low hydrogen-iron powder (EXX28): This electrode is similar to the EXX18, but has 50 percent or more iron powder in the coating. It is usable only when welding in the flat position or for making horizontal fillet welds. The deposition rate is higher than EXX18. Low hydrogen coatings are used for all of the higher-alloy electrodes. By additions of specific metals in the coatings, these electrodes become the alloy types where suffix letters are used to indicate weld metal compositions. Electrodes for welding stainless steel are also the low-hydrogen type.

10. Iron oxide-sodium (EXX20): Coatings with high iron oxide content produce a weld deposit with a large amount of slag. This can be difficult to control. This coating type produces high-speed deposition, and provides medium penetration with low spatter level. The resulting weld has a very smooth finish. The electrode is usable only with flat position welding and for making horizontal fillet welds. The electrode can be used with alternating current or direct current with either polarity.

11. Iron-oxide-iron power (EXX27): This type of electrode is very similar to the iron oxide-sodium type, except it contains 50 percent or more iron power. The increased amount of iron power greatly increases the deposition rate. It may be used with alternating direct current of either polarity.

There are many types of coatings other than those mentioned here, most of which are usually combinations of these types but for special applications such as hard surfacing, cast iron welding, and for nonferrous metals.

Welding Filler Metal Designators: carbon steel electrodes

E XX YY – 1 HZ R

Mandatory Classification Designators:

E = Designates an Electrode

XX = Designates minimum tensile strength, in Ksi, of the as-deposited weld metal.

YY = Designates the welding position, the type of covering and the type of welding current for which the electrodes are suitable.

Optional Supplemental Designators:

1 = Designates that the electrode meet the requirements for improved toughness and ductility.

HZ = Designates that the electrode meets the requirements of the diffusible hydrogen test with an average value not exceeding "Z" mL of H₂ per 100 gms of deposited metal.

R = Designates that the electrode meets the requirements of absorbed moisture.

Table 6 Carbon and Low-Alloy Steel Welding Consumables for SMAW Process

Base material	Carbon Steel	Carbon-Molybdenum Steel	1 and 1 1/4 Cr-1/2 Mo Steel	2 1/4 Cr-1 Mo Steel	5Cr- 1/2 Mo Steel	9Cr-1Mo Steel
Carbon steel	AB	AC	AD	AE	AF	AG
Carbon-Molybdenum Steel		C	CD	CE	CF	CH
1 and 1 1/4 Cr - 1/2 Mo Steel			D	DE	DF	DH
2 1/4 Cr - 1 Mo Steel				E	EF	EH
5 Cr - 1/2 Mo Steel					F	FH
9 Cr- 1 Mo Steel						H

Legend:

- A AWS A 5.1 Classification E 70XX low hydrogen (E7018 preferred)
- B AWS A 5.1 Classification E6010
- C AWS A 5.5 Classification E70XX - A1, low hydrogen
- D AWS A 5.5 Classification E70XX-B2L or E80XX-B2, low hydrogen
- E AWS A 5.5 Classification E80XX-B3L or E90XX-B3, low hydrogen
- F AWS A 5.5 Classification E80XX-B6 or E80XX-B6L, low hydrogen
- G AWS A 5.5 Classification E80XX-B7 or E80XX-B7L, low hydrogen
- H AWS A 5.5 Classification E80XX-B8 or E80XX-B8L, low hydrogen

2.3.1. E7016

Welding electrodes AWS E7016/J506 is a kind of electrode with low-hydrogen potassium type coating AC / DC. All position welding. It has excellent welding performance, stable arc, fewer spatters and good slag detachability. The deposited metal has excellent mechanical properties, crack-resistance and good low temperature impact toughness. Used for welding medium-carbon steel and low-alloy steel structures, such as 16Mn, 09Mn2Si and A, B, D and E steel for ships, and also used for welding on thick plates and hard-to-weld carbon steel structures.

Table 7 Chemical Composition of Deposited Metal (%)

Chemical Composition	C	Mn	S	Si	P	Ni	Mo	Cr	V
Guarantee Value	≤0.12	≤1.60	≤0.75	≤0.035	≤0.040	≤0.30	≤0.30	≤0.20	≤0.08

Table 8 Mechanical Properties of Deposited Metal

Test Item	R _m (MPa)	R _{eL} (Mpa)	A (%)	KV ₂ (J)	KV ₂ (J)
Guarantee Value	≥490	≥400	≥22	≥47(-20°C)	≥27(-30°C)
General Result	520~580	≥410	25~33	110~250	100~240

Diffusible Hydrogen Content in Deposited Metal: ≤8.0ml/100g (Glycerine Hydrogen Test)

X-ray Radiographic Inspection: IDegree

Table 9 Reference Current (AC, DC+)

Electrode Diameter (mm)	φ2.5	φ3.2	φ4.0	φ5.0
Welding Current (A)	60~100	80~140	110~210	160~230

Instructions:

1. The electrodes must be baked under 300~350 °C for an hour before welding and used as soon as baking is completed.
2. The stains on the weldments, such as rust, oil stains, moisture, etc., must be cleared away before welding.
3. When welding, short arc must be used and stringer bead is suitable.

2.4. Welding of HSLA Steel method & Weld ability of HSLA Steel

The development and use of high strength low alloy (HSLA) steels has been driven by the need to reduce costs, the higher strength compared with conventional carbon-manganese steel enabling thinner and lighter structures to be erected. The majority of these steels are to be found in structural applications; offshore structures, yellow goods, buildings, shipbuilding *etc.* Tensile strengths of up to 690MPa are achievable whilst still maintaining good weld ability and high notch toughness, often better than 50J at -60°C.

There are two methods by which both high tensile strength and toughness is achieved - by micro-alloying, adding small amounts of strong carbide and nitride formers and by very careful control of the rolling temperature - controlled rolling or thermo-mechanically controlled processing (TMCP steels).

The highest strengths are achieved by a combination of the two methods. The aim of both methods is to produce as small a grain size as possible, fine grain giving the best notch toughness and each halving of the grain diameter producing a 50% increase in tensile strength.

Improved weld ability is an additional objective and this is achieved by reducing the harden ability of the steel, the carbon content of some steels being lower than 0.05%C, and reducing undesirable elements such as sulphur and phosphorous to as low a level as possible.

To compensate for the loss of carbon and to increase tensile strength small additions of alloying elements such as niobium (<0.10%), titanium (<0.030%) and vanadium (<0.15%) are made, perhaps also with small amounts of molybdenum, chromium, copper and nitrogen. These elements are strong carbide and nitride formers, producing a fine dispersion of stable precipitates that inhibit grain growth during hot rolling and assist in nucleating fine grained ferrite during cooling.

These elements also provide some increase in strength by precipitation hardening. Controlled rolling by the TMCP hot rolling method may also be used to provide additional grain refinement and hence an increase in tensile strength and toughness. TMCP is carried out at a

temperature about or just below the recrystallization temperature of the steel *i.e.* below about 900°C, resulting in elongated crystals of austenite. An accelerated cooling from the rolling temperature then causes very fine grained ferrite to form on the austenite grain boundaries.

Despite the improved weld ability of these steels there are some fabrication problems. Firstly, hydrogen induced cold cracking. The low carbon content - and hence low carbon equivalent, sometimes less than $0.30CE_v$ - means that these steels have a low sensitivity to hydrogen cold cracking (see Job Knowledge 45 but note that the standard IIW carbon equivalent formula is not valid for all of these steels and cannot always be relied upon when calculating preheat temperatures).

The HSLA steels can therefore be welded with lower preheats than would be permitted for conventional carbon-manganese steels, despite their higher strength. The highest risk of cold cracking in these types of steels is therefore in the weld metal, rather than the HAZ. There are several reasons for this; a) The high strength of the parent metal means higher residual stresses during welding, b) To match the tensile strength and toughness of the parent steel, the filler metals need to be more highly alloyed and therefore will have a higher CE_v , perhaps as high as $0.6CE_v$ (IIW) if matching the tensile strength of a 700MPa yield steel with an E11018-G electrode. c) The weld metal transforms from austenite to ferrite at a lower temperature than the parent steel (it is generally the other way round in a conventional carbon-manganese steel) meaning that any hydrogen in the HAZ is rejected into the still austenitic weld metal which has a high solubility for hydrogen. A preheat based on the weld metal composition is therefore advisable and low hydrogen techniques must be used. The exceptions to this rule are those HSLA pipeline steels specifically designed to be welded with cellulosic electrodes. Advice regarding the preheat temperature for specific steels should be sought from the steel manufacturer.

Secondly, even though steels generally have very low levels of sulphur, the steels containing less than 0.05%C may suffer from solidification cracking in the root pass of butt joints, particularly if the root bead is deposited at a high welding speed. The reason for this is that high dilution of the filler metal produces a weld metal low in carbon. This low carbon content in its turn leads to excessive grain growth of the austenite during welding and these large grains increase the risk of centre line solidification cracking in the root bead. This problem appears to be most prevalent in pipe butt joints welded using cellulosic electrodes, probably due to it being possible to use a fast, vertical-down welding technique.

Thirdly, toughness and strength in the HAZ can be an issue. The steel manufacturer takes great care to control rolling temperatures and cooling rates to provide the desired properties. The component is then welded, producing a heat affected zone that has experienced an uncontrolled cycle of heat treatment. The microstructure in the HAZ will vary with respect to the composition of the steel and the welding process heat input. A high heat input will promote grain growth and this will have an adverse effect on both strength and toughness. As a rule of thumb, heat input should be restricted to around 2.5kJ/mm maximum and the inter pass temperature maintained at 250°C maximum, although some of the steels containing titanium and boron can tolerate heat inputs as high as 4.5kJ/mm without undue loss of strength. For a definitive statement on heat input control the advice of the steel manufacturer should be sought.

These steels must under no circumstances be normalised or tempered although post weld heat treatment (PWHT) is often a requirement when the component thickness is greater than some 35 to 40mm. Care needs to be taken if PWHT is applied that the soak temperature does not exceed 600°C; a temperature range of 550°C to 600°C is often specified. The reason for this is that many of the TMCP steels are accelerated cooled to a temperature of around 620°C; heat treating at or close to this temperature will result in a substantial reduction in tensile strength due to over-tempering. The same restriction applies to any hot working activity - plate must not be hot rolled and the temperature of local heating for correction of distortion must not be allowed to exceed 600°C.

2.5. Welding of Chromium-Molybdenum steel method & Weld ability of Chromium-Molybdenum steel

At least a dozen chromium molybdenum (CrMo) steel combinations exist. One of the more recent alloys consists of chromium, molybdenum, vanadium, niobium (columbium), and nitrogen. Beginning sometime in the 1970s, this material became popular for use in high-temperature applications, such as gas and coal-fired power plants. However, it is not intended to replace other CrMo types. Each alloy has its own place in the high-strength, low-alloy group of materials.

Composition

All alloys vary in composition, but ASTM and ASME guidelines specify a range of percentages for the elements in each. This chart shows the nominal percentages for the P-91 type.

Table 10 Nominal percentages for the P-91 type chart

Type	C	Mn	S	P	Si	Cr	Mo
9Cr-1Mo	0.15	0.30-0.60	0.030	0.030	0.20-0.50	8.0-10.0	0.85-0.105
9Cr-1Mo*	0.08-0.12	0.30-0.60	0.010	0.020	0.20-0.50	0.800-0.950	0.85-1.05

*Also may contain 0.18-0.25 vanadium (V); 0.06-0.10 niobium/columbium (Nb/Cb); and 0.03-0.07 nitrogen (N).

The alloy containing V, Nb/Cb, and N is a purer combination of elements. The lower carbon, sulfur, and phosphorus content require stricter refinement. At first glance, it appears that with its lower carbon (C) content, the vanadium-bearing type would have a lower tensile strength. However, the vanadium makes the tensile strength higher. ASME Section IX specifies a minimum 60,000 PSI for the non vanadium type and 85,000 for the vanadium-bearing type.

Note that P-91 is *not* an ASME “P” number designation. The “P” number for the non vanadium type is P-5B, and the vanadium-bearing type is P-15E. It also should be noted that the Unified Numbering System (UNS) differentiates the types as well. The non vanadium-bearing type is listed as K90941, and the vanadium-bearing type is listed as K90901.

Uses

The 9Cr-1Mo material is prevalent for burning nozzles in power plants and other high-temperature applications because of its creep resistance—its ability to maintain tensile strength at elevated temperatures. The 9Cr-1Mo with V, Nb (Cb), and N is even more resistant to creep and high-temperature hydrogen attack. These additions cause the material to maintain its tensile strength even at sustained high temperatures in boilers, furnaces, and furnace cars.

When working with any used CrMo material, particularly 9Cr-1Mo, you must take extra care. Take into consideration the temperature the material has been exposed to and the length of time it has been in-service *and* out-of-service. The material is sensitive to hydrogen attack, and certain applications cause it to be even more prone to hydrogen cracking.

In-service history should be evaluated based on repetitions of heating and cooling, exposure to certain atmospheric conditions, and data reports for any intermediate repairs or alterations that may have been performed. Some out-of-service conditions that can affect the material are incorrect handling, such as lifting and turning; and exposure to extreme

atmospheric conditions, such as excess moisture, chemicals, and temperature variances. Cleaning used material is extremely important. Foreign materials, especially those that produce carbon, can cause serious problems during welding. It often is advisable to blast the material to near white and then apply a chemical cleaning process before welding.

Welding Considerations

Although welding equipment suppliers, handbooks for welding, and other sources say these alloys are readily weld able, extreme care and caution are highly suggested. The very nature of 9Cr-1Mo—its susceptibility to hydrogen attack that can cause delayed cracking, and a limited availability of weld materials, to name a couple of trouble spots—indicates the need for special cleaning, preheating, post heating, and post weld heat treatment. Before beginning a project using any material, it is important that you obtain a copy of the material test report (MTR). It is critical to determine whether some of the elements are on the high or low end of the allowed range in the specification. A typical analysis is not sufficient for determining the projected behavior of the 9Cr-1Mo material. The heat-treatment methods used to produce the material must be considered. For example, was it annealed, quenched and tempered, or purchased as rolled or extruded?

The mechanical properties such as tensile strength, yield strength, elongation, and reduction of area also are important in reference to the material's ductility. This information helps you determine the appropriate welding process, the filler metal type, preheat and the post weld heat treatment (PWHT) temperatures (1,350 degrees to 1,425 degrees F), and method to use. Charpy V-notch tests also can be very useful for determining the material's toughness. As previously mentioned, because the material is susceptible to hydrogen attack, cleaning is critical. The weld area and at least 4 inches on each side of the weld should be super clean. The welding procedure should specify cleaning methods, such as blasting, grinding, wire brushing, and/or chemical. A good chemical may be the citrus type recommended for weld cleaning.

Preheating

Preheating is not an option! It is a must! The minimum preheat and inter pass temperature must be at least 350 degrees F for materials less than 0.500 in. thick and 450 to 550 degrees for greater thicknesses. The preheat temperature must be carefully maintained until the welding is completed. One of the most frequent problems with welding this material is

allowing the heat to diminish ahead of the weld. This is especially true with thicker material. The method of preheating (whether by local torch heating, furnace, or electrical wrap) should be based on the overall size, thickness, and, of course, available equipment. A finely controlled thermo-recordable method always is preferable to the local torch method. This resistance-type equipment typically is readily available for rent.

When performing large fabrications, such as furnace cars with SA387-Gr91, the preheating process is more difficult. It usually is not possible for a small to medium-sized fabricator to place 20- to 30-ft.-long parts in a furnace. The resistance heating method is a good choice in these cases. The blanket can be lifted in the area to be welded without cycling the heat throughout the whole part. This is very handy for welding in the small bosses and other attachments. These parts can be placed in a small furnace until they are ready to be welded to the main structure.

Electrodes and Filler Metals

Use low-hydrogen electrodes and filler metal with this material. Some preferred electrodes for welding 9Cr-1Mo with shielded metal arc welding (SMAW) are E505-1X (produced to be corrosion-resistant), E8018-B8, or B8L. For the solid-wire processes—gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW)—use ER505 or ER80S-B8. Submerged arc welding (SAW) also uses the same classification of wires and a suitable flux.

For flux-cored arc welding (FCAW), E505T-1 or T-2, E815-B8, or E60T5-B8L can be used. However, there is some concern about the Charpy impact values and FCAW wires. For 9Cr-1Mo with V, Nb/Cb, and N, the preferred SMAW electrodes are E9018-B9 or E9015-B9. The E9015-B9 electrode is less likely to cause hydrogen attack because the coating does not contain all the elements, such as iron powder, that absorb hydrogen. The same processes, electrodes, filler metals, and flux can be used for welding SA387-Gr9 and SA387-Gr91. Use ER90S-B9 filler metal when welding 9Cr-1Mo containing V, Nb/Cb, and N with GTAW and GMAW. This wire is unlikely to cause hydrogen problems, especially with GTAW. The same filler metal may be used for SAW. The filler metal also minimizes the possibility of hydrogen attack with the SAW process, provided the flux is kept hydrogen-free by continuous drying. Using a *vented* heater in the flux hopper is a good way to prevent moisture. The flux should not be reused when welding this material. Relatively few fabricators are familiar with this material. Although it can be fabricated and welded satisfactorily, you need to understand the material and its requirements fully before welding.

2.6. Fusion Welding

Types of welding processes

Welding is a material joining process for a permanent combining of two (or more) parts that involves melting and subsequent solidification of the material from two parts thus forming a strong joint between them. The assemblage of parts is called a weldment.

There are two groups of welding processes according to the state of the base material during the welding process:

1. Liquid-state welding (fusion welding).
2. Solid-state welding.

Fusion welding is by far the more important category. In fusion welding, the base material is heat to melt. The most important processes in this group fall in the following categories:

1. Oxyfuel gas welding: an oxyfuel gas produces a flame to melt the base material.
2. Arc welding: heating and melting of the material is accomplished by an electric arc.
3. Resistance welding: the source of heat is the electrical resistance on the interface between two parts held together under pressure.

In solid-state welding, two parts are jointed together under pressure or a combination of pressure and heat. If heat is applied, the contact temperature is below the melting point of the base metal. Two welding processes are the most popular from this group.

1. Diffusion welding: parts coalesce by solid-state diffusion.
2. Friction welding: coalescence is achieved by the heat of friction between two parts.

Most of the processes for fusion welding and for solid-state welding are discussed in the present section.

Oxyfuel gas welding

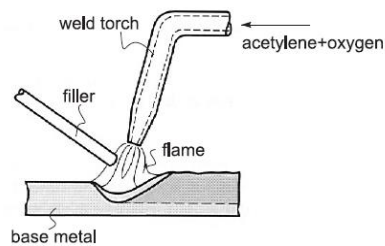


Figure 4 Oxyfuel gas welding operation

Oxyfuel gas welding is the term used to describe the group of fusion operations that burn various fuels mixed with oxygen to perform welding or cutting and separate metal plates and other parts. The most important oxyfuel gas welding process is oxyacetylene welding.

Oxyacetylene welding (OAW) is a fusion welding process performed by a high-temperature flame from combustion of acetylene and oxygen. The flame is directed by a welding torch and a filler metal in the form of rod is added if the process is applied to weld. Composition of the filler must be similar to that of the base metal.

A typical oxyacetylene welding operation is sketched in the Figure 4. Oxyacetylene welding uses equipment that is relatively inexpensive and portable. It is therefore an economical, versatile process that is well suited to low-quantity production and repair jobs. It is rarely used on the welding of sheet and plate stock thicker than 6 mm because of the advantages of arc welding in such applications. Although OAW can be mechanized, it is usually performed manually and is hence dependent on the skill of the welder to produce a high-quality weld joint.

Arc welding with consumable electrodes

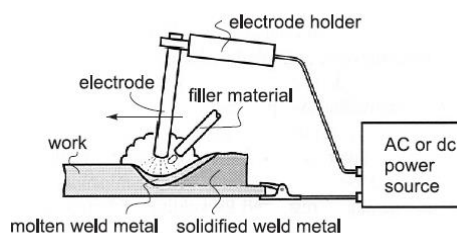


Figure 5 The basic configuration of an arc welding operation

Arc welding (AW) is a fusion welding process in which coalescence of the metals is achieved by the heat from an electric arc between an electrode and the work. A generic AW process is shown in the Figure 5

An electric arc is a discharge of electric current across a gap in a circuit. To initiate the arc in an AW process, the electrode is brought into contact with the work and then quickly separated from it by a short distance. The electric energy from the arc thus formed produces temperatures of 5000o C or higher, sufficiently hot to melt any metal. A pool of molten metal, consisting of base metal(s) and filler metal (if one is used), is formed near the tip of the electrode. In most arc welding processes, filler metal is added during the operation to increase the volume and strength of the weld joint. As the electrode is moved along the joint, the molten weld pool solidifies in its wake.

Movement of the electrode relative to the work is accomplished by either a human welder (manual welding) or by mechanical means (machine welding, automatic welding, or robotic welding). In manual arc welding, the quality of the weld joint is very dependent on the skill and experience of the human welder. The weld quality is much better in the machine, automatic, and robotic welding.

Electrodes in AW process are classified as

1. Consumable, which melts continuously in the process of arc welding thus providing the required filler material.
2. Non-consumable, which resist melting by the arc. The filler material must be supplied separately.

The same classification is applied to the arc welding processes; some of the most important processes based on consumable electrodes are discussed in this section, and processes, which use non-consumable electrodes, are included in the next section.

Shielded Metal Arc Welding

Shielded Metal Arc Welding (SMAW) is an arc welding process that uses a consumable electrode consisting of a filler metal rod coated with chemicals that provide flux and shielding. The process is illustrated in the Figure 6

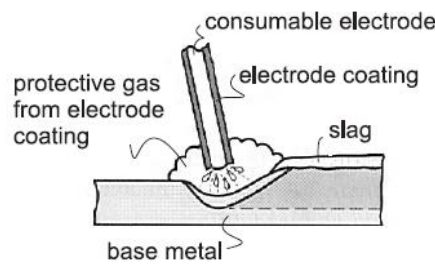


Figure 6 Shielded metal arc welding operation.

The coated welding stick (SMAW is sometimes called stick welding) is typically 200 to 450 mm long and 1.5 to 9.5 mm in diameter. The heat of the welding process melts the coating to provide a protective atmosphere and slag for the welding operation. During operation the bare metal end of the welding stick is clamped in an electrode holder connected to the power source. The holder has an insulated handle so that it can be held and manipulated by a human welder. Currents typically used in SMAW range between 30 and 300 A at voltages from 15 to 45 V depending on the metals being welded, electrode type and length and depth of weld penetration required.

Shielded metal arc welding is usually performed manually. Common applications include construction, pipelines, machinery structures, shipbuilding, fabrication job shops, and repair work. It is preferred over oxyfuel welding for thicker sections above 5 mm because of its higher power density. The equipment is portable and low cost, making SMAW highly versatile and probably the most widely used of the AW welding processes. Base metals include steels, stainless steels, cast irons, and certain nonferrous alloys.

Submerged Arc Welding

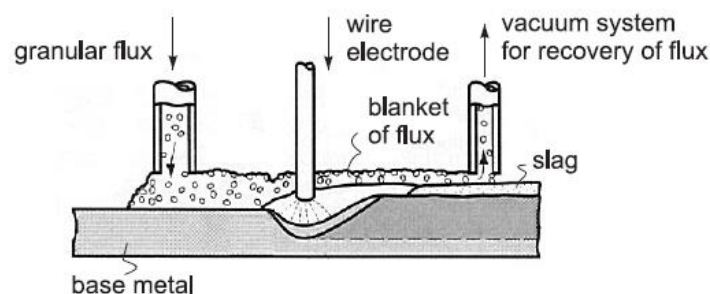


Figure 7 Submerged arc welding operation.

Submerged arc welding (SAW) is an arc welding process that uses a continuous, consumable bare wire electrode. The arc shielding is provided by a cover of granular flux. The electrode wire is fed automatically from a coil into the arc. The flux is introduced into the joint slightly ahead of the weld arc by gravity from a hopper, as shown in the Figure 7

The blanket of granular flux completely submerges the arc welding operation, preventing sparks, spatter, and radiation that are so hazardous in other arc welding processes. The portion of the flux closest to the arc is melted, mixing with the molten weld metal to remove impurities and then solidifying on top of the weld joint to form a glasslike slag. The slag and infused flux granules on top provide good protection from the atmosphere and good thermal insulation for the weld area. This results in relatively slow cooling and a high-quality weld joint. The infused flux remaining after welding can be recovered and reused. The solid slag covering the weld must be chipped away usually by manual means.

This process is widely used for automated welding of structural shapes, longitudinal and circumferential seams for large-diameter pipes, tanks, and pressure vessels. Because of the gravity feed of the granular flux, the parts must always be in a horizontal orientation.

Gas Metal Arc Welding

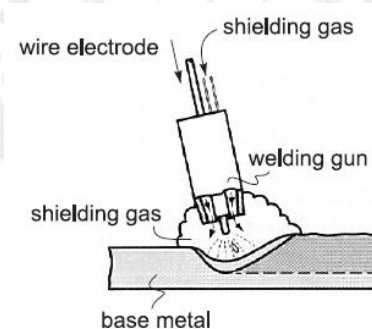


Figure 8 Gas metal arc welding operation.

Gas Metal Arc Welding (GMAW) is an arc welding process in which the electrode is a consumable bare metal wire and shielding is accomplished by flooding the arc with a gas. The bare wire is fed continuously and automatically from a spool through the welding gun, as illustrated in the Figure 8

Wire diameters ranging from 1 to 6 mm are used in GMAW, the size depending on the thickness of the parts being joined. Gases used for shielding include inert gases such as argon and helium and active gases such as carbon dioxide. Selection of gases depends mainly on the metal being welded.

Inert gases are used for welding aluminum alloys and stainless steel and in this case the process is often referred to as MIG/MAG welding (for metal-inert gas/metal-argon welding). In welding steel, carbon dioxide (CO₂), which is less expensive than inert gases, is used. Hence, the term CO₂ welding is applied.

Arc welding with non-consumable electrodes

Several arc welding processes use non-consumable electrodes.

Gas Tungsten Arc Welding

Gas Tungsten Arc Welding (GTAW) is an arc welding process that uses a non-consumable tungsten electrode and an inert gas for arc shielding. Shielding gases typically used include argon, helium or a mixture of these gases. The GTAW process can be implemented with or without a filler metal. The Figure 9 illustrates the latter case. When thin sheets are welded to close tolerances, filler metal is usually not added. When a filler metal is used, it is added to the weld pool from a separate rod or wire. The term TIG welding (tungsten inert gas welding) is often applied to this process.

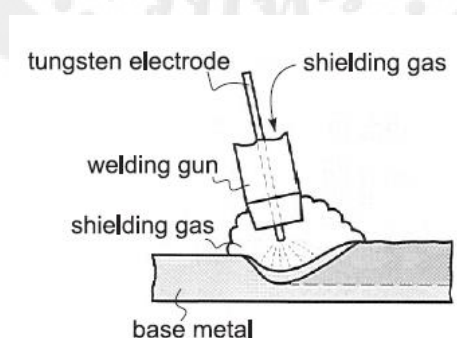


Figure 9 Gas tungsten arc welding operation.

GTAW is applicable to nearly all metals in a wide range of stock thickness. It can also be used for joining various combinations of dissimilar metals. Its most common applications are for aluminum and stainless steel.

The process can be performed manually or by machine and automated methods for all joint types. Advantages of GTAW in the applications to which it is suited include high-quality welds, no weld spatter because no filler metal is transferred across the arc, and little or no post-weld cleaning because no flux is used.

Plasma Arc Welding

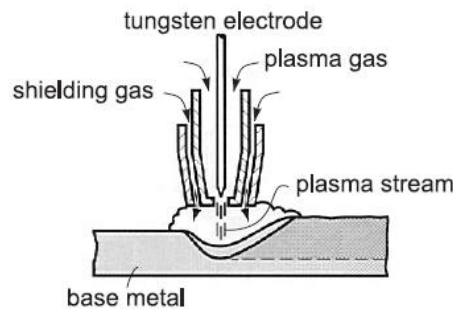


Figure 10 Plasma Arc Welding.

Plasma Arc Welding (PAW) is a special form of gas tungsten arc welding in which a plasma arc is directed at the weld area. The tungsten electrode is contained in a specially designed nozzle that focuses a high-velocity stream of inert gas (for example, argon or argon-hydrogen mixtures, and helium) into the region of the arc to produce a high-velocity plasma jet of small diameter and very high-energy density, as in the Figure 10. Temperatures in plasma arc welding reach 30,000o C or greater, hot enough to melt any known metal.

Plasma Arc Welding is used as a substitute for GTAW in applications such as automobile subassemblies, metal cabinets, door and window frames, and home appliances. The process can be used to weld almost any metal, including tungsten.

Weld quality in arc welding

The rapid heating and cooling in localized regions of the work during fusion welding, especially arc welding, result in thermal expansion and contraction, which cause transverse and longitudinal residual stresses in the weldment. These stresses are likely to cause distortion of the welded assembly.

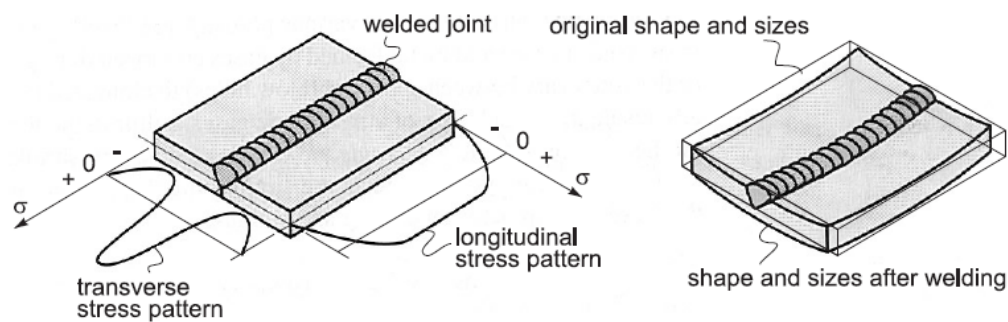


Figure 11 Transverse and longitudinal residual stress pattern (Left) and likely distortion in the welded assembly (Right).

The welding begins at one end and travels to the opposite end of the welded joint. As it proceeds, the molten metal quickly solidifies behind the moving arc. The portions of the work immediately adjacent to the weld bead become extremely hot and expand, while portions removed from the weld remain relatively cool. This results in an additional shrinkage across the width of the weldment, as seen in the Figure 11. Residual stresses and shrinkage also occur along the length of the weld bead.

Various techniques can be employed to minimize distortion in a weldment. Some of these techniques include the following:

1. Welding fixtures that physically restrain movement of the parts during welding.
2. Tack welding at multiple points along the joint to create a rigid structure prior to continuous welding.
3. Preheating the base parts, which reduces the level of thermal stresses experienced by the parts
4. Stress relief heat treatment of the welded assembly.

In addition to residual stresses and distortion in the final assembly, other defects can also occur in welding.

1. Cracks: Fracture-type interruptions either in the weld or in the base metal adjacent to the weld. This type is perhaps the most serious welding defect because it constitutes a discontinuity in the metal that causes significant reduction in the strength of the weldment. Generally, this defect can and must be repaired.

2. Cavities: These include various porosity and shrinkage voids. Porosity consists of small voids in the weld metal formed by gases entrapped during solidification. Porosity usually results from inclusion of atmospheric gases, or contaminants on the surfaces. Shrinkage voids are cavities formed by shrinkage during solidification.

3. Solid inclusions: Solid inclusions are any nonmetallic solid material entrapped in the weld metal. The most common form is slag inclusions generated during the various welding processes that use flux.

4. Incomplete fusion: Fusion does not occur throughout the entire cross section of the joint.

Resistance welding

Resistance welding (RW) is a group of fusion welding processes that utilizes a combination of heat and pressure to accomplish coalescence. The heat required is generated by electrical resistance to current flow at the interface of two parts to be welded. The resistance welding processes of most commercial importance are spot and seam welding.

Resistance Spot Welding

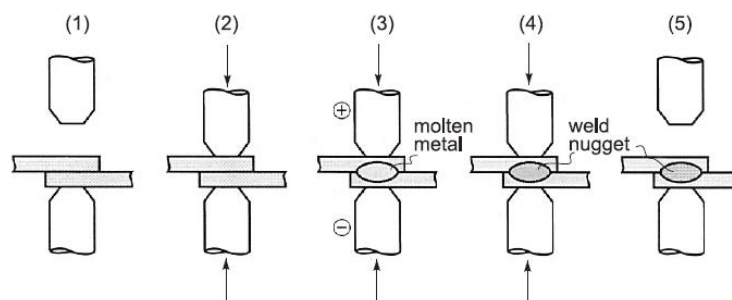


Figure 12 Steps in a spot welding cycle: (1) parts inserted between open electrodes, (2) electrodes close and force is applied, (3) weld time (Current is switched), (4) current is turned off but force is maintained, and (5) electrodes are opened, and the welded assembly is removed.

Resistance spot welding (RSW) is a resistance welding process in which fusion of the base metal is achieved at one location by opposing electrodes. The cycle in a spot welding operation consists of the steps depicted in the Figure 12.

Resistance spot welding is widely used in mass production of automobiles, appliances, metal furniture, and other products made of sheet metal of thickness 3 mm or less. Because of its widespread industrial use, various machines and methods are available to perform spot welding operations. The equipment includes rocker arm and press-type spot welding machines for larger work. For large, heavy work, portable spot welding guns are available in various sizes and configurations. They are widely used in automobile final assembly plants to spot-weld the sheet-metal car bodies. Human workers operate some of these guns, but industrial robots have become the preferred technology.

Resistance Seam Welding

In Resistance Seam Welding (RSEW), the electrodes are two rotating wheels as shown in Figure 13

In the process of welding, a series of overlapping spot welds is made along the lap joint. The process is capable of producing airtight joints, and its industrial applications include the production of gasoline tanks, automobile mufflers, and various others fabricated sheet-metal containers.

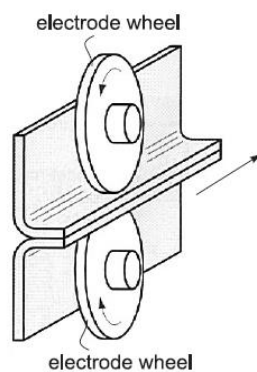


Figure 13 Resistance seam welding operation.

The spacing between the weld nuggets in resistance seam welding depends on the motion of the electrode wheels relative to the application of the weld current. In the usual method of operation, called continuous motion welding, the wheel is rotated continuously at a constant velocity, and current is turned on at timing intervals consistent with the desired spacing between spot welds along the seam so that overlapping weld spots are produced. But if the frequency of current switching is reduced sufficiently, there will be spacing between the weld spots, and this method is termed roll spot welding. In another variation, the welding

current remains on at a constant level so that a truly continuous welding seam is produced. These variations are depicted in Figure 14.

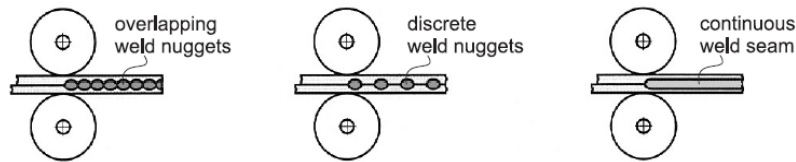


Figure 14 Different types of seam welding (from left to right) conventional seam welding, roll spot welding, continuous resistance seam welding.

Since the operation is usually carried out continuously, rather than discretely, the seams should be along a straight or uniformly curved line. Sharp corners and similar discontinuities should be avoided.

2.7. Mechanical Test

Mechanical testing is carried out to produce data that may be used for design purposes or as part of a material joining procedure or operator acceptance scheme. The most important function may be that of providing design data since it is essential that the limiting values that a structure can withstand without failure are known.

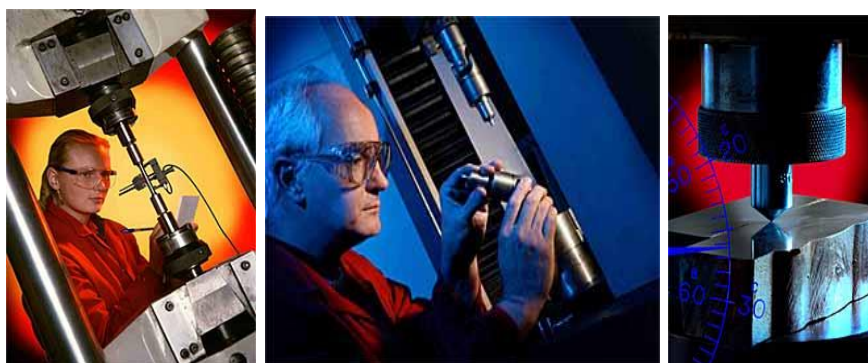


Figure 15 Typical tensile testing machine

Inadequate control of the material properties by the supplier, or incompetent joining procedures and operatives are, however, equally crucial to the supply of a product that is safe in use. An example of this dual role of mechanical testing is the tensile test that may be used

either to determine the yield strength of steel for use in design calculations or to ensure that the steel complies with a material specification's strength requirements.

Mechanical tests may also be divided into quantitative or qualitative tests. A quantitative test is one that provides data that will be used for design purposes, a qualitative test where the results will be used for making comparisons - hardness or Charpy-V tests - for example as a 'go/no go test' such as the bend test.

Mechanical property data are obtained from a relatively small number of standard tests and these will be covered over the next several articles. These will include tensile and toughness tests, the tests used for welding procedure and welder approval and those used for the determination of in-service properties.

2.7.1. Tensile Testing

As mentioned earlier the tensile test is used to provide information that will be used in design calculations or to demonstrate that a material complies with the requirements of the appropriate specification - it may therefore be either a quantitative or a qualitative test.

The test is made by gripping the ends of a suitably prepared standardized test piece in a tensile test machine and then applying a continually increasing uni-axial load until such time as failure occurs. Test pieces are standardized in order that results are reproducible and comparable as shown in Figure 16.

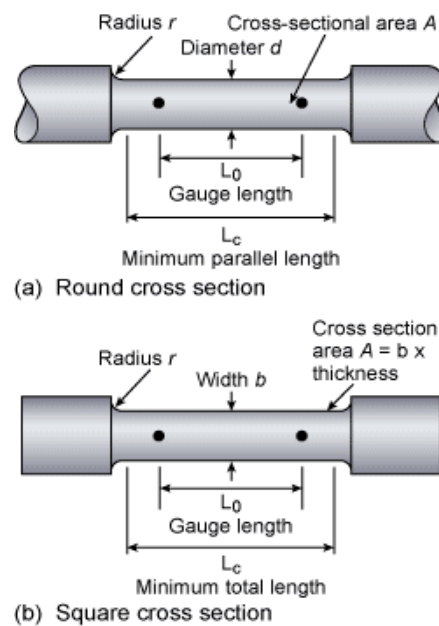


Figure 16 Standard shape tensile specimens

Specimens are said to be *proportional* when the *gauge length*, L_0 , is related to the original cross sectional area, A_0 , expressed as $L_0 = k\sqrt{A_0}$. The constant k is 5.65 in EN specifications and 5 in the ASME codes. These give gauge lengths of approximately 5x specimen diameter and 4 x specimen diameters respectively - whilst this difference may not be technically significant it is important when claiming compliance with specifications.

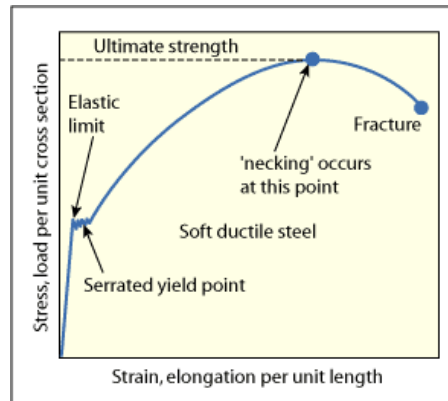


Figure 17 Stress/strain curve

Both the load (stress) and the test piece extension (strain) are measured and from this data an engineering stress/strain curve is constructed, Figure 17. From this curve we can determine:

1. The tensile strength, also known as the ultimate tensile strength, the load at failure divided by the original cross sectional area where the ultimate tensile strength (U.T.S.), $\sigma_{\max} = P_{\max} / A_0$, where $P_{\max}$ = maximum load, A_0 = original cross sectional area. In EN specifications this parameter is also identified as $R_{\frac{1}{m^2}}$

2. The *yield point* (YP), the stress at which deformation changes from elastic to plastic behavior i.e. below the yield point unloading the specimen means that it returns to its original length, above the yield point permanent plastic deformation has occurred, YP or $\sigma_y = P_{yp} / A_0$ where P_{yp} = load at the yield point. In EN specifications this parameter is also identified as $R_{\frac{1}{m^2}}$

3. By reassembling the broken specimen we can also measure the *percentage elongation*, EI% how much the test piece had stretched at failure where EI% =

$(L_f - L_0 / L_0) \times 100$ where L_f = gauge length at fracture and L_0 = original gauge length. In EN specifications this parameter is also identified as 'A' (Fig 18 a).

4. The *percentage reduction of area*, how much the specimen has necked or reduced in diameter at the point of failure where R of $A\% = (A_0 - A_f / A_0) \times 100$ where A_f = cross sectional area at site of the fracture. In EN specifications this parameter is also identified as 'Z', (Fig 18 b).

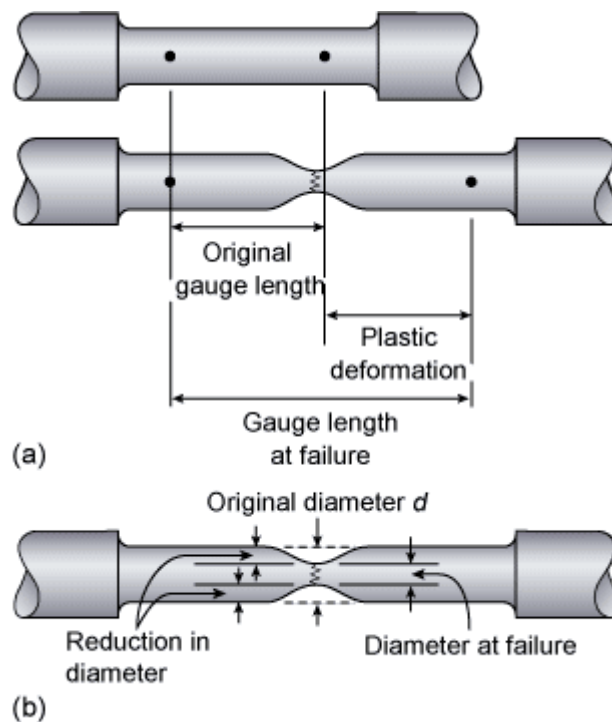


Figure 18 Calculation of percentage elongation (a), Calculation of percentage reduction of area (b).

(a) And (b) are measures of the strength of the material, (c) and (d) indicating the ductility or ability of the material to deform without fracture. The slope of the elastic portion of the curve, essentially a straight line, will give Young's Modulus of Elasticity, a measure of how much a structure will elastically deform when loaded. A low modulus means that a structure will be flexible, a high modulus a structure that will be stiff and inflexible. To produce the most accurate stress/strain curve an extensometer should be attached to the specimen to measure the elongation of the gauge length. A less accurate method is to measure the movement of the cross-head of the tensile machine. The stress strain curve in Figure 18 shows a material that has a well pronounced yield point but only annealed carbon steel exhibits this

sort of behavior. Metals that are strengthened by alloying, by heat treatment or by cold working do not have a pronounced yield and some other method must be found to determine the 'yield point'. This is done by measuring the proof stress (offset yield strength in American terminology), the stress required to produce a small specified amount of plastic deformation in the test piece.

The proof stress is measured by drawing a line parallel to the elastic portion of the stress/strain curve at a specified strain, this strain being a percentage of the original gauge length, hence 0.2% proof, 1% proof (see Figure 19).

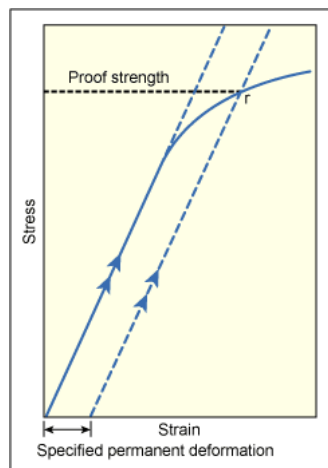


Figure 19 Determination of proof (offset yield) strength.

For example, 0.2% proof strength would be measured using 0.2mm of permanent deformation in a specimen with a gauge length of 100mm. Proof strength is therefore not a fixed material characteristic, such as the yield point, but will depend upon how much plastic deformation is specified. It is essential therefore when considering proof strengths that the percentage figure is always quoted. Most steel specifications use 0.2% deformation, $R_{P0.2}$ in the EN specifications.

Some materials such as annealed copper, grey iron and plastics do not have a straight line elastic portion on the stress/strain curve. In this case the usual practice, analogous to the method of determining proof strength, is to define the 'yield strength' as the stress to produce a specified amount of permanent deformation.

Welding procedure approval for tensile testing

To approve a butt welding procedure most specifications such as ISO 15614 and ASME IX require tensile tests to be carried out.

These are generally cross joint (CJ) tensile tests of square or rectangular cross section that, as the name suggests, are oriented across the weld so that both parent metals, both heat affected zones (HAZs) and the weld metal itself are tested (Figure 20). The excess weld metal in the cap of the weld may be left in-situ or machined off.

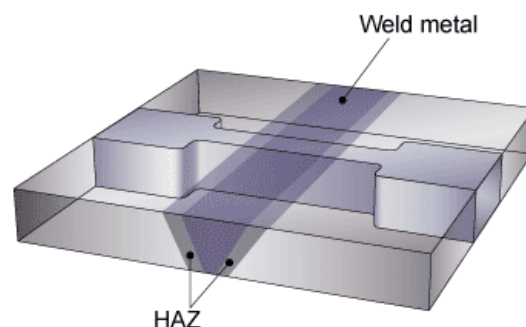


Figure 20 Square or rectangular cross joint tensile test piece.

While it is possible to measure the yield strength, the elongation and the reduction of area of CJ specimens the fact that there are at least three different areas with dissimilar mechanical properties makes such measurements inaccurate and unreliable, although this is sometimes carried out purely for information purposes.

The specifications mentioned above require the UTS and the position of the fracture only to be recorded. The cross joint strength is usually required to exceed the minimum specified UTS of the parent metal. In most situations the weld metal is stronger than the parent metal - it is overmatched - so that failure occurs in the parent metal or the HAZ at a stress above the specified minimum.

In cases where the weld and/or the HAZs are weaker than the parent metal - welded age-hardened or cold worked aluminum alloys are a good example - this is covered in most specifications. The designer must also take this into account in design calculations and provide some method of compensating for this loss of strength.

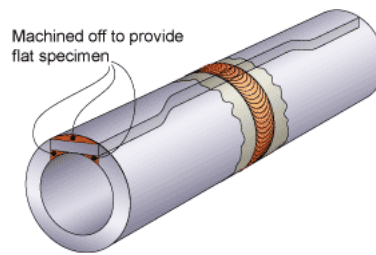


Figure 21 Flat cross joint tensile specimen machined from tube.

The tensile testing of flat plate butt welds presents few problems of specimen shape but those machined from a pipe butt joint are not flat and this curvature can affect the results. In the context of welding procedure approval testing, this is not significant since the test is used only for the determination of the UTS and the position of the fracture. For more accurate results the test piece may be waited and may be machined flat as illustrated in Figure 21.

It may be necessary to machine a number of specimens through the thickness of a weld, particularly on very thick joints where the capacity of the tensile machine is insufficient to pull a full thickness specimen, Figure 22.

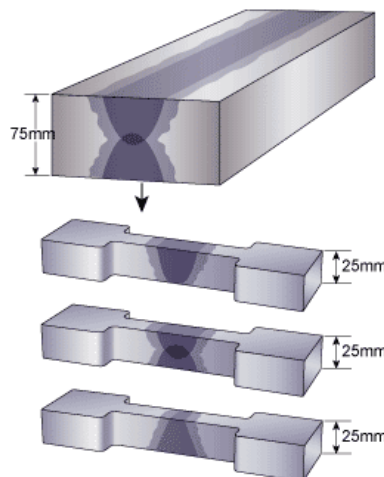


Figure 22 Multiple cross joint specimens machined from thick plate.

To test a small diameter tube, a solid bar is inserted in the bore of the tube to prevent the tube collapsing when the sample is clamped into the tensile machine. Most weld testing is carried out with CJ specimens but longitudinally oriented specimens are useful

particularly where the weld metal or the HAZ is very strong but ductility is low. In a CJ specimen the parent metal can yield and finally fail without the weld metal or the HAZ experiencing any significant amount of deformation whereas in a longitudinal test piece the load is shared more equally. A brittle weld or HAZ will not elongate with the parent metal but will crack, with the cracks opening, but not necessarily propagating into the parent metal, as testing proceeds.

The testing described above is that required by the welding procedure approval specifications. These provide no assurance that the welds in a structure will be suitable for their purpose such as elevated or cryogenic service and many application standards such as PD 5500 Unfired Pressure Vessels, and ASME VIII Pressure Vessels, require additional tests.

Since the strength of a metal falls as the temperature raises these specifications require elevated temperature tensile tests to be carried out at the maximum design temperature. These tests are required to be carried out on the weld metal only and use a longitudinally orientated round cross section specimen from which an accurate measurement of the proof strength can be obtained.

Many application standards such as PD 5500 require tests additional to those required by, for example, ISO 15614-1. This must be remembered when procedure approval documentation is submitted for approval by the inspecting authority or the client.

Validity of tensile data

The samples taken are assumed to be representative of the bulk of the material but this is not always the case.

Tensile strength of a casting, for instance, is often determined from a specimen machined from a riser and this will have a grain size different from that of the bulk of the casting. A rolled steel plate will be found to have different properties in the longitudinal, transverse and through thickness directions. Material specifications such as BS EN 10028, Flat Products in Steel for Pressure Purposes, therefore, require the tensile test to be taken transverse to the rolling direction so that the steel is tested across the 'grain' - the lower strength, lower ductility direction.

The size of a product can also influence the properties as, during heat treatment, the section thickness will affect the cooling rate with slower cooling rates, and hence softer structures, at the centre of thicker sections. This is dealt with in material standards by

specifying what is known as the 'limiting ruling section', the maximum diameter of bar at which the required mechanical properties can be achieved at the centre.

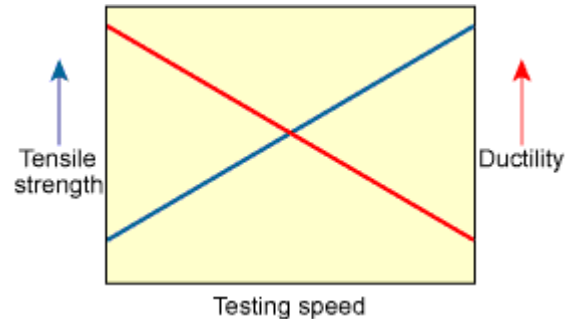


Figure 23 Effect of speed of testing on strength and ductility

In addition to variations of the properties due to the shape of the specimens and the testing temperature, the rate of loading will also affect the results.

Figure 23 shows how the tensile strength increases but ductility decreases as the testing speed is increased. The speed of the cross head of the tensile machine therefore needs to be controlled and BS EN 10002 specifies a stress rate range of 6MPa per second to 60MPa per second. The ASTM specifications have similar - but not identical - requirements.

2.7.2. Hardness testing

The hardness of a material can have a number of meanings depending upon the context, which in the case of metals generally means the resistance to indentation. There are a number of test methods of which only the Brinell, Vickers and portable hardness testing will be covered in this article.

Brinell hardness Test

The Brinell test was devised by a Swedish researcher at the beginning of the 20th century. The test comprises forcing a hardened steel ball indenter into the surface of the sample using a standard load as shown in Figure 24 (a) the diameter/load ratio is selected to provide an impression of an acceptable diameter. The ball may be 10, 5 or 1mm in diameter, the load may be 3000, 750 or 30kgf, The load, P , is related to the diameter, D by the relationship P/D^2 and this ratio has been standardized for different metals in order that test results are accurate and reproducible. For steel the ratio is 30:1 - for example a 10mm ball can

be used with a 3000kgf load or a 1mm ball with a 30kgf load. For aluminum alloys the ratio is 5:1. The load is applied for a fixed length of time, usually 30 seconds. When the indenter is retracted two diameters of the impression, d_1 and d_2 , are measured using a microscope with a calibrated graticule and then averaged as shown in Figure 24 (b).

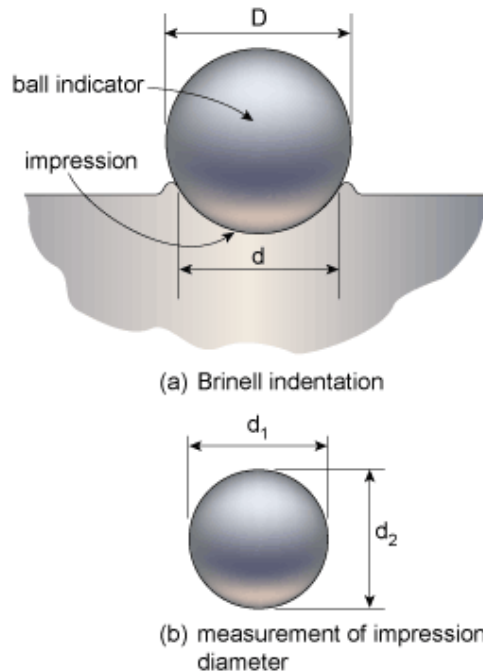


Figure 24 Brinell Hardness Test

The Brinell hardness number (BHN) is found by dividing the load by the surface area of the impression. There is a somewhat tedious calculation that can be carried out to determine the hardness number but it is more usual and far simpler to refer to a set of standard tables from which the Brinell hardness number can be read directly.

The Brinell test is generally used for bulk metal hardness measurements - the impression is larger than that of the Vickers test and this is useful as it averages out any local heterogeneity and is affected less by surface roughness. However, because of the large ball diameter the test cannot be used to determine the hardness variations in a welded joint for which the Vickers test is preferred. Very hard metals, over 450BHN may also cause the ball to deform resulting in an inaccurate reading. To overcome this limitation a tungsten carbide ball is used instead of the hardened steel ball but there is also a hardness limit of 600BHN with this indenter.

Vickers Hardness Test

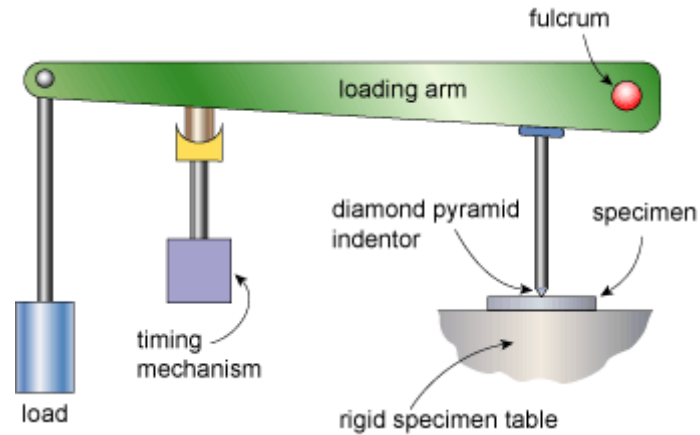


Figure 25 Schematic principles of operation of Vickers hardness machine.

The Vickers hardness test operates on similar principles to the Brinell test, the major difference being the use of a square based pyramidal diamond indenter rather than a hardened steel ball. Also, unlike the Brinell test, the depth of the impression does not affect the accuracy of the reading so the P/D^2 ratio is not important. The diamond does not deform at high loads so the results on very hard materials are more reliable. The load may range from 1 to 120kgf and is applied for between 10 and 15 seconds.

The basic principles of operation of the Vickers hardness test are illustrated in Figure 25 where it can be seen that the load is applied to the indenter by a simple weighted lever. In older machines and oil filled dash pot is used as a timing mechanism - on more modern equipment this is done electronically.

As illustrated in Figure 26 (b) two diagonals, d_1 and d_2 , are measured, averaged and the surface area calculated then divided into the load applied. As with the Brinell test the diagonal measurement is converted to a hardness figure by referring to a set of tables. The hardness may be reported as Vickers Hardness number (VHN), Diamond Pyramid Number (DPN) or, most commonly, Hv_{xx} where 'xx' represents the load used during the test.

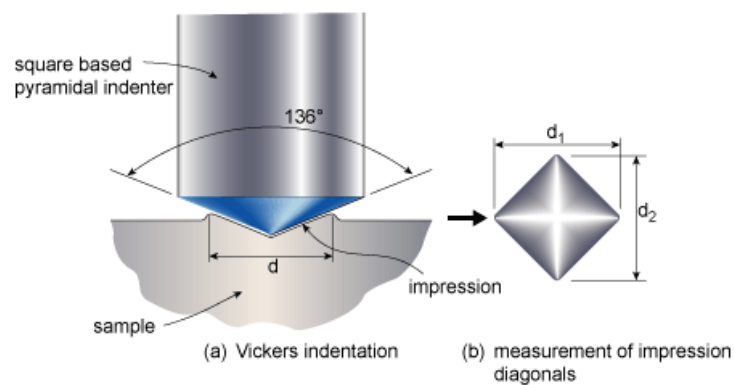


Figure 26 Vickers hardness test

As mentioned earlier, the Vickers indentation is smaller than the Brinell impression and thus far smaller areas can be tested, making it possible to carry out a survey across a welded joint, including individual runs and the heat affected zones. The small impression also means that the surface must be flat and perpendicular to the indenter and should have a better than 300 grit finish.

Errors in Hardness Testing

There are many factors that can affect the accuracy of the hardness test. Some of these such as flatness and surface finish have already been mentioned above but it is worth re-emphasizing the point that flatness is most important - a maximum angle of approximately $\pm 1^\circ$ would be regarded as acceptable.

To achieve the required flatness tolerance and surface finish surface grinding or machining may be necessary. The correct load must be applied and to achieve this there must be no friction in the loading system otherwise the impression will be smaller than expected - regular maintenance and calibration of the machine is therefore essential. The condition of the indenter is crucial - whilst the Vickers diamond is unlikely to deteriorate with use unless it is damaged or loosened in its mounting by clumsy handling, the Brinell ball will deform over a period of time and inaccurate readings will result. This deterioration will be accelerated if a large proportion of the work is on hard materials. The length of time that the load is applied is important and must be controlled.

The specimen dimensions are important - if the test piece is too thin the hardness of the specimen table will affect the result. As a rule of thumb the specimen thickness

should be ten times the depth of the impression for the Brinell test and twice that of the Vickers diagonal. Similarly, if the impression is too close to the specimen edge then low hardness values will be recorded - again as a rule the impression should be some 4 to 5 times the impression diameter from any free edge. Performing hardness testing on cylindrical surfaces e.g. pipes and tubes, the radius of curvature will affect the indentation shape and can lead to errors. It may be necessary to apply a correction factor - this is covered in an ISO specification.

The specimen table should be rigidly supported and must be in good condition - burrs or raised edges beneath the sample will give low readings. Impact loading must be avoided. It is very easy to force the indenter into the specimen surface when raising the table into position. This can strain the equipment and damage the indenter. Operator training is crucial and regular validation or calibration is essential if hardness test results are to be accurate and reproducible.

The previous article dealt with the conventional Vickers and Brinell hardness tests. This second article reviews micro-hardness and portable hardness testing. The investigation of metallurgical problems in welds often requires the determination of hardness within a very small area or on components in service or too large to be able to test in a laboratory environment.

Micro-hardness testing may be carried out using any one of three common methods and, as with the macro-hardness tests, measure the size of the impression produced by forcing an indenter into the specimen surface under a dead load, although many of the new test machines use a load cell system.

The three most common tests are the Knoop test, the Vickers test and the ultrasonic micro-hardness test.

The Knoop test uses a pyramidal indenter that gives an elongated diamond shaped impression with an aspect ratio of around 7:1, the Vickers test uses the pyramidal indenter described in the previous article (January/February 2005). The Knoop test is rarely used in Europe where the Vickers test is the preferred method. The loads used for the tests vary from 1gmf to 1kgf and produce impressions that need to be measured by using a microscope with magnifications of up to 100X, although modern machines may be equipped with an image analysis system that enables the process to be automated.

The ultrasonic hardness test does not rely upon measuring the size of an impression. Instead, the test uses a Vickers diamond attached to the end of a metal rod. The rod is vibrated at its natural frequency by a piezoelectric converter and then brought into

contact with the specimen surface under a small load. The resonant frequency is changed by the size of the impression produced and this change can be measured and converted to a hardness value.

The size of the impression is extremely small and the test may be regarded as non-destructive since it is non-damaging in most applications.

The micro-hardness test has a number of applications varying from being a metallurgical research tool to a method of quality control. The test may be used to determine the hardness of different micro-constituents in a metal, as shown in Figure 27. Where an impression would be damaging, for instance on a finished product, micro-hardness tests, particularly the ultrasonic test, may be used for quality control purposes. Micro-hardness testing also finds application in the testing of thin foils, case hardened items and decarburized components.

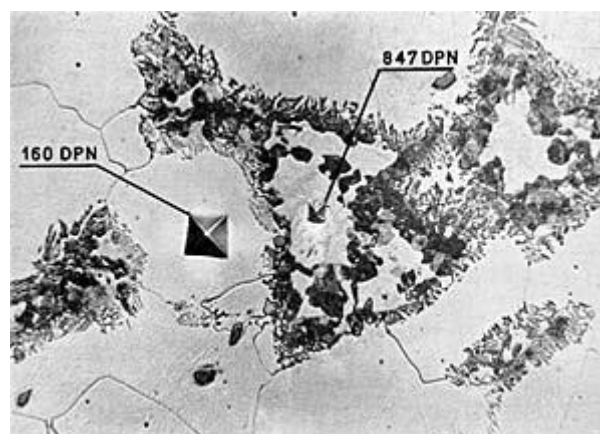


Figure 27 Micro-hardness test.

Portable hardness tests may be used where the component is too large to be taken to the testing machine or in on-site applications. It is useful on-site, for example, for checking that the correct heat treatment has been carried out on welded items or that welded joints comply with the hardness limits specified by NACE for sour service. There are three principal methods - dynamic rebound, Brinell or Vickers indentation or ultrasonic testing.

The Leeb hardness test uses dynamic rebound where a hammer is propelled into the test piece surface and the height of the rebound is measured. This gives a measure of the elasticity of the material and hence its hardness.

This type of test is typified by the 'Equotip' test, Figure 28, a trademark of Proceq SA. The Equotip tester comprises a hand-held tube that contains a spring loaded hammer. The device is cocked by compressing the hammer against the spring, the device is then positioned vertically on the test surface and the release button is pressed. The hammer strikes the surface, rebounds and the result displayed digitally. Generally the average of five readings is taken.



Figure 28 Equotip test.

To obtain a valid result, the position of the device, the flatness of the surface and the flexibility of the component all affect the accuracy of the results. Needless to say the skill and experience of the operator is one of the key factors in producing accurate hardness figures. The results are generally converted to give hardness in Vickers or Brinell units.

The other type of portable hardness test in common use is the ultrasonic method described above. Commercially available machines are typified by the Microdur unit supplied by GE Inspection Technologies as shown in Figure 29. This type of equipment is electronically based and can be programmed to give hardness readings of any type - Vickers, Brinell, or Rockwell. Needless to say, any of these methods of hardness testing require regular calibration of the equipment, fully trained operators and well prepared surfaces.

Although there are several different methods of hardness testing the results can be compared and converted. The ASTM specification E140 contains conversion tables for metals - ferritic and austenitic steels, nickel alloys, copper and brass- for converting Vickers to Brinell or Rockwell or vice versa. To end this article on hardness testing let us look at the significance of the results.



Figure 29 Ultrasonic testing using a Microdur unit

Hardness is related to tensile strength - multiplying the Vickers hardness number of a carbon steel by 3.3 will give the approximate ultimate tensile strength in N/mm^2 . A hardness traverse across a weld and its HAZs will therefore reveal how the tensile strength varies. In carbon or low alloy steels a hardness of above approximately 380HV suggests that the hard brittle microstructure, martensite, has been formed leading to the possibility of cold cracking during fabrication or brittle fracture in service. This fact has been recognized in the specification EN ISO 15614 Part 1 so that a maximum hardness of 380HV is permitted on a hardness traverse of a macro-section from a carbon steel procedure qualification test.

Relevant Specifications

1. ASTM E 10 Brinell Hardness of Metallic Materials
2. ASTM E 140 Hardness Conversion Tables for Metals.
3. ASTM E 110 Portable Hardness Testing.
4. ASTM E 384 Micro hardness testing of Metallic Materials.
5. ASTM E 103 Rapid Indentation Hardness Testing.
6. ASTM E 18 Rockwell Hardness Testing.
7. ASTM E 92 Vickers Hardness of Metallic Materials

2.8. Grain Size

ASM Metals HandBook Volume 09 was prepared under the direction of the ASM Handbook Committee. Investigations of the structures of metals are generally carried out on sections that have been cut from a bulk specimen. Frequently, only a single section surface is prepared, and the structural features exposed on this surface may be investigated using various techniques. All these techniques involve the reflection of some form of radiation from the section surface; an image of the surface is formed from the reflected radiation that allows variations in crystal structure or composition over the surface to be discerned. The other investigative techniques mentioned earlier are doubtless crucial in many research investigations and have pushed the frontiers of metallography far beyond what would have been possible by optical metallography alone. Nevertheless, most metallography in industry and in general investigations is still carried out by optical microscopy, so this article will also consider the preparation of surfaces for examination by optical microscopy.

Any classification of the numerous processes used to cut a section, then to prepare the cut surface suitably for metallographic examination, inevitably is arbitrary and arguable. One convenient system, however, is to classify the processes as machining, grinding and abrasion, or polishing. A preparation procedure must produce a surface that accurately represents the structure as it existed in the metal before sectioning. All structural features that should be detected by the particular examination technique being used must be detectable, and false structures must not be introduced. This is a more demanding requirement.

In Metalog Process, the preparation process is divided into several stages which must be executed correctly to ensure a satisfactory result. The three stages, cutting, mounting and mechanical preparation, will be explained in detail in the following pages. No matter which result we want to achieve, the preparation must be performed systematically to ensure reproducible results.

In the metallographic laboratory, analyzing grains in metallic and alloy samples, such as aluminum or steel, is important for quality-control. Most metals are crystalline in nature and contain internal boundaries, commonly known as "grain boundaries". When a metal or alloy is processed, the atoms within each growing grain are lined up in a specific pattern, depending on the crystal structure of sample. With growth, each grain will eventually impact others and form an interface where the atomic orientations differ. It has been established that the mechanical properties of the sample improve as the grain size decreases. Therefore, alloy composition and processing must be carefully controlled to obtain the desired grain size. After metallographic

sample preparation, grains in a specimen are often analyzed via microscopy, where the size and distribution of these grains can demonstrate the integrity and quality of the sample.

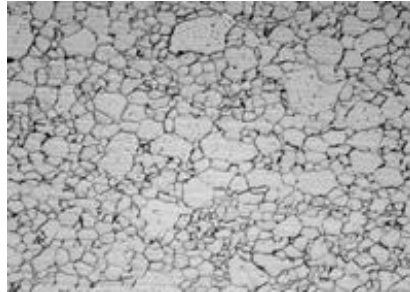


Fig 30 Image of Grains in Steel at 100x Magnification

Although a wide-variety of international standards exist¹, ASTM E112 is the dominant standard that grains are analyzed under in North and South America. In former times, and even still in practice today, most quality-control laboratories would analyze grains via the "Chart Comparison" method. Here, operators perform a visual estimation of the grain size by comparing a live image under an optical microscope to a micrograph chart, often posted on the wall near the microscope. Or, instead of comparing to a micrograph poster, one can insert an eyepiece reticle containing images of predefined grain size patterns, directly into the microscope's optical path. This way, the comparison is performed directly in the microscope, where the operator can see both the sample at question as well as a "golden" image simultaneously. Since the grain size is being estimated by the operator, these methodologies can produce inaccurate and unrepeatable results, often not reproducible between different operators. Further, quality-control technicians are required to manually enter their results into a computer-based spreadsheet or report providing an additional opportunity for errors.

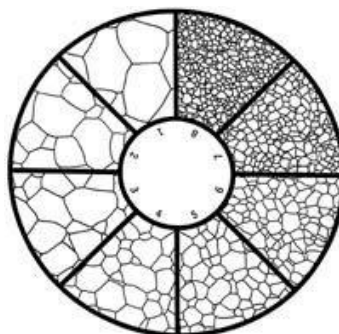


Figure 31 Example of a microscope eyepiece reticle used to compare against a live image

The ferrite grain size is an important fundamental physical property of steel. In particular, the strength of many steels such as micro alloyed steel. So that we can use the result in this paper to predict and analyze the ferrite grain size at the welding joint and HAZ.

The mechanical properties of materials have shown the microstructural dimensions. Based on Hall – Petch. A relationship of yield strength was predicted between grain size and the mechanical properties of steel (HSLA) and formulated.

$$\sigma_y = \sigma_0 + kd^{-1/2} \quad (1)$$

For HSLA,

$$\sigma_y = 35.77\text{MPa} + \frac{0.881\text{MPa}\cdot\text{m}^{1/2}}{d^{1/2}\text{m}} \quad (2)$$

Where σ_y is the yield stress, σ_0 is the materials constant for the starting stress for dislocation movement and k is the materials constant for the strengthening coefficient, d is the average grain diameter. Normally the stress can be used or applied to the yield strength for division of plasticity and elasticity behavior. Hall – Petch relationship was focused on the large variety of material properties more than the lower yield point and the stress of material such as hardness. Hall – Petch relationship related to find or to measure the grain size for describe the microstructure. However the strength of different grain sizes was estimated by applying a weighting fact or equal to the volume of the grains each area such HAZ. The grain size indicate the yield strength and can be explained by the grain boundary because they are also much more disordered than inside the grain. But several studies with the average grain diameter can be obtained from the experimental measurements.

In the calculation process the ASTM E112 standard was measured in accordance to the ferrite grain size in each material and gives a value of grain size relationships computed for uniform, randomly oriented, equiaxed grains. It is validated for microstructure and the recommended measurement procedure for linear intercept length method coupled with used other measurement method such as optical microscope for comparing the results of the calculation. The ASTM commonly used included “Comparison method”, “Planimetric method or Jeffries method” and “Intercept method”

2.8.1. Comparison method

Normally imaging microstructure or photomicrographs that extends at 100X. Then compare the grain size with standard microscopic structure and called “ASTM grain size number” This method is suitable for equiaxed grain. The ASTM grain size number can be calculated by counting the number of grains in one square inch at the surface area which extends at 100X. Thus, calculated according to the equation as follow. Where the quantity of grains is N in per square inch and n is the ASTM grain size number.

$$N = 2^{n-1} \quad (3)$$

2.8.2. Planimetric method or Jeffries method

In the “Planimetric method or Jeffries method” created a circle or rectangle on the area on the photomicrographs (usually to simplify the calculations) and the quantity of grains no less than 50 grains. Equation of Planimetric method or Jeffries method as follow.

$$N_A = f \left(N_{inside} + \frac{N_{intercept}}{2} \right) \quad (4)$$

Where N_A is the number of grains per square millimeter at 1X, f is the Jeffries' multiplier ([5] Table 5), N_{inside} is the number of grains completely inside the test circle and $N_{intercept}$ is the number of grains that intercept the test circle. The ASTM Grain Size, G and N_A in unit mm^{-2} , using the following equations.

$$G = (3.321928 \log_{10} \bar{N}_A) - 2.954 \quad mm^{-2} \quad (5)$$

$$G = (6.643856 \log_{10} \bar{N}_L) - 3.288 \quad mm^{-1} \quad (6)$$

$$G = (36.643856 \log_{10} \bar{P}_L) - 3.288 \quad mm^{-1} \quad (7)$$

$$G = (-6.6438568 \log_{10} \ell) - 3.288 \quad mm \quad (8)$$

2.8.3. Intercept method

“Intercept method”, is more convenient to use than the planimetric such as the Heyn lineal intercept procedure or Circular intercept procedure. There is no direct mathematical relationship between the ASTM grain size number and the mean lineal intercept as follow

$$\ell = \sqrt{\frac{\pi}{4} \bar{A}} \quad (9)$$

Where ℓ is the mean lineal intercept, $\bar{A}$ is exact for circles. Therefore, the relationship between the ASTM grain size number and the mean lineal intercept has been defined. ASTM No.0 has a mean intercept size of precisely 32.00 mm for the macroscopically determined grain size scale and of 32.00 mm at 100X on a field of view magnification for the microscopically determined grain size scale.

$$G = 2 \log_2 \frac{\ell_0}{\ell} \quad (10)$$

$$G = 10.00 - 2 \log_2 \bar{\ell} \quad (11)$$

$$G = 10.00 + 2 \log_2 \bar{N}_L \quad (12)$$

Where ℓ_0 is 32 mm and $\bar{\ell}$ and $\bar{N}_L$ are in millimetres at 1X or number of intercepts per mm for the macroscopically determined grain size numbers and in millimetres or number per mm on a field at 100X for the microscopically determined grain size numbers.

2.8.3.1. Heyn lineal intercept procedure

In the heyne lineal intercept procedure, that use a several cross line through on a photomicrograph and count the number of grains which intercept the line to calculate the arithmetic average or mark a line on the surface of specimen to measure grain size with a length of 0.005 inches and 3.75 inches at 750X. If number of grains about 8-12 grains it means rough grain but if the number of grains is about 8-12 grains it's called a fine grain and if more than 15 grains it's called very fine grain.

2.8.3.2. Circular intercept procedure

In the circular intercept procedure, that use drawing of three circle on the photomicrograph to find the grain size and except that circles of known circumference are used instead of lines. Three circles with a diameter at 26.53 mm, 53.05 mm, and 79.58 mm respectively. The circumference length of the three circles combined are 500 mm. Then count the amount of grain that was cut through the line. Every grain that was intercepted on the three circles is equivalent to 1, while the line of the circles that intercept through three grain equivalent 1.5 and number of grain boundary intersections per unit length of test line as follows

$$\bar{N}_L = \frac{N_i}{L/M} \quad (13)$$

$$\bar{P}_L = \frac{P_i}{L/M} \quad (14)$$

$$\bar{\ell} = \frac{1}{N_i} = \frac{1}{P_i} \quad (15)$$

Where $\bar{N}_L$ and $\bar{P}_L$ are number of grain boundary intersections per unit length of the test line, $\bar{\ell}$ is the mean lineal intercept value for each field, L is the total test line length (500 mm) and M is the magnification. Therefore, they are used to calculate in (6), (7) and (8) or determine the microscopically measured ASTM grain.

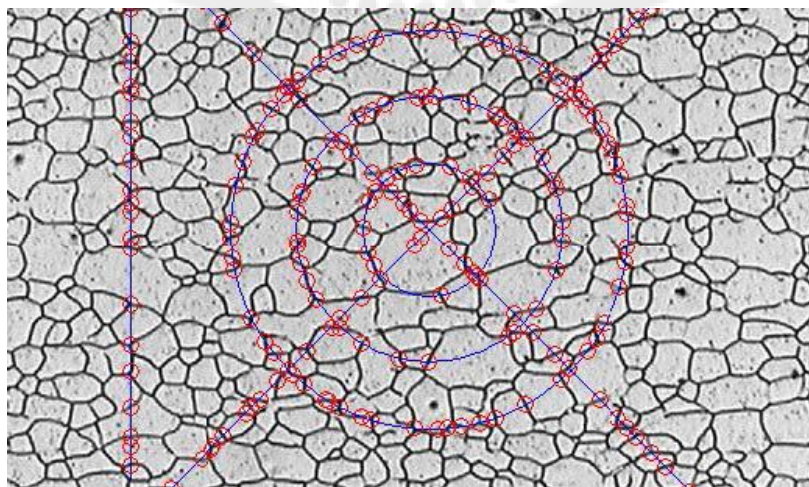


Figure 32 Grain Analysis via the Intercept method

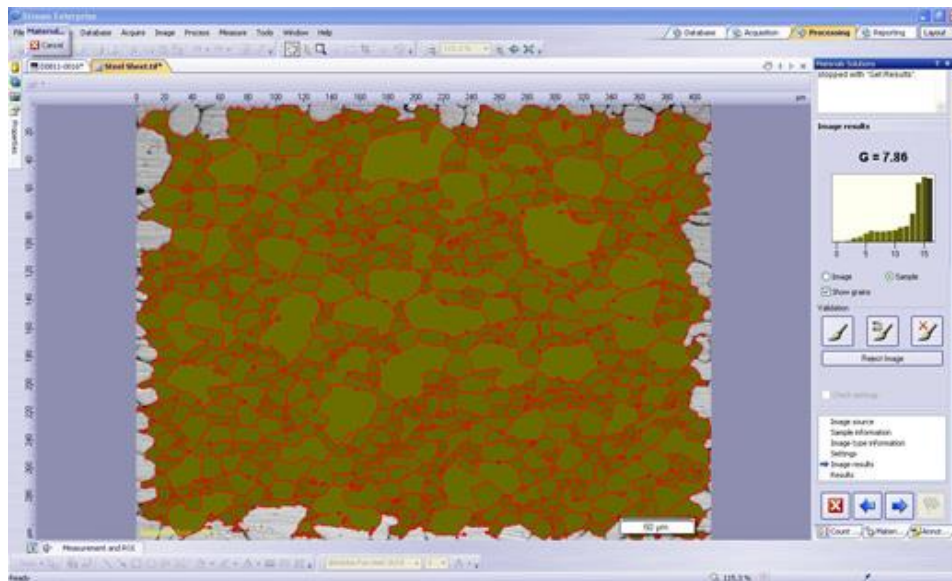


Figure 33 Grain Analysis via the Planimetric method

Another popular method for calculating grain size in the digital metallurgical laboratory is known as the "Planimetric" method. Unlike the Intercept method, the Planimetric method determines the grain size on an image (live or captured) by calculating the number of grains per unit area.

Since the results are calculated internally within the image-analysis software, the guesswork attributed to the human element is removed. In many instances, overall accuracy and repeatability, as well as reproducibility has shown improvement. What's more, many metallurgical-specific microscope image-analysis software packages can be configured to archive the grains results automatically into a spreadsheet or optional integrated database.

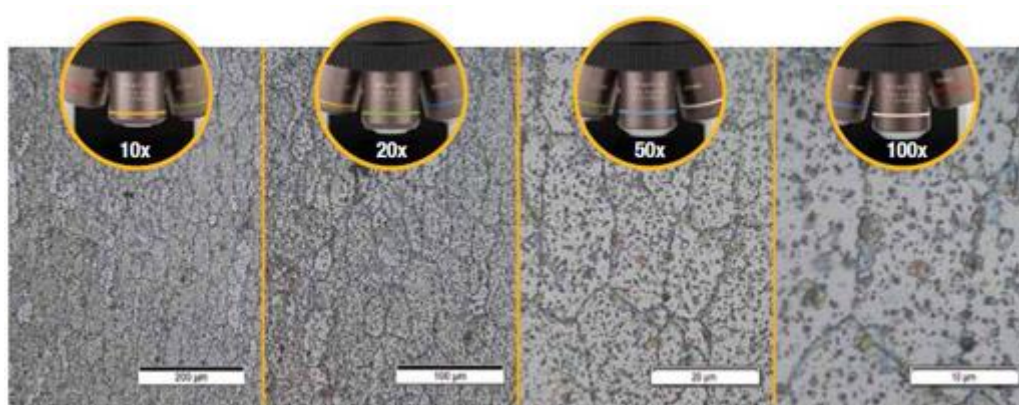


Figure 34 Illustrates the microscope magnification

2.9. Finite element method

Finite element method is a numerical method to approximate a given problem. With the appearance of the problem into smaller parts, called elements, these elements are connected together (Node) at a later point in the position to calculate the parameters as desired (Dependent Variables) by creating an equation for each element corresponding to the differential equations of the problem. Then the equation of individual elements crafted to combine.

2.9.1. General Steps of the Finite Element Method

Then the equation of each element that created it. At the tribute to cause large set of equations in which the shape of the real issues, Then set the boundary conditions that came into the system of equations for this great theme, then the equation will cause the solution to approximate with Finite element method will allow us to know the behavior of stress and strain, as well as moving around the various positions of the back lash. The area of interest is divided into small elements to get answers to the most real close. The area that we do not interested can share elements with larger ones to reduce the computation time. Current has developed a computer program used to calculate stress finite element method makes it so easy and quick to find the stress in parts that we want to study.

Keep in mind that the analyst must make decisions regarding dividing the structure or continuum into finite elements and selecting the element type or types to be used in the analysis (step 1), the kinds of loads to be applied, and the types of boundary conditions or supports to be applied. The other steps, 2–7, are carried out automatically by a computer program.

Step 1 Discretize and select the element types

Step 1 involves dividing the body into an equivalent system of finite elements with associated nodes and choosing the most appropriate element type to model most closely the actual physical behavior. The total number of elements used and their variation in size and type within a given body are primarily matters of engineering judgment. The elements must be made small enough to give usable results and yet large enough to reduce computational effort. Small elements (and possibly higher order elements) are generally desirable where the results are changing rapidly, such as where changes in geometry occur; large elements can be used where results are relatively constant.

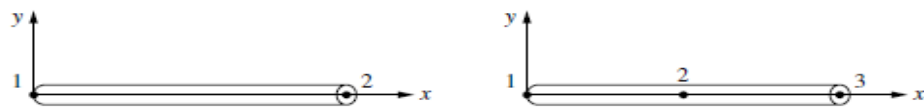
The choice of elements used in a finite element analysis depends on the physical makeup of the body under actual loading conditions and on how close to the actual behavior the analyst wants the results to be. Judgment concerning the appropriateness of one-, two-, or three-dimensional idealizations is necessary. Moreover, the choice of the most appropriate element for a particular problem is one of the major tasks that must be carried out by the designer/analyst. Elements that are commonly employed in practice-most of which are considered in this text-are shown in Figure 35.

The primary line elements [Figure 35 (a)] consist of bar (or truss) and beam elements. They have a cross-sectional area but are usually represented by line segments. In general, the cross-sectional area within the element can vary, but throughout this text it will be considered to be constant. The simplest line element (called a linear element) has two nodes, one at each end, although higher-order elements having three nodes [Figure 35 (a)] or more (called quadratic, cubic, etc. elements).

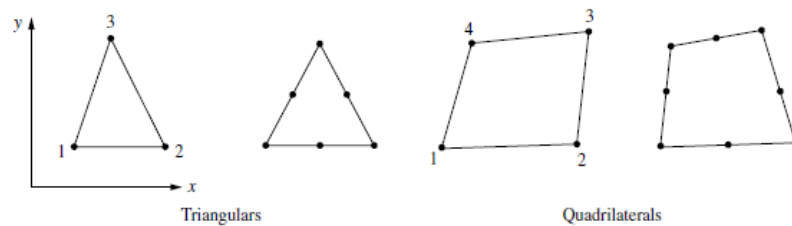
The basic two-dimensional (or plane) elements [Figure 35 (b)] are loaded by forces in their own plane (plane stress or plane strain conditions). They are triangular or quadrilateral elements. The simplest two-dimensional elements have corner nodes only (linear elements) with straight sides or boundaries, although there are also higher-order elements, typically with midsize nodes [Figure 35 (b)] (called quadratic elements) and curved sides. The elements can have variable thicknesses throughout or be constant.

The most common three-dimensional elements [Figure 35 (c)] are tetrahedral and hexahedral (or brick) elements; they are used when it becomes necessary to perform a three-dimensional stress analysis. The basic three-dimensional elements have corner nodes only and straight sides, whereas higher-order elements with mid-edge nodes (and possible mid-face nodes) have curved surfaces for their sides [Figure 35 (c)].

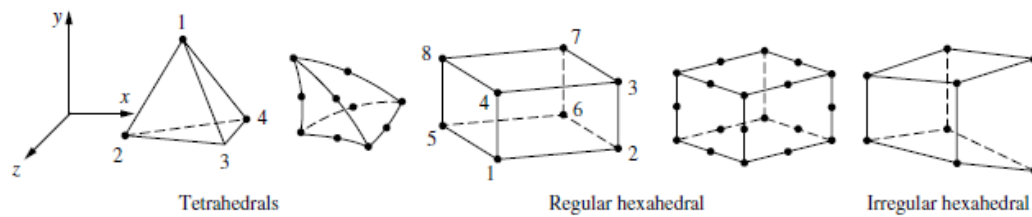
The axisymmetric element [Figure 35 (d)] is developed by rotating a triangle or quadrilateral about a fixed axis located in the plane of the element through 360. This element can be used when the geometry and loading of the problem are axisymmetric.



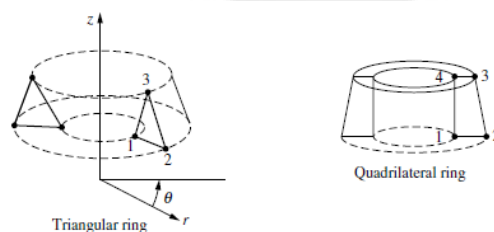
(a) Simple two-noded line element (typically used to represent a bar or beam element) and the higher-order line element



(b) Simple two-dimensional elements with corner nodes (typically used to represent plane stress/strain) and higher-order two-dimensional elements with intermediate nodes along the sides



(c) Simple three-dimensional elements (typically used to represent three-dimensional stress state) and higher-order three-dimensional elements with intermediate nodes along edges



(d) Simple axisymmetric triangular and quadrilateral elements used for axisymmetric problems

Figure 35 Various types of simple lowest-order finite elements with corner nodes only and higher-order elements with intermediate nodes

Step 2 Select a displacement function

Step 2 involves choosing a displacement function within each element. The function is defined within the element using the nodal values of the element. Linear, quadratic, and cubic polynomials are frequently used functions because they are simple to work with in finite element formulation. However, trigonometric series can also be used. For a two-dimensional element, the displacement function is a function of the coordinates in its plane (say, the x-y plane). The functions are expressed in terms of the nodal unknowns (in the two-dimensional problem, in terms of an x and a y component). The same general displacement function can be used repeatedly for each element. Hence the finite element method is one in which a continuous quantity, such as the displacement throughout the body, is approximated by a discrete model composed of a set of piecewise-continuous functions defined within each finite domain or finite element.

Step 3 Define the strain / Displacement and stress / Strain relationships

Strain/displacement and stress/strain relationships are necessary for deriving the equations for each finite element. In the case of one-dimensional deformation, say, in the x direction, we have strain ϵ_x related to displacement u by

$$\epsilon_x = \frac{d_u}{d_x} \quad (17)$$

For small strains, In addition, the stresses must be related to the strains through the stress/strain law-generally called the constitutive law. The ability to define the material behavior accurately is most important in obtaining acceptable results. The simplest of stress/strain laws, Hooke's law, which is often used in stress analysis, is given by

$$\sigma_x = E\epsilon_x \quad (18)$$

Where are σ_x = stress in the x direction and E = modulus of elasticity.

Step 4 Derive the element stiffness matrix and equations

Initially, the development of element stiffness matrices and element equations was based on the concept of stiffness influence coefficients, which presupposes a background

in structural analysis. We now present alternative methods used in this text that do not require this special background.

1. Direct Equilibrium Method

According to this method, the stiffness matrix and element equations relating nodal forces to nodal displacements are obtained using force equilibrium conditions for a basic element, along with force/deformation relationships. Because this method is most easily adaptable to line or one-dimensional elements, this method for spring, bar, and beam elements, respectively.

2. Work or Energy Methods

To develop the stiffness matrix and equations for two- and three-dimensional elements, it is much easier to apply a work or energy method. The principle of virtual work (using virtual displacements), the principle of minimum potential energy, and Castigliano's theorem are methods frequently used for the purpose of derivation of element equations.

3. Methods of Weighted Residuals

The methods of weighted residuals are useful for developing the element equations; particularly popular is Galerkin's method. These methods yield the same results as the energy methods wherever the energy methods are applicable. They are especially useful when a functional such as potential energy is not readily available. The weighted residual methods allow the finite element method to be applied directly to any differential equation.

Using any of the methods just outlined will produce the equations to describe the behavior of an element. These equations are written conveniently in matrix form as

$$\begin{Bmatrix} f_1 \\ f_2 \\ f_3 \\ \vdots \\ \vdots \\ f_n \end{Bmatrix} = \begin{bmatrix} k_{11} & k_{12} & k_{13} & \dots & k_{1n} \\ k_{21} & k_{22} & k_{23} & \dots & \\ k_{31} & k_{32} & k_{33} & \dots & \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ k_{n1} & \vdots & \vdots & \dots & k_{nn} \end{bmatrix} \begin{Bmatrix} d_1 \\ d_2 \\ d_3 \\ \vdots \\ \vdots \\ d_n \end{Bmatrix} \quad (19)$$

Or in compact matrix form as $\{f\} = [k]\{d\} \quad (20)$

Where $\{f\}$ is the vector of element nodal forces, $[k]$ is the element stiffness matrix (normally square and symmetric), and $\{d\}$ is the vector of unknown element nodal degrees of freedom or generalized displacements, n .

Step 5 Assemble the element equations to obtain the global or total equations and introduce boundary conditions

In this step the individual element nodal equilibrium equations generated in step 4 are assembled into the global nodal equilibrium equations. Another more direct method of superposition (called the direct stiffness method), whose basis is nodal force equilibrium, can be used to obtain the global equations for the whole structure. Implicit in the direct stiffness method is the concept of continuity, or compatibility, which requires that the structure remain together and that no tears occur anywhere within the structure. The final assembled or global equation written in matrix form is

$$\{F\} = [K]\{d\} \quad (21)$$

Where $\{F\}$ is the vector of global nodal forces, $[K]$ is the structure global or total stiffness matrix, (for most problems, the global stiffness matrix is square and symmetric) and $\{d\}$ is now the vector of known and unknown structure nodal degrees of freedom or generalized displacements. It can be shown that at this stage, the global stiffness matrix $[K]$ is a singular matrix because its determinant is equal to zero. To remove this singularity problem, we must invoke certain boundary conditions (or constraints or supports) so that the structure remains in place instead of moving as a rigid body.

Step 6 Solve for the unknown degrees of freedom (or generalized displacements)

Modified to account for the boundary conditions, is a set of simultaneous algebraic equations that can be written in expanded matrix form as

$$\begin{Bmatrix} F_1 \\ F_2 \\ \vdots \\ F_n \end{Bmatrix} = \begin{Bmatrix} K_{11} & K_{12} & \dots & K_{1n} \\ K_{21} & K_{22} & \dots & K_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ K_{n1} & K_{n2} & \dots & K_{nn} \end{Bmatrix} \begin{Bmatrix} d_1 \\ d_2 \\ \vdots \\ d_n \end{Bmatrix} \quad (22)$$

Step 7 Solve for the element strains and stresses

For the structural stress-analysis problem, important secondary quantities of strain and stress (or moment and shear force) can be obtained because they can be directly expressed in terms of the displacements determined in step 6. Typical relationships between strain and displacement and between stress and strain for one-dimensional stress given in step 3-can be used.

Step 8 Interpret the results

The final goal is to interpret and analyze the results for use in the design/analysis process. Determination of locations in the structure where large deformations and large stresses occur is generally important in making design/analysis decisions. Postprocessor computer programs help the user to interpret the results by displaying them in graphical form.

2.9.2. Applications of the Finite Element Method

The finite element method can be used to analyze both structural and nonstructural problems. Typical structural areas

1. Stress analysis, including truss and frame analysis, and stress concentration problems typically associated with holes, fillets, or other changes in geometry in a body.
2. Buckling
3. Vibration analysis

Finally, some biomechanical engineering problems (which may include stress analysis) typically include analyses of human spine, skull, hip joints, jaw/gum tooth implants, heart, and eye.

We now present some typical applications of the finite element method. These applications will illustrate the variety, size, and complexity of problems that can be solved using the method and the typical discretization process and kinds of elements used.

Figure 36 illustrates a control tower for a railroad. The tower is a three-dimensional frame comprising a series of beam-type elements. The 48 elements are labeled by the circled numbers, whereas the 28 nodes are indicated by the uncircled numbers. Each node has three rotation and three displacement components associated with it. The rotations (θ)

and displacements (ds) are called the degrees of freedom. Because of the loading conditions to which the tower structure is subjected, we have used a three-dimensional model.

The finite element method used for this frame enables the designer/analyst quickly to obtain displacements and stresses in the tower for typical load cases, as required by design codes. Before the development of the finite element method and the computer, even this relatively simple problem took many hours to solve.

Another problem, that of the hydraulic cylinder rod end shown in Figure 37, was modeled by 120 nodes and 297 plane strain triangular elements. Symmetry was also applied to the whole rod end so that only half of the rod end had to be analyzed,

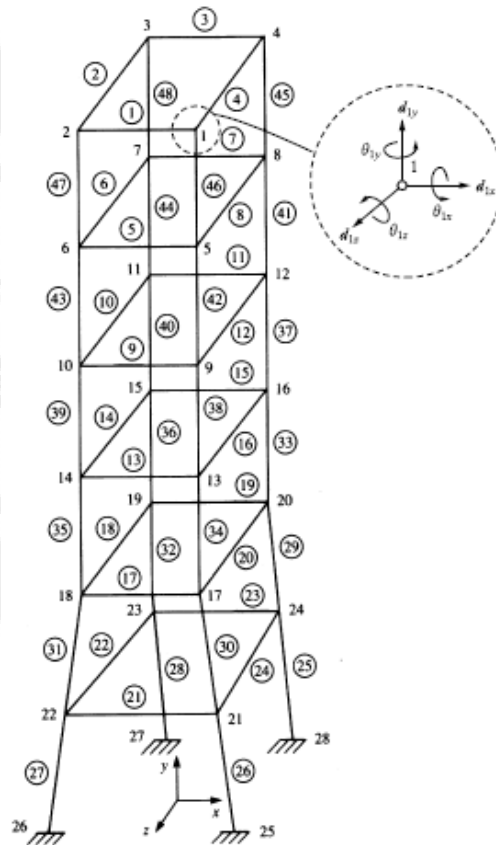


Figure 36 Discretized railroad control tower (28 nodes, 48 beam elements) with typical degrees of freedom shown at node 1

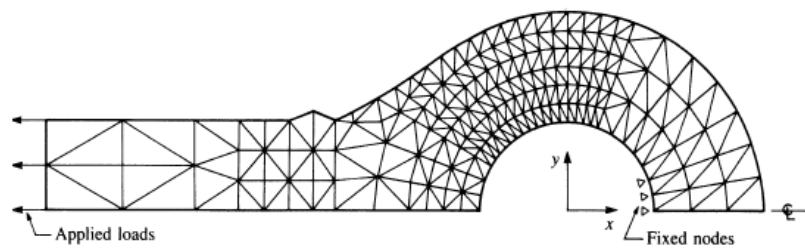


Figure 37 Two-dimensional analysis of a hydraulic cylinder rod end (120 nodes, 297 plane strain triangular elements)

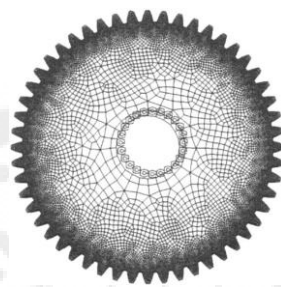


Figure 38 Finite element model of a spur gear

2.9.3. Three-Dimensional Stress and Strain

We begin by considering the three-dimensional infinitesimal element in Cartesian coordinates with dimensions dx , dy and dz and normal and shear stresses as shown in Figure 39. This element conveniently represents the state of stress on three mutually perpendicular planes of a body in a state of three-dimensional stress. As usual, normal stresses are perpendicular to the faces of the element and are represented by

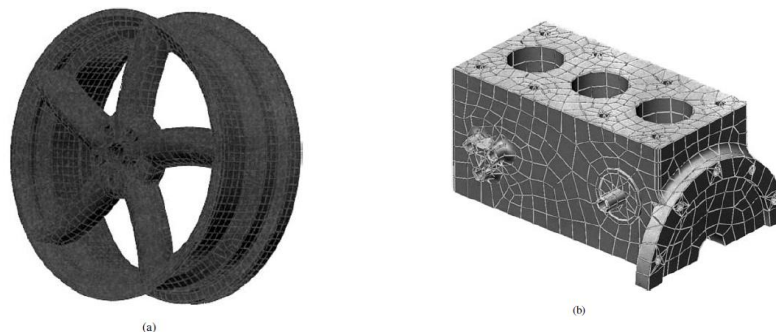


Figure 39 (a) wheel rim; (b) engine block ((a) Courtesy of Mark Blair; (b) courtesy of Mark Guard)

σ_x , σ_y and σ_z Shear stresses act in the faces (planes) of the element and are represented by τ_{xy} , τ_{yz} , τ_{zx} and so on. From moment equilibrium of the element, we show in Appendix C that

$$\tau_{xy} = \tau_{yx} \quad \tau_{yz} = \tau_{zy} \quad \tau_{zx} = \tau_{xz} \quad (23)$$

Hence, there are only three independent shear stresses, along with the three normal stresses.

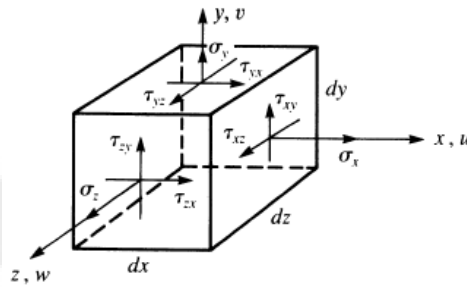


Figure 40 Three-dimensional stresses on an element

The element strain/displacement relationships are obtained in Appendix C. They are repeated here, for convenience, as

$$\varepsilon_x = \frac{\partial u}{\partial x} \quad \varepsilon_y = \frac{\partial v}{\partial y} \quad \varepsilon_z = \frac{\partial w}{\partial z} \quad (24)$$

Where u , v , and w are the displacements associated with the x , y , and z directions. The shear strains γ are now given by

$$\begin{aligned} \gamma_{xy} &= \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = \gamma_{yx} \\ \gamma_{yz} &= \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} = \gamma_{zy} \\ \gamma_{zx} &= \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} = \gamma_{xz} \end{aligned} \quad (25)$$

Where, as for shear stresses, only three independent shear strains exist. We again represent the stresses and strains by column matrices as

$$\{\sigma\} = \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{Bmatrix}, \quad \{\varepsilon\} = \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} \quad (26)$$

The stress/strain relationships for an isotropic material are again given by

$$\{\sigma\} = [D]\{\varepsilon\} \quad (27)$$

Where $\{\sigma\}$ and $\{\varepsilon\}$ are defined by Esq. (26), and the constitutive matrix $[D]$ is now given by

$$[D] = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & \nu & 0 & 0 & 0 \\ & 1-\nu & \nu & 0 & 0 & 0 \\ & & 1-\nu & 0 & 0 & 0 \\ & & & \frac{1-2\nu}{2} & 0 & 0 \\ & & & & \frac{1-2\nu}{2} & 0 \\ & & & & & \frac{1-2\nu}{2} \end{bmatrix} \quad (12)$$

Symmetry

2.9.4. Tetrahedral Element

We now develop the tetrahedral stress element stiffness matrix by again using the steps outlined. The development is seen to be an extension of the plane element previously described.

Step 1 Select Element Type

Consider the tetrahedral element shown in Fig 41 with corner nodes 1–4. This element is a four-noded solid. The nodes of the element must be numbered such that when

viewed from the last node (say, node 4), the first three nodes are numbered in a counterclockwise manner, such as 1, 2, 3, 4 or 2, 3, 1, 4. This ordering of nodes avoids the calculation of negative volumes and is consistent with the counterclockwise node numbering associated with the CST element. (Using an isoperimetric formulation to evaluate the k matrix for the tetrahedral element enables us to use the element node numbering in any order. The isoperimetric formulation of k is left

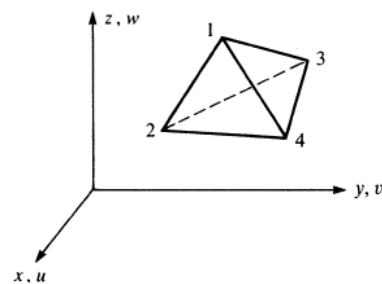


Figure 41 Tetrahedral solid element

The unknown nodal displacements are now given by

$$\{d\} = \begin{Bmatrix} u_1 \\ v_1 \\ w_1 \\ . \\ u_4 \\ v_4 \\ w_4 \end{Bmatrix} \quad (28)$$

Hence, there are 3 degrees of freedom per node, or 12 total degrees of freedom per element.

Step 2 Select Displacement Functions

For a compatible displacement field, the element displacement functions u , v , and w must be linear along each edge because only two points (the corner nodes) exist along each edge, and the functions must be linear in each plane side of the tetrahedron. We then select the linear displacement functions as

$$u(x, y, z) = a_1 + a_2x + a_3y + a_4z$$

$$v(x, y, z) = a_5 + a_6x + a_7y + a_8z \quad (29)$$

$$w(x, y, z) = a_9 + a_{10}x + a_{11}y + a_{12}z$$

In the same manner, we can express the a_i s in terms of the known nodal coordinates $x_1, y_1, z_1, \dots, z_4$ and the unknown nodal displacements $u_1, v_1, w_1, \dots, w_4$ of the element. Skipping the straightforward but tedious details, we obtain

$$u(x, y, z) = \frac{1}{6V} \left\{ (\alpha_1 + \beta_1x + \gamma_1y + \delta_1z)u_1 + (\alpha_2 + \beta_2x + \gamma_2y + \delta_2z)u_2 + (\alpha_3 + \beta_3x + \gamma_3y + \delta_3z)u_3 + (\alpha_4 + \beta_4x + \gamma_4y + \delta_4z)u_4 \right\} \quad (30)$$

Where $6V$ is obtained by evaluating the determinant

$$6V = \begin{vmatrix} 1 & x_1 & y_1 & z_1 \\ 1 & x_2 & y_2 & z_2 \\ 1 & x_3 & y_3 & z_3 \\ 1 & x_4 & y_4 & z_4 \end{vmatrix} \quad (31)$$

And V represents the volume of the tetrahedron. The coefficients $\alpha_i, \beta_i, \gamma_i$ and δ_i ($i=1,2,3,4$) in Eq. (30) are given by

$$\alpha_1 = \begin{vmatrix} x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \\ x_4 & y_4 & z_4 \end{vmatrix} \quad \beta_1 = -\begin{vmatrix} 1 & y_2 & z_2 \\ 1 & y_3 & z_3 \\ 1 & y_4 & z_4 \end{vmatrix} \quad (32)$$

$$\gamma_1 = \begin{vmatrix} 1 & x_2 & z_2 \\ 1 & x_3 & z_3 \\ 1 & x_4 & z_4 \end{vmatrix} \quad \delta_1 = -\begin{vmatrix} 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \\ 1 & x_4 & y_4 \end{vmatrix}$$

$$\alpha_2 = - \begin{vmatrix} x_1 & y_1 & z_1 \\ x_3 & y_3 & z_3 \\ x_4 & y_4 & z_4 \end{vmatrix} \quad \beta_2 = \begin{vmatrix} 1 & y_1 & z_1 \\ 1 & y_3 & z_3 \\ 1 & y_4 & z_4 \end{vmatrix} \quad (33)$$

$$\gamma_2 = - \begin{vmatrix} 1 & x_1 & z_1 \\ 1 & x_3 & z_3 \\ 1 & x_4 & z_4 \end{vmatrix} \quad \delta_2 = \begin{vmatrix} 1 & x_1 & y_1 \\ 1 & x_3 & y_3 \\ 1 & x_4 & y_4 \end{vmatrix}$$

$$\alpha_3 = \begin{vmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_4 & y_4 & z_4 \end{vmatrix} \quad \beta_3 = - \begin{vmatrix} 1 & y_1 & z_1 \\ 1 & y_2 & z_2 \\ 1 & y_4 & z_4 \end{vmatrix} \quad (34)$$

$$\gamma_3 = \begin{vmatrix} 1 & x_1 & z_1 \\ 1 & x_2 & z_2 \\ 1 & x_4 & z_4 \end{vmatrix} \quad \delta_3 = - \begin{vmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_4 & y_4 \end{vmatrix}$$

$$\alpha_4 = - \begin{vmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{vmatrix} \quad \beta_4 = \begin{vmatrix} 1 & y_1 & z_1 \\ 1 & y_2 & z_2 \\ 1 & y_3 & z_3 \end{vmatrix} \quad (35)$$

$$\gamma_4 = - \begin{vmatrix} 1 & x_1 & z_1 \\ 1 & x_2 & z_2 \\ 1 & x_3 & z_3 \end{vmatrix} \quad \delta_4 = \begin{vmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \end{vmatrix}$$

Expressions for v and w are obtained by simply substituting v_i 's for all u_i 's and then w_i 's for all u_i 's in Esq. (30).

The displacement expression for u , with similar expressions for v and w , can be written equivalently in expanded form in terms of the shape functions and unknown nodal displacements as

$$\begin{Bmatrix} u \\ v \\ w \end{Bmatrix} = \begin{bmatrix} N_1 & 0 & 0 & N_2 & 0 & 0 & N_3 & 0 & 0 & N_4 & 0 & 0 \\ 0 & N_1 & 0 & 0 & N_2 & 0 & 0 & N_3 & 0 & 0 & N_4 & 0 \\ 0 & 0 & N_1 & 0 & 0 & N_2 & 0 & 0 & N_3 & 0 & 0 & N_4 \end{bmatrix} \begin{Bmatrix} u_1 \\ v_1 \\ w_1 \\ . \\ u_4 \\ v_4 \\ w_4 \end{Bmatrix} \quad (36)$$

Where the shape functions are given by

$$\begin{aligned} N_1 &= \frac{(\alpha_1 + \beta_1 x + \gamma_1 y + \delta_1 z)}{6v} & N_2 &= \frac{(\alpha_2 + \beta_2 x + \gamma_2 y + \delta_2 z)}{6v} \\ N_3 &= \frac{(\alpha_3 + \beta_3 x + \gamma_3 y + \delta_3 z)}{6v} & N_4 &= \frac{(\alpha_4 + \beta_4 x + \gamma_4 y + \delta_4 z)}{6v} \end{aligned} \quad (37)$$

And the rectangular matrix on the right side of Eq. (36) is the shape function matrix $[N]$

Step 3 Define the Strain / Displacement and Stress / Strain Relationships

The element strains for the three-dimensional stress state are given by

$$\{\varepsilon\} = \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial u}{\partial y} \\ \frac{\partial u}{\partial z} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \\ \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \\ \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \end{Bmatrix} \quad (38)$$

Using Eq. (36) in Eq. (38), we obtain

$$E = [B]\{d\} \quad (39)$$

$$[B] = [\underline{B}_1 \quad \underline{B}_2 \quad \underline{B}_3 \quad \underline{B}_4] \quad (40)$$

The sub matrix $\underline{B}_1$ in Eq. (40) is defined by

$$\underline{B}_1 = \begin{bmatrix} N_{1,x} & 0 & 0 \\ 0 & N_{1,y} & 0 \\ 0 & 0 & N_{1,z} \\ N_{1,y} & N_{1,x} & 0 \\ 0 & N_{1,z} & N_{1,y} \\ N_{1,z} & 0 & N_{1,x} \end{bmatrix} \quad (41)$$

Where, again, the comma after the subscript indicates differentiation with respect to the variable that follows. Sub matrices $\underline{B}_2, \underline{B}_3$ and $\underline{B}_4$ are defined by simply indexing the subscript in Eq. (11) from 1 to 2, 3, and then 4, respectively. Substituting the shape functions from Eq. (37) into Eq. (31), $\underline{B}_1$ is expressed as

$$\underline{B}_1 = \frac{1}{6v} \begin{bmatrix} \beta_1 & 0 & 0 \\ 0 & \gamma_1 & 0 \\ 0 & 0 & \delta_1 \\ \gamma_1 & \beta_1 & 0 \\ 0 & \delta_1 & \gamma_1 \\ \delta_1 & 0 & \beta_1 \end{bmatrix} \quad (42)$$

with similar expressions for $\underline{B}_2, \underline{B}_3$ and $\underline{B}_4$

The element stresses are related to the element strains by

$$\{\sigma\} = [D]\{\varepsilon\} \quad (43)$$

where the constitutive matrix for an elastic material is now given by Eq. (27)

Step 4 Derive the Element Stiffness Matrix and Equations

The element stiffness matrix is given by

$$[k] = \iiint_V [B]^T [D][B] dV \quad (44)$$

Because both matrices $[B]$ and $[D]$ are constant for the simple tetrahedral element, Eq. (44) can be simplified to

$$[k] = [B]^T [D][B]V \quad (45)$$

Where again V is the volume of the element. The element stiffness matrix is now of order 12×12 .

Body Forces

The element body force matrix is given by

$$[f_b] = \iiint_V [N]^T \{X\} dV \quad (46)$$

where $[N]$ is given by the 3×12 matrix in Eq. (36), and

$$[X] = \begin{Bmatrix} X_b \\ Y_b \\ Z_b \end{Bmatrix} \quad (47)$$

For constant body forces, the nodal components of the total resultant body forces can be shown to be distributed to the nodes in four equal parts. That is,

$$\{f_b\} = \frac{1}{4} [X_b \ Y_b \ Z_b \ X_b \ Y_b \ Z_b \ X_b \ Y_b \ Z_b \ X_b \ Y_b \ Z_b]^T \quad (48)$$

The element body force is then a 12×1 matrix.

Surface Forces

Again, the surface forces are given by

$$\{f_s\} = \iint_S [N_s]^T \{T\} dS \quad (49)$$

where $[N_s]$ is the shape function matrix evaluated on the surface where the surface traction occurs?

For example, consider the case of uniform pressure p acting on the face with nodes 1–3 of the element. The resulting nodal forces become

$$\{f_s\} = \iint_S [N]^T \left| \begin{array}{l} \text{evaluated on} \\ \text{surface 1, 2, 3} \end{array} \right. \begin{Bmatrix} p_x \\ p_y \\ p_z \end{Bmatrix} dS \quad (50)$$

where p_x, p_y and p_z are the x, y , and z components, respectively, of p . Simplifying and integrating Eq. (51), we can show that

$$\{f_s\} = \frac{S_{123}}{3} \begin{Bmatrix} p_x \\ p_y \\ p_z \\ p_x \\ p_y \\ p_z \\ p_x \\ p_y \\ p_z \\ 0 \\ 0 \\ 0 \end{Bmatrix} \quad (51)$$

Here S_{123} is the area of the surface associated with nodes 1 – 3. The use of volume coordinates facilitates the integration of Eq. (50).

2.8.5. Computer Programs for the Finite Element Method

There are two general computer methods of approach to the solution of problems by the finite element method. One is to use large commercial programs, many of which have been configured to run on personal computers (PCs); these general-purpose programs are designed to solve many types of problems. The other is to develop many small, special-purpose programs to solve specific problems. In this section, we will discuss the advantages and disadvantages of both methods. We will then list some of the available general-purpose programs and discuss some of their standard capabilities.

Some advantages of general-purpose programs:

1. The input is well organized and is developed with user ease in mind. Users do not need special knowledge of computer software or hardware. Preprocessors are readily available to help create the finite element model.
2. The programs are large systems that often can solve many types of problems of large or small size with the same input format.
3. Many of the programs can be expanded by adding new modules for new kinds of problems or new technology. Thus they may be kept current with a minimum of effort.
4. With the increased storage capacity and computational efficiency of PCs, many general-purpose programs can now be run on PCs.
5. Many of the commercially available programs have become very attractive in price and can solve a wide range of problems

Some disadvantages of general-purpose programs:

1. The initial cost of developing general-purpose programs is high.
2. General-purpose programs are less efficient than special-purpose programs because the computer must make many checks for each problem, some of which would not be necessary if a special-purpose program were used.
3. Many of the programs are proprietary. Hence the user has little access to the logic of the program. If a revision must be made, it often has to be done by the developers.

Some advantages of special-purpose programs:

1. The programs are usually relatively short, with low development costs.
2. Small computers are able to run the programs.
3. Additions can be made to the program quickly and at a low cost.
4. The programs are efficient in solving the problems they were designed

to solve.

The major disadvantage of special-purpose programs is their inability to solve different classes of problems. Thus one must have as many programs as there are different classes of problems to be solved.

There are numerous vendors supporting finite element programs, and the interested user should carefully consult the vendor before purchasing any software. However, to give you an idea about the various commercial personal computer programs now available for solving problems by the finite element method, we present a partial list of existing programs.

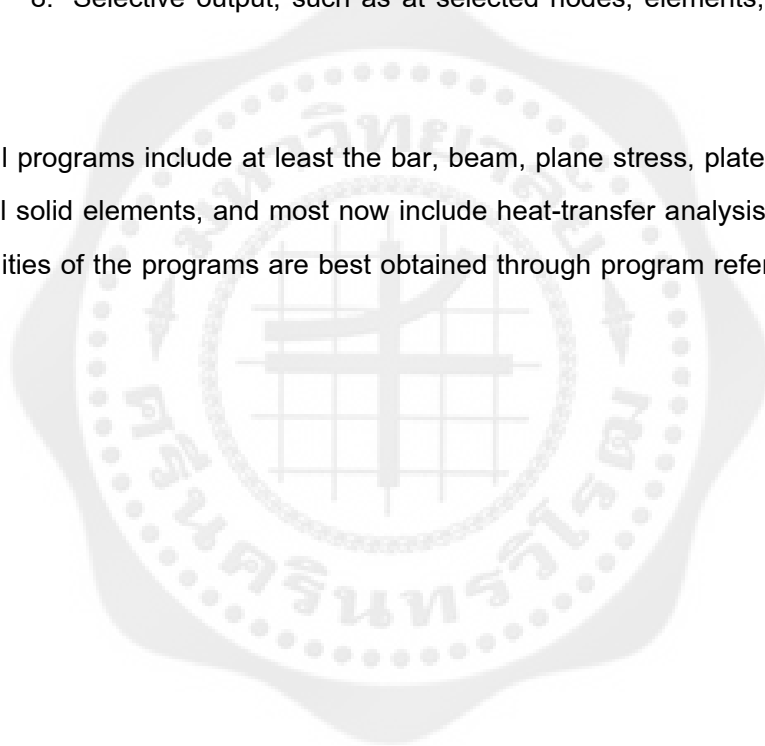
1. Algor
2. Abaqus
3. ANSYS
4. COSMOS/M
5. GT-STRUDL
6. MARC
7. MSC/NASTRAN
8. NISA
9. Pro/MECHANICA
10. SAP2000
11. STARDYNE

Standard capabilities of many of the listed programs are provided in the preceding references. These capabilities include information on

1. Element types available, such as beam, plane stress, and three dimensional solid.
2. Type of analysis available, such as static and dynamic.
3. Material behavior, such as linear-elastic and nonlinear.

4. Load types, such as concentrated, distributed, thermal, and displacement (settlement).
5. Data generation, such as automatic generation of nodes, elements, and restraints (most programs have preprocessors to generate the mesh for the model).
6. Plotting, such as original and deformed geometry and stress and temperature contours (most programs have postprocessors to aid in interpreting results in graphical form).
7. Displacement behavior, such as small and large displacement and buckling.
8. Selective output, such as at selected nodes, elements, and maximum or minimum values

All programs include at least the bar, beam, plane stress, plate-bending, and three dimensional solid elements, and most now include heat-transfer analysis capabilities. Complete capabilities of the programs are best obtained through program reference manuals and websites.



CHAPTER 3

EXPERIMENTAL METHOD

The development and use of high strength low alloy (HSLA) steels and Chromium-molybdenum steel have been driven by the need to reduce costs. The microstructure as chemical composition analysis with a spectrometer. ABS EH36 is a part of HSLA and AISI 4140 is a part of Chromium-molybdenum steel. The chemical composition of specimen and standard property details of them as shown in the reference.

Often materials are calculated for stress, so when they are used and performing the test on the materials for strength such as mechanical properties (tensile test or harness test) and microstructures (OM, SEM and EDS) as a function of applied load, time, temperature, and other conditions or standards which are published by the ASTM and ASM. Thus, these processes are used for this experiment. Therefore the process is approximately as follows:

3.1. Materials Used

3.1.1. Low alloy steel plate ABS EH36 is the most common steel grade in steel standard. Steel plate owned the minimum yield strength at 350 Mpa and the minimum tensile strength at 450 Mpa. Generally for the thickness equal and bellows 40 mm of steel plate.



Figure 42 HSLA Steel (ABS EH36)

3.1.2. Chromium-molybdenum steel (AISI: 4140) this is one of the chromium, molybdenum, manganese low alloy steels noted for toughness, good torsion strength and good fatigue strength.

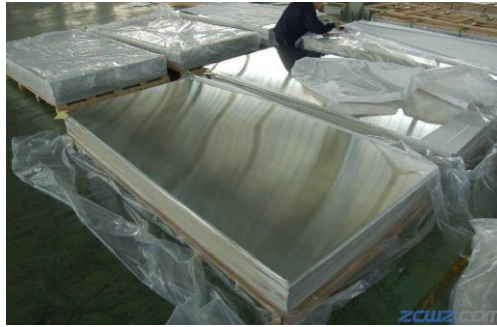


Figure 43 Chromium-molybdenum steel (AISI: 4140)

3.2. Chemical composition analysis

Chemical composition of specimens were analyzed using an optical emission spectrometer (THERMO model ARL 3460). Specimens for microstructural examination were prepared in accordance with C E407 standard.



Figure 44 Spectrophotometer test machine (THERMO model ARL 3460)

3.3. Weld Setup

Welding process by Shielded Metal Arc Welding (SMAW) and the setup refer to An American National Standard “*Structural Welding Code-Steel*”

An electric arc is generated between a coated electrode and the parent metal. The coated electrode carries the electric current to form the arc, produces a gas to control the atmosphere and provides filler metal for the weld bead. Electric current may be AC or DC. If the current is DC, the polarity will affect the weld size and application.

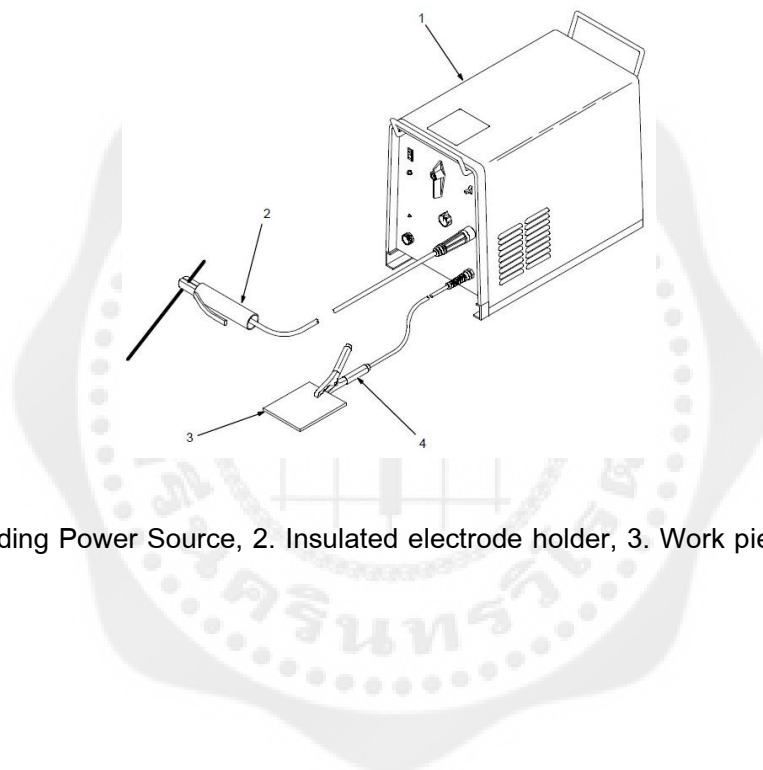


Figure 45 1. Welding Power Source, 2. Insulated electrode holder, 3. Work piece, 4. Work Clamp

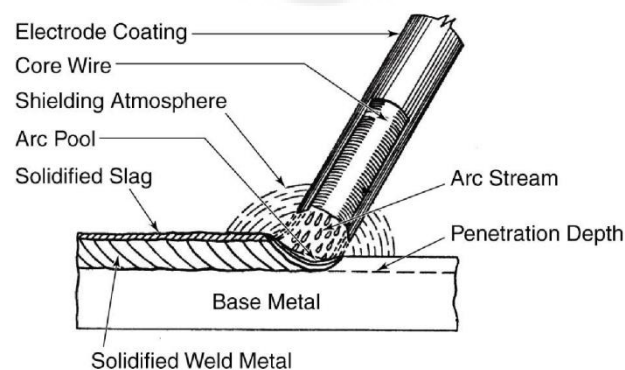


Figure 46 Shielded metal arc welding (SMAW).

3.4. Joint Weld

Refer to An American National Standard “*Structural Welding Code-Steel*” The sample has the single V groove and welds shall be made with minimum face reinforcement unless otherwise specified. In the case of butt joints, face reinforcement shall not exceed 1/8 in. [3 mm] in height. All welds shall have a gradual transition to the plane of the base-metal surfaces with transition areas free from undercut except as allowed by this code



Figure 47 Joint Design

In SMAW Process or any process of welding, the important parameters for influence input an influence on the joint mechanical properties. By varying the input process parameters the combination of output would be different welded joints with significant variation in their mechanical properties. Accordingly, welding is usually done with the aim of getting a welded joint with excellent mechanical properties. To determine these welding combinations that would lead to excellent mechanical properties. Different methods and approaches have been used to achieve this aim. The following is a review of some articles that utilized these techniques for the purpose of optimizing the welding process in order to achieve the desired mechanical properties of the welded joint. This method follow with ISO-9606 standard and used welding DC+ at 26.4 volt, 85 Amp and the speed is 120 mm/min. Welding electrodes AWS-A 5.1 E7016 2.4 mm was using for weld butt joint of two specimens shape V.

Welding electrodes AWS E7016 is a kind of electrode with low-hydrogen potassium type coating AC / DC. All position welding. It has excellent welding performance, stable arc, fewer spatters and good slag detachability. The welding joint process as follow

1. HSLA steel& HSLA steel (EH36 & EH36)
2. Chromium-molybdenum steel & Chromium-molybdenum steel (4140 & 4140)
3. Chromium-molybdenum steel & HSLA steel (4140 & EH36)

3.5. Mechanical Tests

After the weld process, prepare the specimen for the test 2 kind method. They consist of the specimen for hardness and tensile test method. Refer to An American National Standard “Standard Methods for Mechanical Testing of Welds”.

3.5.1. Tensile Tests

The tensile test use to study the relationship between stress and strain of specimen derived from the pull test and using a universal testing machine INSTRON MODEL 8801

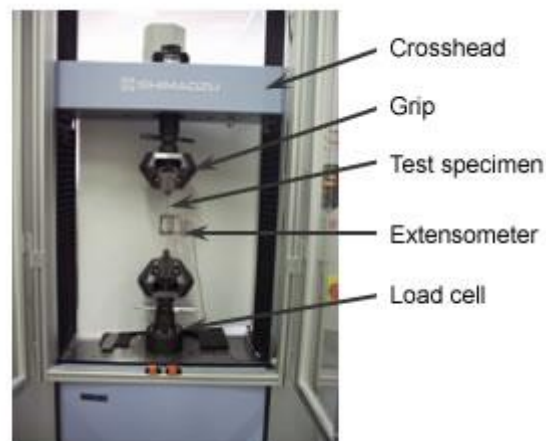


Figure 48 Typical tensile testing machine

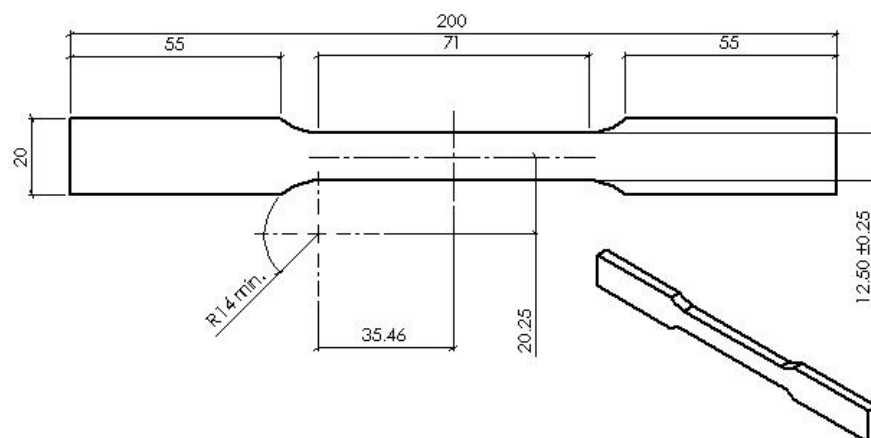


Figure 49 Standard shape for tensile testing

For the tensile testing, specimen include of

1. ABS EH36 and ABS EH36 shape (Welding joint)
2. AISI 4140 and AISI 4140 shape (Welding joint)
3. AISI 4140 and AISI 4140 shape (Welding joint)



Figure 50 Specimens shape for tensile testing (Welding joint)

3.5.2. Hardness Tests

The specimen was then sectioned for a micro-hardness measurement. Micro-hardness was measured using ANTON PAAR model MHT-10 with diamond pyramid angle of 136° indenter and conditions Force 100 g. Pressing time 10 sec, Magnification 500x. A total of 11 points were measured to establish the hardness profile of the specimen by press throughout the axial of surface at left to right under ASTM E92-82 (Reapproved 1997)



Figure 51 Micro-Vickers hardness testing machines (MITUTOYO: HM-210A)

3.6. Microstructure examination

In Metallography examination process, the preparation process is divided into several stages which must be executed correctly to ensure a satisfactory result. The three stages, cutting, mounting and mechanical preparation, will be done before used to grain size analysis step.



Figure 52 Metallography examination process

Specimen can be embedded in resin to facilitate their handling and to improve the preparation result. Specimens which need perfect edge retention or protection of layers require mounting.

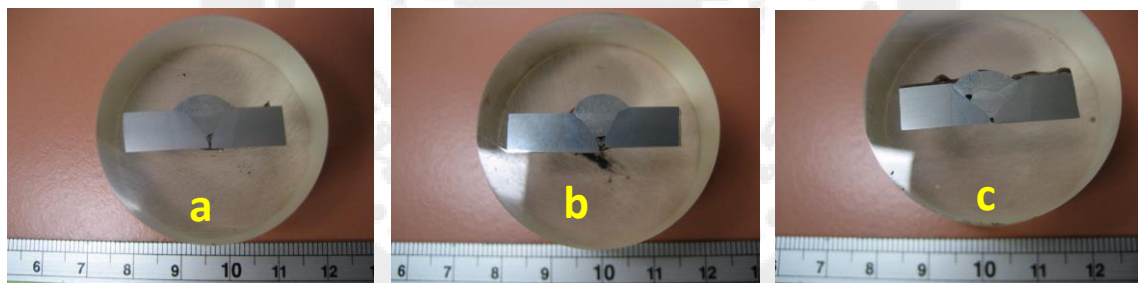


Figure 53 Mounting small a sample specimens in a synthetic resin a) EH36-EH36, b) 4140-4140, c) 4140-EH36

The microstructures were examined for the small scale structure of the specimen using an optical microscope (OM) by OLYMPUS LEXT OLS4000 LASER SCANNING CONFOCAL MICROSCOPES. The structure of the grain size can use the optical microscope to analyze and apply to find grain size number such as the intercept method.



Figure 54 Optical microscope (Olympus laser microscopes model OLS 4000)

Then scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS) is used to study the morphology and surface characteristics of a specimen and analyzed using SEM and EDS techniques. They are employed were HITACHI: S-3400N Energy Dispersive Spectroscopy microanalysis system. The modes of analysis used consist of point analysis, line scanning, and elemental mapping.

In all of the test methods, there will be testing at the three surfaces consisting of the base zone, heat affect zone (HAZ) and weld zone.



Figure 55 HITACHI S-3400N-II Scanning Electron Microscope (SEM)

3.7. Finite element method

The welding joint was imported in ANSYS and the boundary conditions were applied to the welding model. The model welding was analyzed for the root bending stress for the applied tangential, axial and radial force.

ANSYS provides a great number of new and advanced features that deliver solutions for customers to amplify engineering, simulate their most complex engineered products, and drive innovation with high-performance computing (HPC)

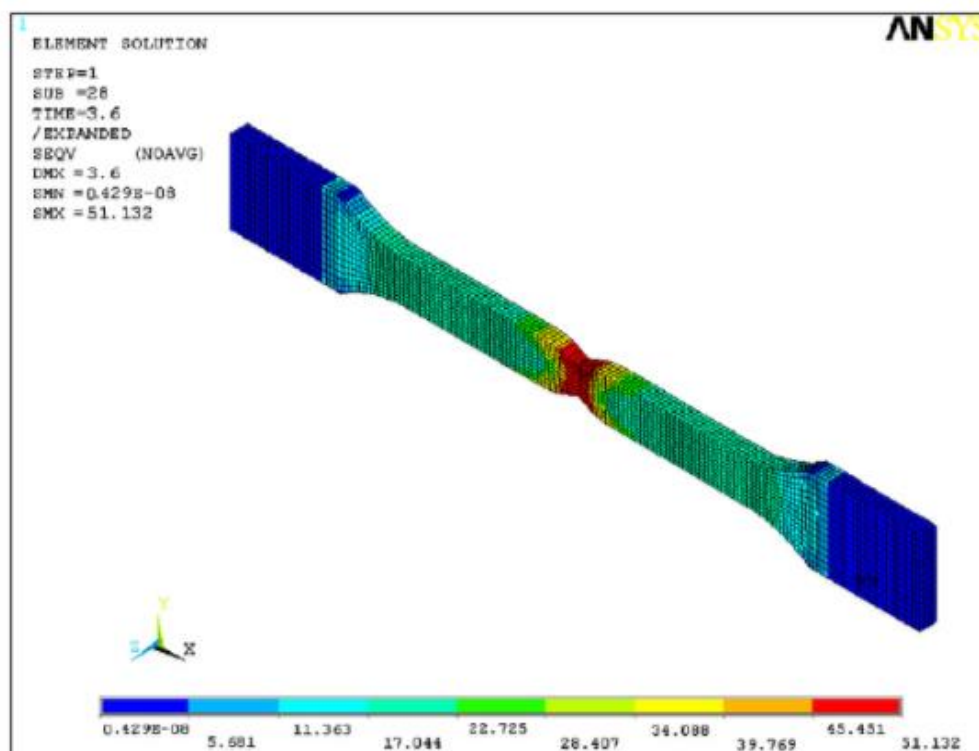


Figure 57 Example for analysis of tensile test by ANSYS

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1. Chemical composition

Chemical composition of the ABS EH36 and AISI: 4140 were analyzed using an emission spectrometer (ARL 3460 Metals Analyzer) by emission spectroscopy method. They are made from low-alloyed steels. The average values of the chemical composition of them were shown in Table 11

Table 11 Chemical composition of ABS EH36 and AISI: 4140

Elements	C	Si	Mn	P	S	Cr	Mo	Ni	V	Al	Cu	Ti	Nb	Fe
ABS EH36	0.0704	0.322	1.4834	0.0102	0.0025	0.0247	0.0129	0.0569	0.0033	0.0333	0.0772	0.0107	0.0174	Balance
AISI: 4140	0.3725	0.2504	0.6115	0.0052	0.0025	0.9936	0.1911	0.0290	0.0030	0.0296	0.0223	0.0022	0.0013	Balance

4.2. Mechanical Tests

4.2.1. Hardness Tests

The hardness test (Micro hardness) used a press throughout the axial of surface at the left to right of the specimen was measured using a Vickers hardness tester force 100 g, pressing time 10 sec and magnification 500X. The results were shown table 12.

Table 12 The results of Vickers hardness tester

Specimen / Point	2 mm.	4 mm.	6 mm.	8 mm.	10 mm.	12 mm.	14 mm.	16 mm.	18 mm.	20 mm.	22 mm.
EH36 & EH36	151.4	150.06	162.04	162	163.64	192.61	163.64	157.36	158.93	152.92	151.48
4140 & 4140	238.63	236.63	229.48	220.11	208.35	205.48	214.29	221.46	228.13	234.18	239.95
4140 & EH36	235.59	230.81	232.19	222.6	206.89	207.46	196.84	183.59	177.21	158.88	155.95

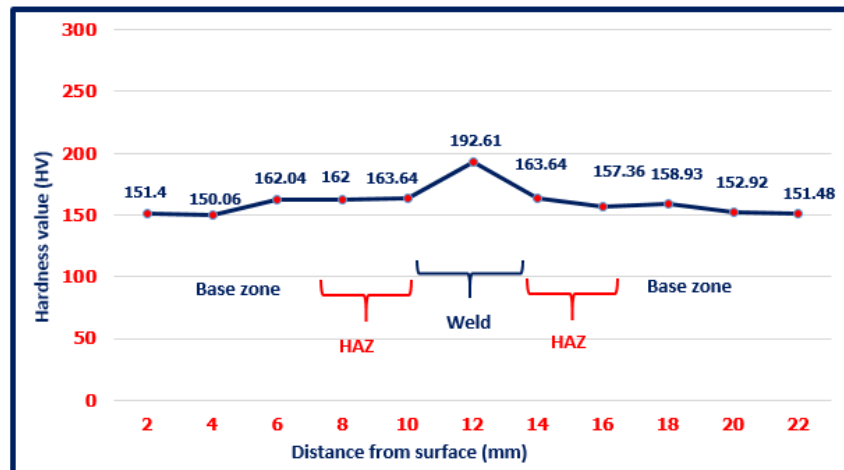


Figure 57 The results of Vickers hardness tester for EH36 & EH36

Figure 57 illustrates the maximum hardness of approximately 192.61 HV occurred near the surface of weld zone and minimum hardness diminish with distance at about 150.06 HV of the base zone. The hardness test used a press throughout the axial of surface at the left to right of the specimen

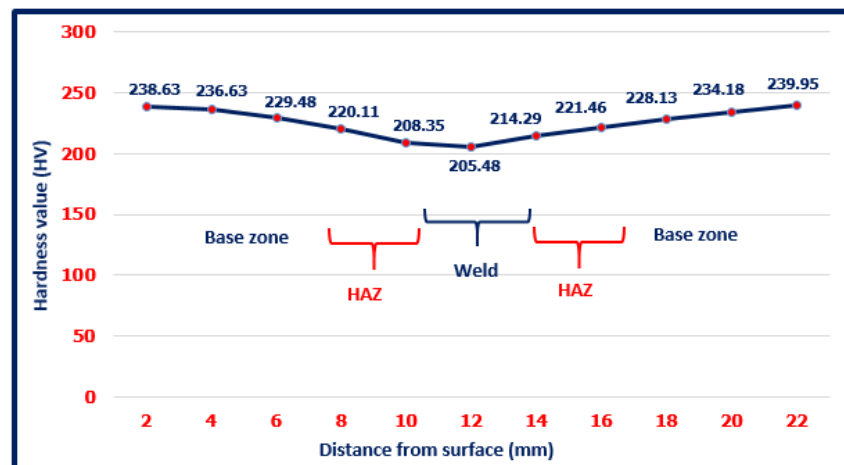


Figure 58 The results of Vickers hardness tester for 4140 & 4140

Figure 58 illustrates the maximum hardness of approximately 239.95 HV occurred at base zone and the minimum hardness diminish with distance at about 205.48 HV at the weld zone. The hardness test used a press throughout the axial of surface at the left to right of the specimen

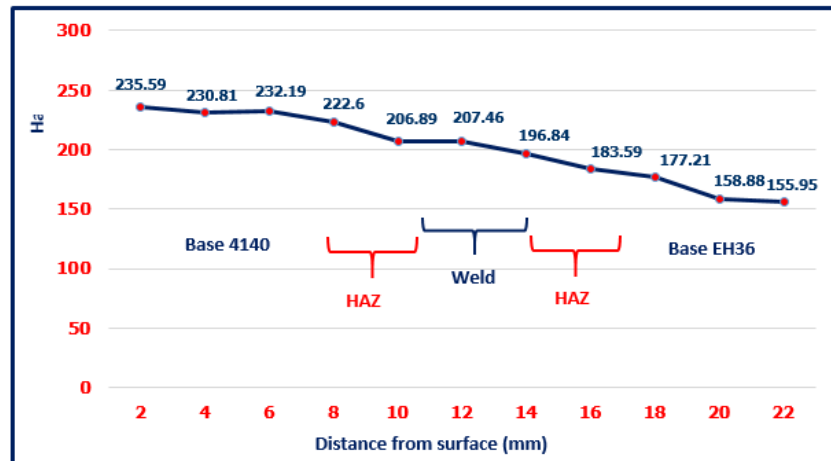


Figure 59 The results of Vickers hardness tester for 4140 & EH36

Figure 59 illustrates the maximum hardness of approximately 235.59 HV occurred at base zone of AISI: 4140 and the minimum hardness diminish with distance at about 155.95 HV at the base zone of ABS EH36. The hardness test used a press throughout the axial of surface at the left to right of the specimen

4.2.2. Tensile Tests

The results in Table 13 from this testing was shown in the tensile test and they are indicated to be known that to reference from the standard with similar values.

Table 13 The results of tensile test

Specimen	Max. Load (kN)	Yield (MPa)	Tensile strength (MPa)	Modulus (Automatic Young's) (MPa)	Tensile strain (%)
EH36 & EH36	33.18	474.04	511.71	101,919.12	9.96
4140 & 4140	43.31	598.32	653.13	94,637.94	1.64
4140 & EH36	36.33	477.79	531.92	99,516.89	13.97

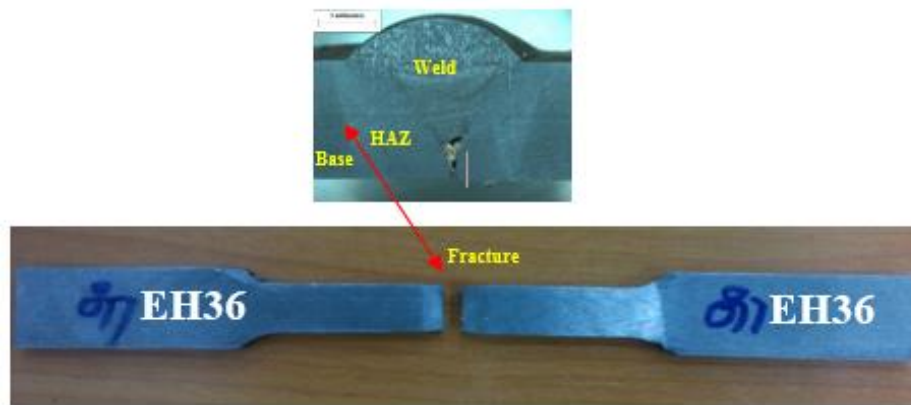


Figure 60 The results of tensile testing for EH36 & EH36

The results in Figure 60 from this testing was shown in the fracture point that nearby between the base zone and HAZ and they are indicated to be known that to reference from the standard with similar values.

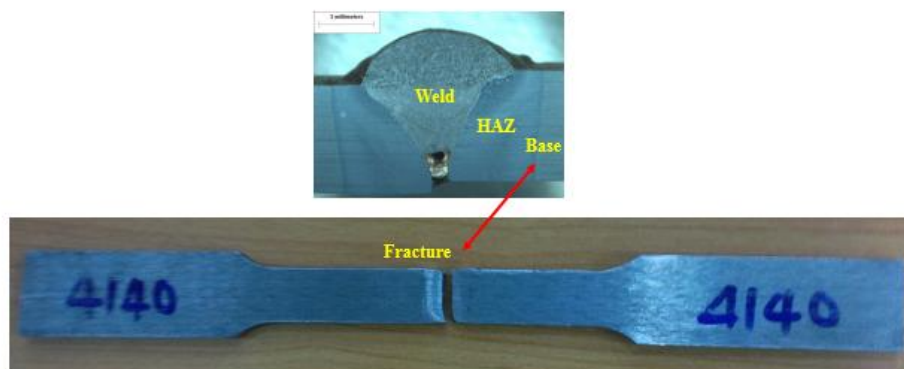


Figure 61 The results of tensile testing for 4140 & 4140

The results in Figure 61 from this testing was shown in the fracture point that nearby between the HAZ and base zone and they are indicated to be known that to reference from the standard with similar values.

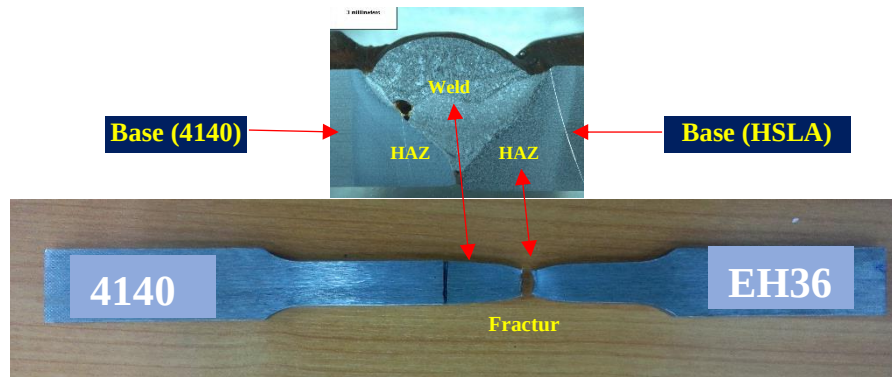


Figure 62 The results of tensile testing for 4140 & EH36

The results in Figure 62 from this testing was shown in the fracture point at the base zone of ABS EH36 and they are indicated to be known that to reference from the standard with similar values.

4.3. Microstructure

4.3.1. OM (Optical Microscope)

4.3.1.1. ABS EH36 & ABS EH36

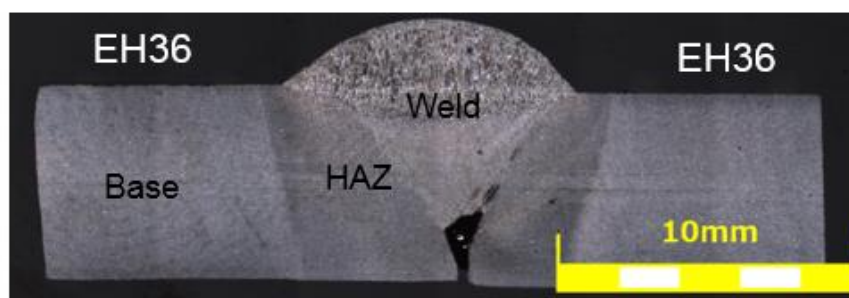


Figure 63 Optical micrographs of EH36 & EH36 and apply to find the grain size number

Figure 63 used for partitioning and apply this figure to find the grain size number by optical microscope. At the left to right of the specimen Base zone, Heat affect zone (HAZ) and Welding zone (Weld) are ABS EH36.

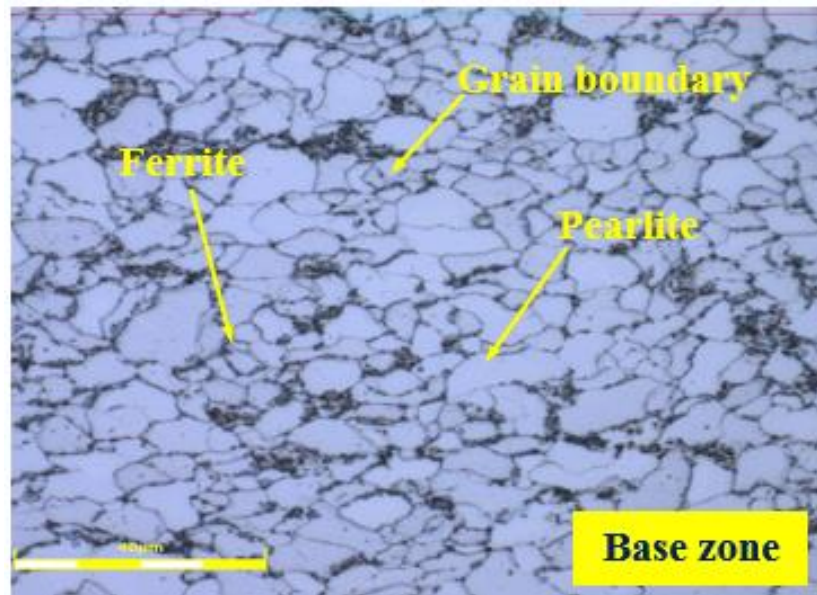


Figure 64 Variety of grain sizes at Base zone (EH36 & EH36)

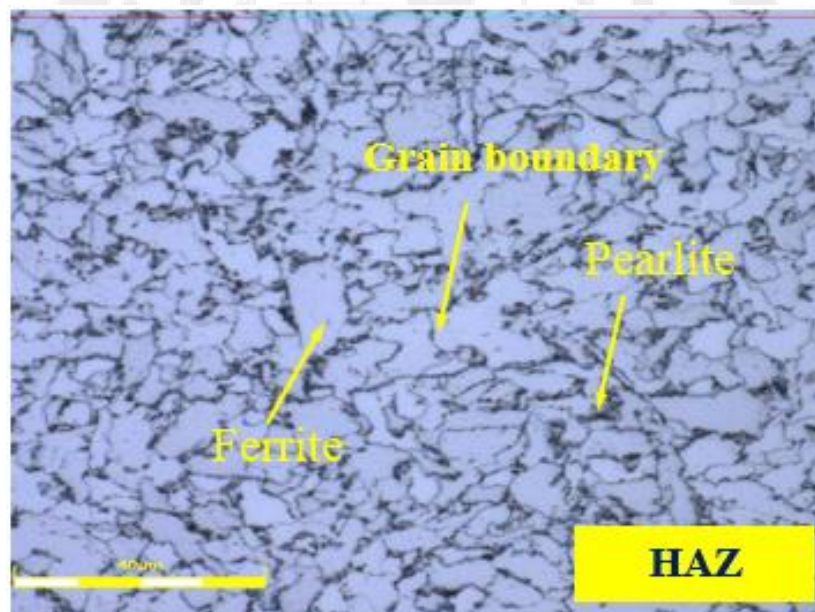


Figure 65 Variety of grain sizes at HAZ (EH36 & EH36)



Figure 66 Variety of grain sizes at Welding zone (EH36 & EH36)

Figure 64 illustrates the microstructures (OM) results shown original grain size boundary of EH36 at the base zone which consist of ferrite and pearlite. Therefore apply this figure to find the grain size number with the intercept method. The grain size number (G)=11.41 and compared to the table from ASTM E112 can know that the average grain diameter (d)=0.006916mm. Considering the Hall-Petch relationship from equation (1) in chapter 2 to determine the yield stress (σ_y)=371MPa

Figure 65 illustrates the microstructures (OM) results show the grain size boundary of EH36 at HAZ. They consist of ferrite and pearlite which are similar to the base zone. But the differences of the both in the figure is the size of grain. Grain size at HAZ began to change the shape to smaller. Therefore apply this figure to find the grain size number with the intercept method. The grain size number (G)=12.10 and compared to the table from ASTM E112 can know that the average grain diameter (d)=0.00542mm. Considering the Hall-Petch relationship from equation (1) in chapter to determine the yield stress (σ_y)=414MPa

Figure 66 illustrates the microstructures (OM) results shown the grain size boundary of EH36 at the weld zone. Ferrite grain size are smaller than in the base zone and HAZ and the shape being sharpened also known as acicular ferrite. In the case of acicular ferrite, they are very small and a barrier to count the grain size. They affect to find the grain size number and cannot calculated the yield stress.

4.3.1.2. AISI 4140 & AISI 4140

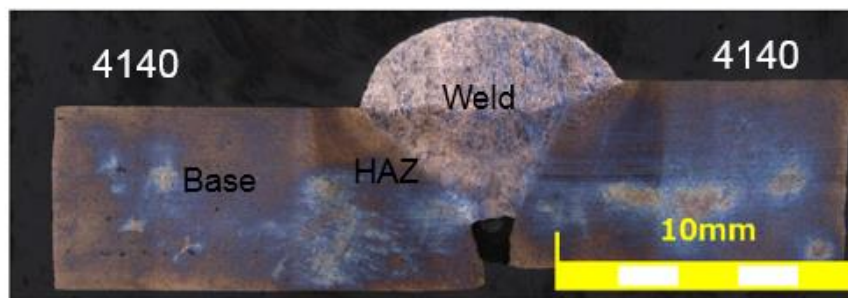


Figure 67 Optical micrographs of 4140 & 4140 and apply to find the grain size number

Figure 67 used for partitioning and apply this figure to find the grain size number by optical microscope. At the left to right of the specimen Base zone, Heat affect zone (HAZ) and Welding zone (Weld) are AISI 4140.

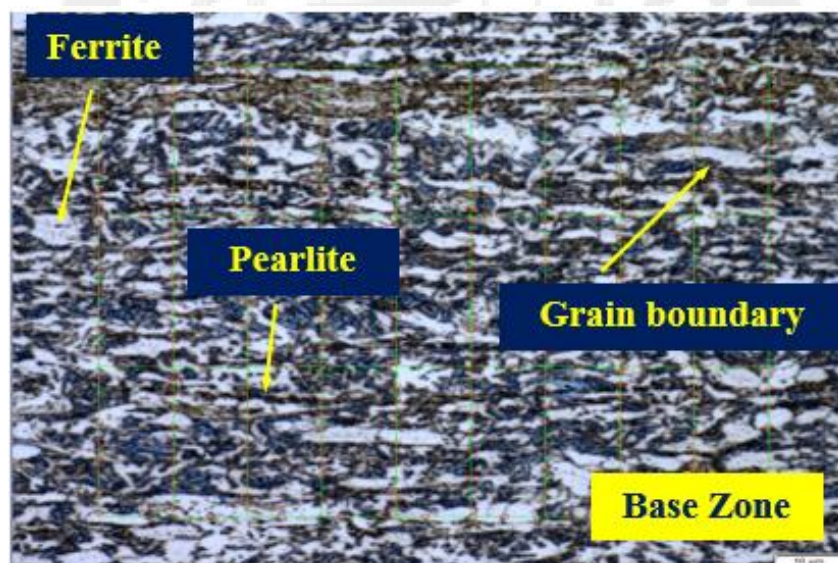


Figure 68 Variety of grain sizes at Base zone (4140 & 4140)

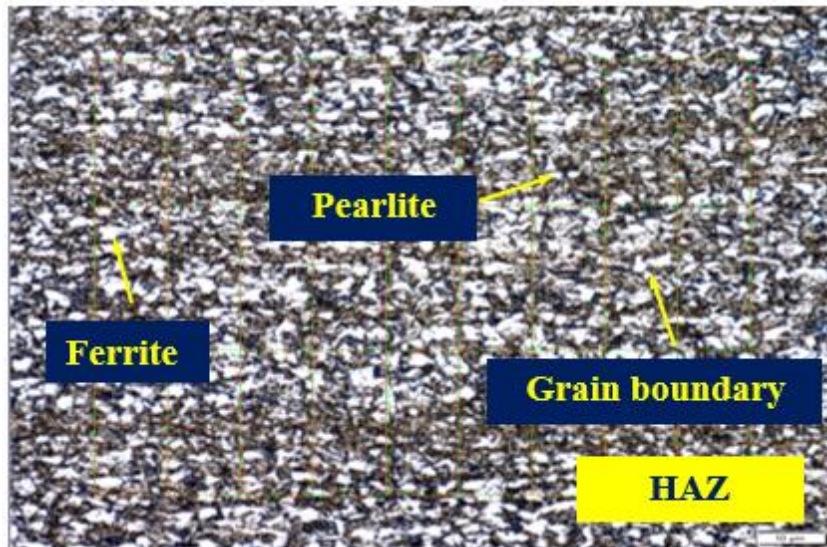


Figure 69 Variety of grain sizes at HAZ (4140 & 4140)

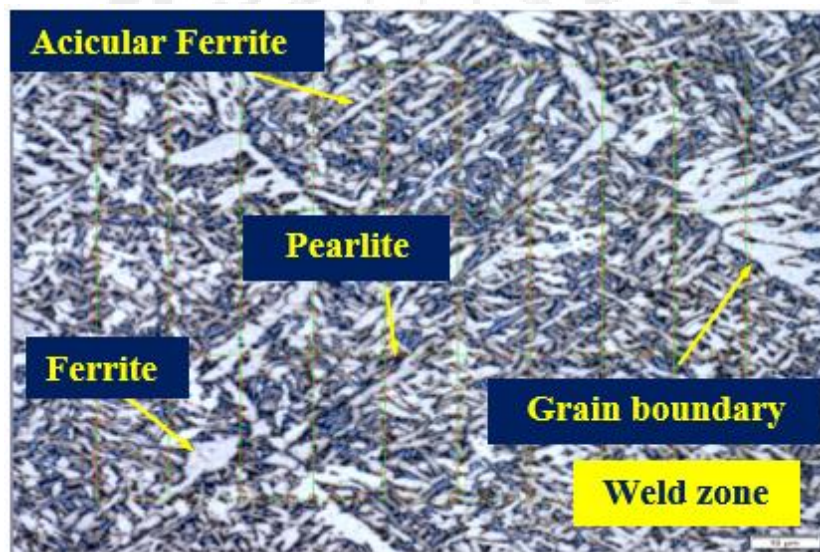


Figure 70 Variety of grain sizes at Welding zone (4140 & 4140)

Figure 68 illustrates the microstructures (OM) results shown original grain size boundary of AISI 4140 at the base zone which consist of ferrite and pearlite. Therefore apply this figure to find the grain size number with the intercept method. The grain size number (G) = 12.49 and compared to the table from ASTM E112 can know that the average grain diameter (d) = 0.004718mm. Considering the Hall-Petch relationship from equation (1) in chapter 2 to determine the yield stress (σ_y) = 441MPa

Figure 69 illustrates the microstructures (OM) results show the grain size boundary of AISI 4140 at HAZ. They consist of ferrite and pearlite which are similar to the base zone. But the differences of the both in the figure is the size of grain. Grain size at HAZ began to change the shape to smaller. Therefore apply this figure to find the grain size number with the intercept method. The grain size number (G) = 13.22 and compared to the table from ASTM E112 can know that the average grain diameter (d) = 0.003692mm. Considering the Hall-Petch relationship from equation (1) in chapter to determine the yield stress (σ_y) = 494MPa

Figure 70 illustrates the microstructures (OM) results shown the grain size boundary of AISI 4140 at the weld zone. Ferrite grain size are smaller than in the base zone and HAZ and the shape being sharpened also known as acicular ferrite. In the case of acicular ferrite, they are very small and a barrier to count the grain size. They affect to find the grain size number and cannot calculated the yield stress.

4.3.1.3. AISI 4140 & ABS EH36

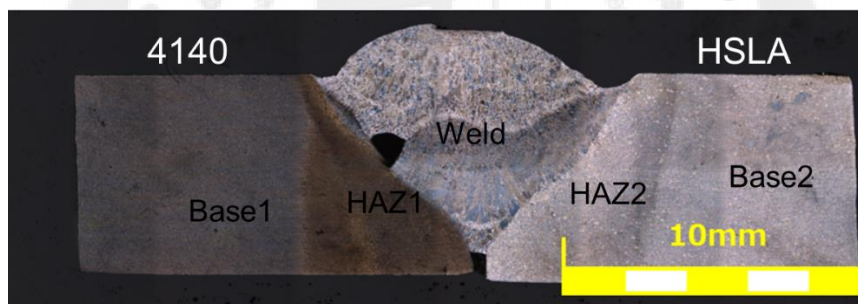


Figure 71 Optical micrographs of 4140 & EH36 and apply to find the grain size number

Figure 67 used for partitioning and apply this figure to find the grain size number by optical microscope. At the left to right of the specimen, Base zone1 and HAZ1 are AISI: 4140. Base zone2 and HAZ2 are ABS EH36.

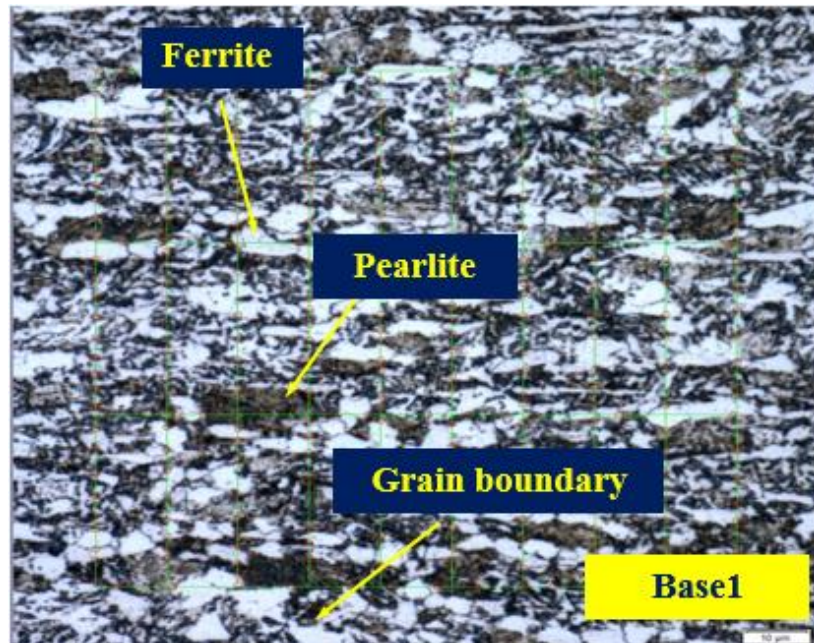


Figure 72 Variety of grain sizes at Base zone1 (4140 & EH36)

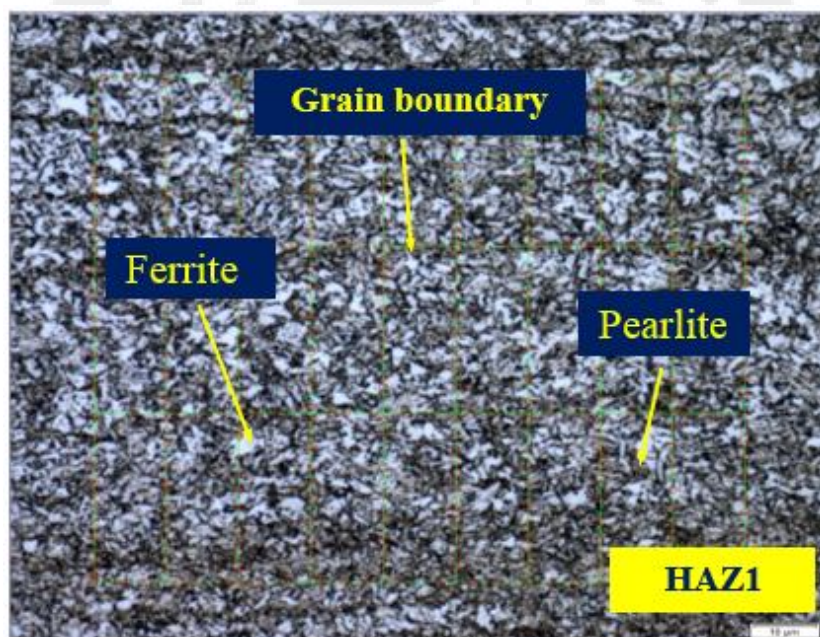


Figure 73 Variety of grain sizes at HAZ1 (4140 & EH36)

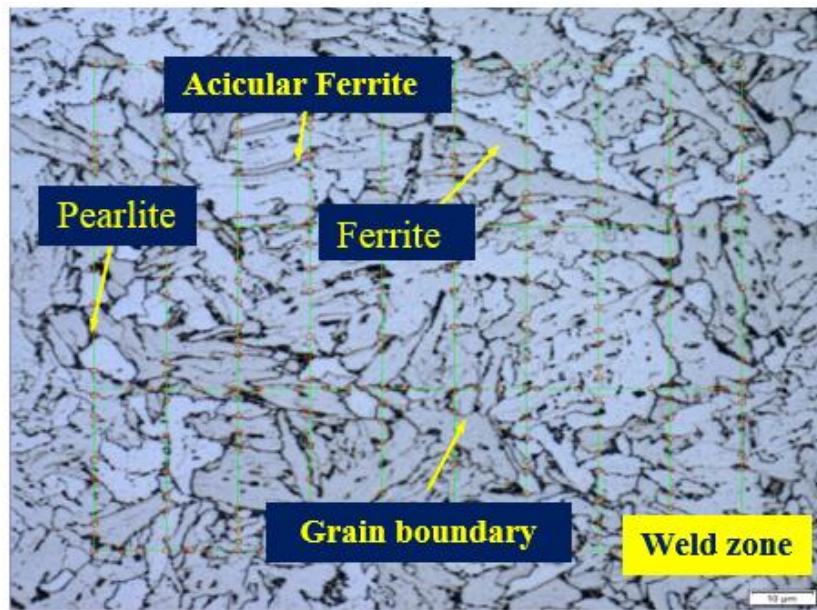


Figure 74 Variety of grain sizes at Welding zone (4140 & EH36)

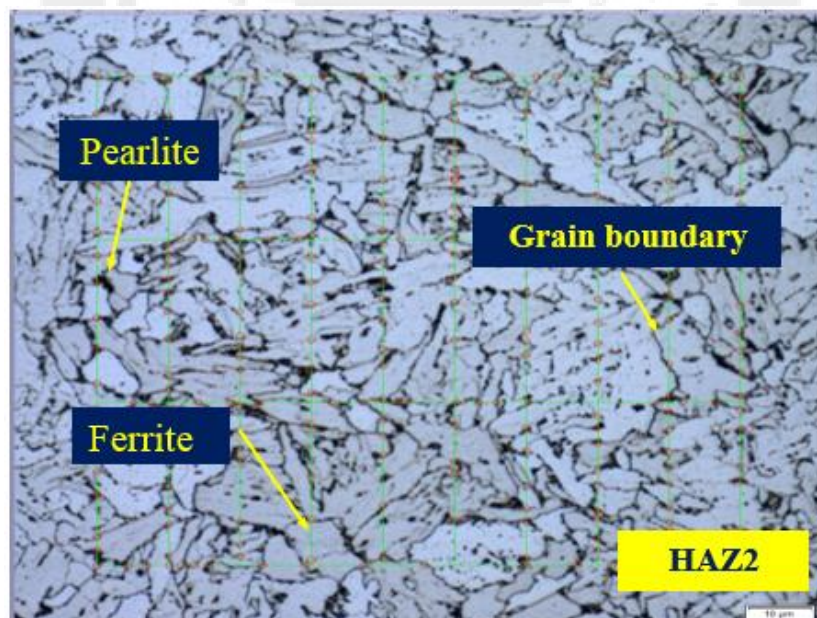


Figure 75 Variety of grain sizes at HAZ2 (4140 & EH36)

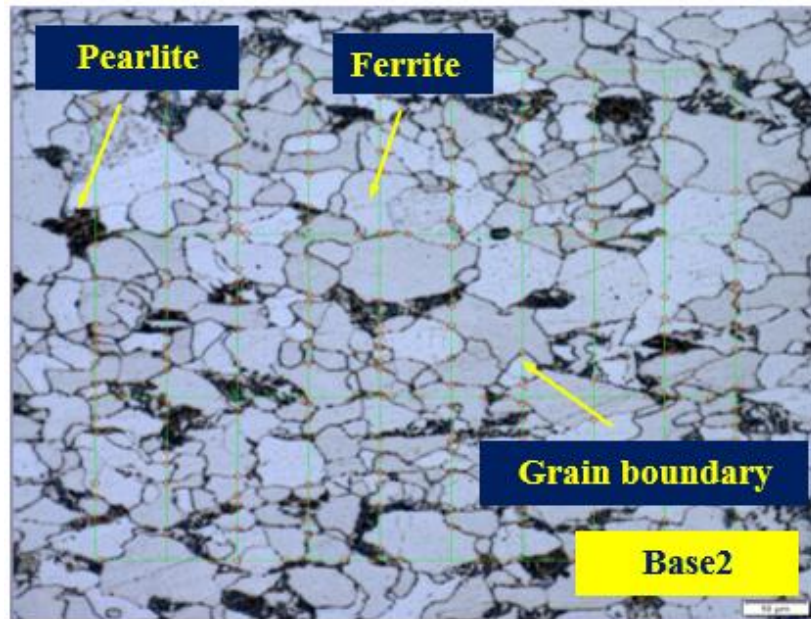


Figure 76 Variety of grain sizes at Base zone2 (4140 & EH36)

Figure 72 illustrates the microstructures (OM) results shown original grain size boundary of 4140 at the base zone1 which consist of ferrite and pearlite. Therefore apply this figure to find the grain size number with the intercept method. The grain size number (G)=12.99 and compared to the table from ASTM E112 can know that the average grain diameter (d)=0.004014mm. Considering the Hall-Petch relationship from equation (1) in chapter 2 to determine the yield stress (σ_y)=476MPa

Figure 73 illustrates the microstructures (OM) results show the grain size boundary of 4140 at HAZ1. The differences of the both in the figure is the size of grain. Grain size at HAZ1 began to change the shape to smaller. Therefore apply this figure to find the grain size number with the intercept method. The grain size number (G)=11.95 and compared to the table from ASTM E112 can know that the average grain diameter (d)=0.005710mm. Considering the Hall-Petch relationship from equation (1) in chapter 2 to determine the yield stress (σ_y)=404MPa

Figure 74 illustrates the microstructures (OM) results shown the grain size boundary of 4140 and EH36 at the weld zone. Ferrite grain size are bigger than in the base zone1 and HAZ1 but compared to the other side (base zone2 and HAZ2) and the shape being sharpened also known as acicular ferrite. In the case of acicular ferrite, they are very small and a barrier to count the grain size and affect to find the grain size number. Therefore apply this figure to find the grain size number with the intercept method. The grain size number (G)=11.71 and compared to the table from ASTM E112 can know that the average grain diameter (d)=0.006238mm. Considering the Hall-Petch relationship from equation (1) in chapter 2 to determine the yield stress (σ_y)=389MPa

Figure 75 illustrates the microstructures (OM) results show the grain size boundary of EH36 at HAZ2. They consist of ferrite and pearlite which are similar to the base zone2. But the differences of the both in the figure is the size of grain. Grain size at HAZ2 began to change the shape to smaller than base zone2. Therefore apply this figure to find the grain size number with the intercept method. The grain size number (G)=11.68 and compared to the table from ASTM E112 can know that the average grain diameter (d)=0.006304mm. Considering the Hall-Petch relationship from equation (1) in chapter 2 to determine the yield stress (σ_y)=387MPa

Figure 76 illustrates the microstructures (OM) results shown original grain size boundary of EH36 at the base zone2 which consist of ferrite and pearlite. Therefore apply this figure to find the grain size number with the intercept method. The grain size number (G)=11.35 and compared to the table from ASTM E112 can know that the average grain diameter (d)=0.007030mm. Considering the Hall-Petch relationship from equation (1) in chapter 2 to determine the yield stress. For HSLA $\sigma_0 = 35.77MPa$ and $k = 0.881MPa.m^{\frac{1}{2}}$

For HSLA,

$$\sigma_y = \sigma_0 + kd^{-1/2}$$

$$\sigma_y = 35.77MPa + \frac{0.881MPa.m^{\frac{1}{2}}}{\sqrt{\frac{0.007030}{1000}m^{\frac{1}{2}}}}$$

$$\sigma_y = 35.77MPa + 332.28MPa$$

$$\sigma_y = 368MPa$$

Typical, all of results were shown in Table 14,

Table 14 The result of OM (Optical Microscope)

Specimen	Area / Results	The grain size number, (G)	The average grain size number, $d(mm)$	the yield stress $\sigma_y(MPa)$
EH36 & EH36	Base zone	11.41	0.006916	371
	HAZ	12.10	0.00542	414
	Weld zone	NA	NA	NA
4140 & 4140	Base zone	12.49	0.004718	441
	HAZ	13.22	0.003692	494
	Weld zone	NA	NA	NA
4140 & 4140	Base zone 1	12.99	0.004014	476
	HAZ 1	11.95	0.005710	404
	Weld zone	11.71	0.006238	389
	HAZ 2	11.68	0.006304	387
	Base zone 2	11.35	0.007030	368

4.3.2. SEM and EDS (Scanning Electron Microscope and Energy Dispersive Spectroscopy or Energy Dispersive X-ray)

4.3.2.1. ABS EH36 & ABS EH36

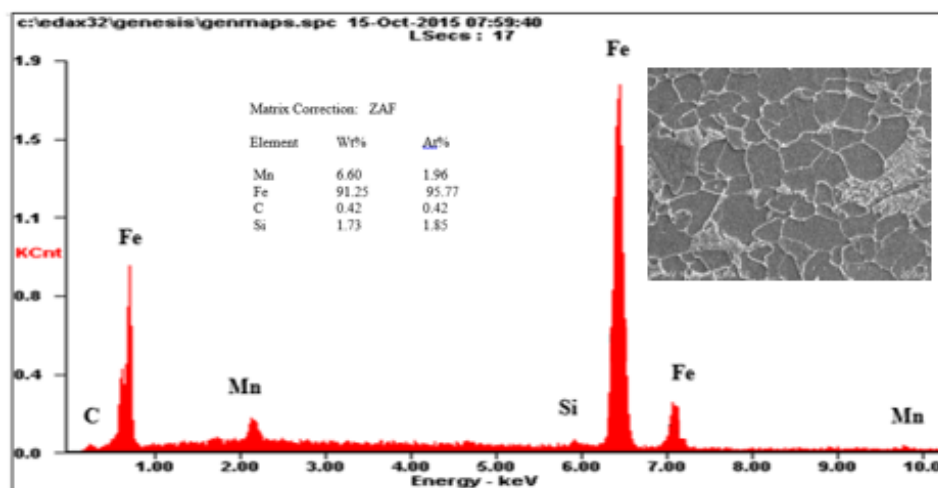


Figure 77 The EDS (analysis on the SEM) spectrum analysis at Base zone (EH36 & EH36)

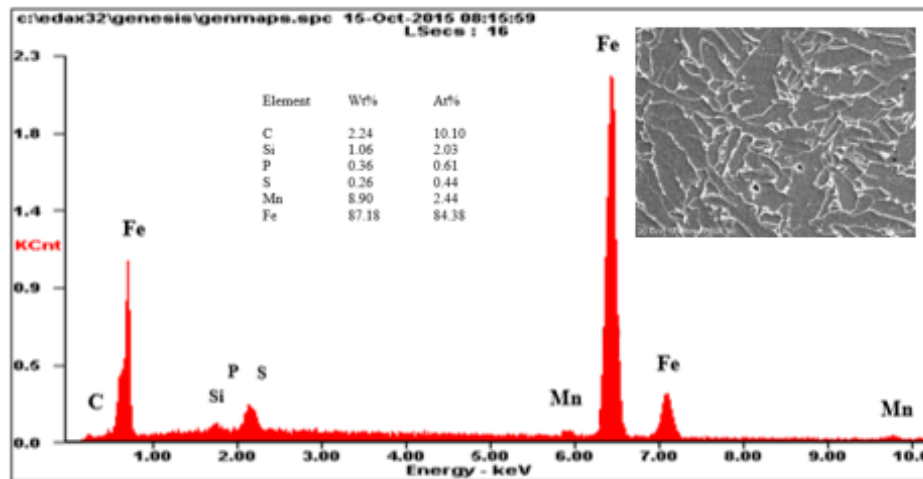


Figure 78 The EDS (analysis on the SEM) spectrum analysis at HAZ (EH36 & EH36)

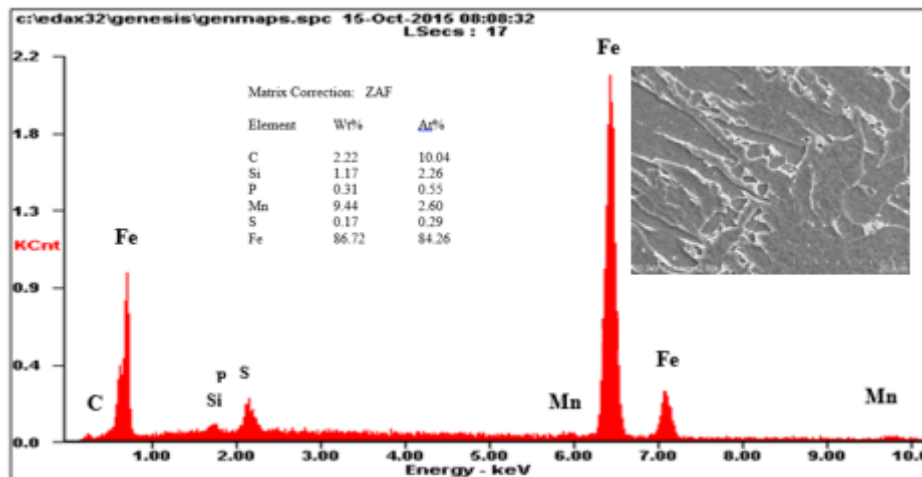


Figure 79 The EDS (analysis on the SEM) spectrum analysis at Weld zone (EH36 & EH36)

Usually, initial EDS analysis involves the generation of an X-ray spectrum from the scan area of the SEM or also call this method the EDS analysis on the SEM. They consist of the Y-axis which shows the result of counts (number of X-rays received and processed by the detector) and the X-axis shows the energy level of those counts. Figure 77 illustrates the microstructures and EDS results of the base zone. The results show enriched amounts of Mn, Fe, C, and Si. At HAZ and the weld zone, the thermal from welding resulting in a number of element found that changes in the base area and the results in Figure 78 and Figure 79 were shown C, Si, P, S, Mn, and Fe. However, another reason for the increased amounts of elements possibly from mixing between the welding electrode and base metal such as HAZ and the weld zone. They found similar element but the differences in them are the value of the element (Wt%) and the percentage of Fe decreases respectively from base zone to weld zone.

4.3.2.2. AISI 4140 & AISI 4140

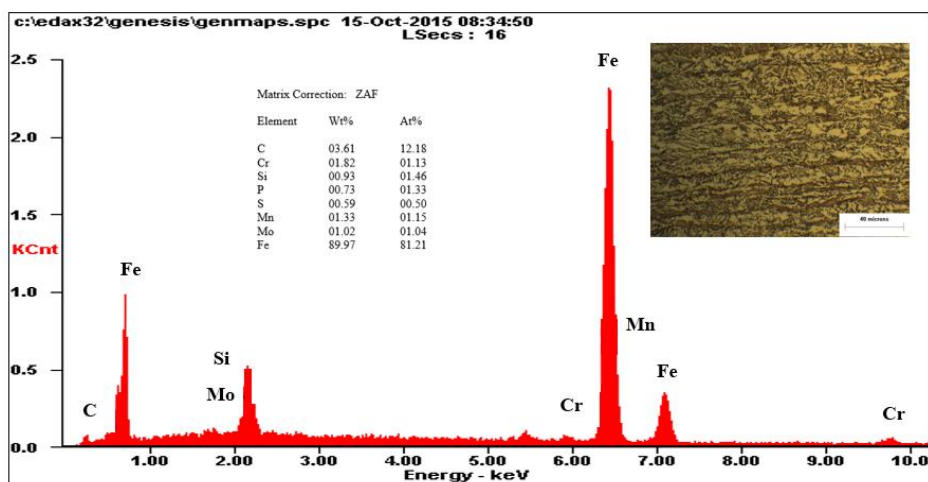


Figure 80 The EDS (analysis on the SEM) spectrum analysis at Base zone (4140 & 4140)

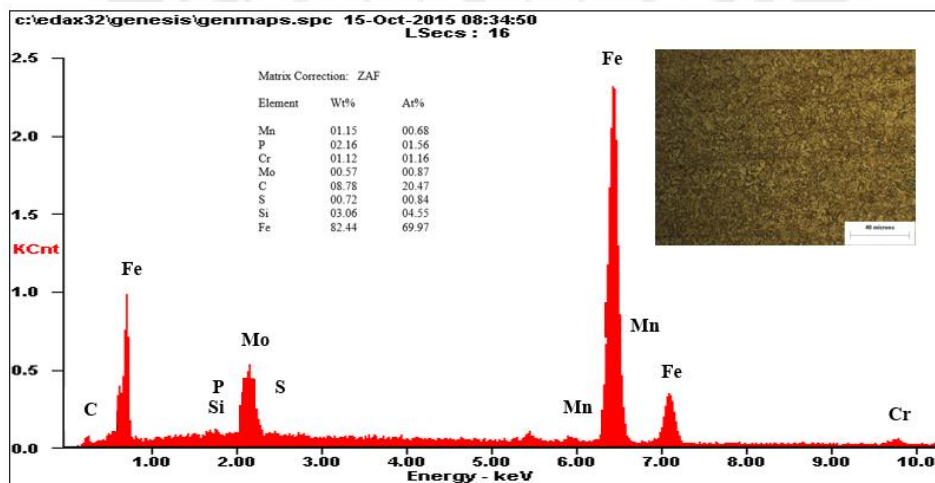


Figure 81 The EDS (analysis on the SEM) spectrum analysis at HAZ (4140 & 4140)

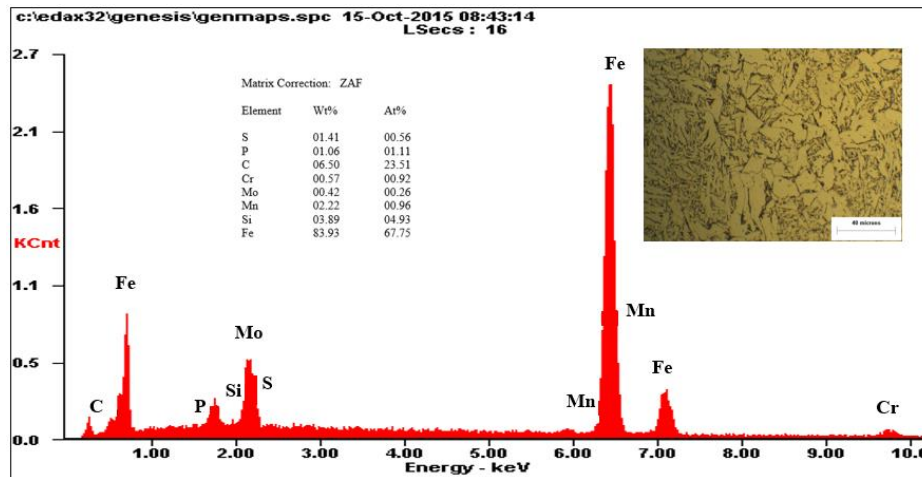


Figure 82 The EDS (analysis on the SEM) spectrum analysis at Weld zone (4140 & 4140)

Figure 80 illustrates the microstructures and EDS results of the base zone. The results show enriched amounts of C, Si, P, Mo, Mn, Cr and Fe. At HAZ and the weld zone, the thermal from welding resulting in a number of element found that changes in the base area and the results in Figure 81 and Figure 82 were shown C, Si, P, S, Mo, Mn, Cr and Fe. However, another reason for the increased amounts of elements possibly from mixing between the welding electrode and base metal such as HAZ and the weld zone. They found similar element but the differences in them are the value of the element (Wt%) and the percentage of Fe decreases respectively from base zone to weld zone.

4.3.2.3. AISI 4140 & ABS EH36

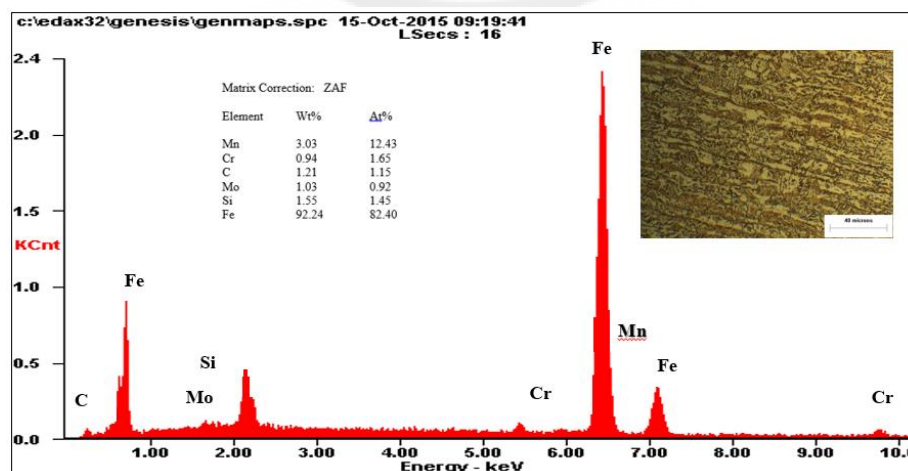


Figure 83 The EDS (analysis on the SEM) spectrum analysis at Base zone1 (4140 & EH36)

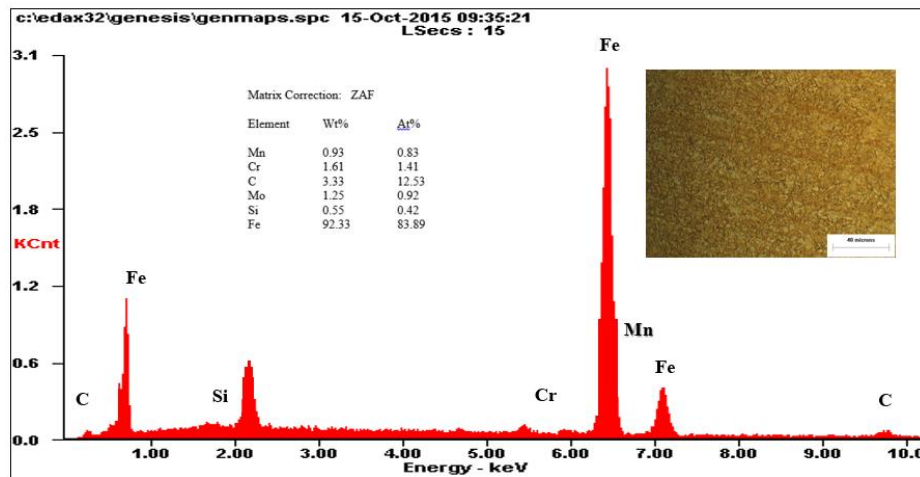


Figure 84 The EDS (analysis on the SEM) spectrum analysis at HAZ1 (4140 & EH36)

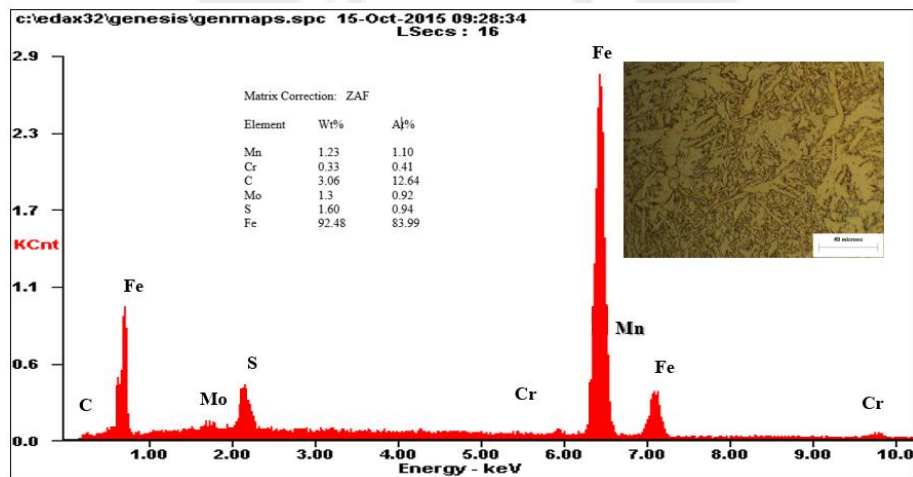


Figure 85 The EDS (analysis on the SEM) spectrum analysis at Welding zone (4140 & EH36)

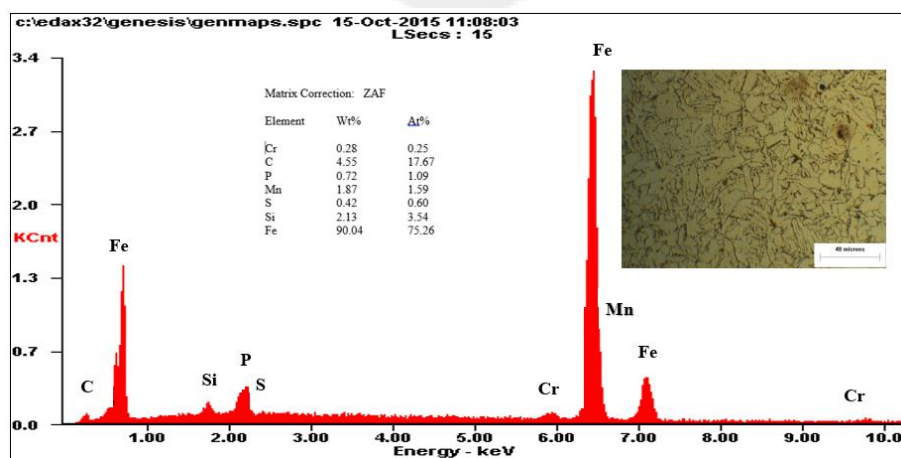


Figure 86 The EDS (analysis on the SEM) spectrum analysis at HAZ2 (4140 & EH36)

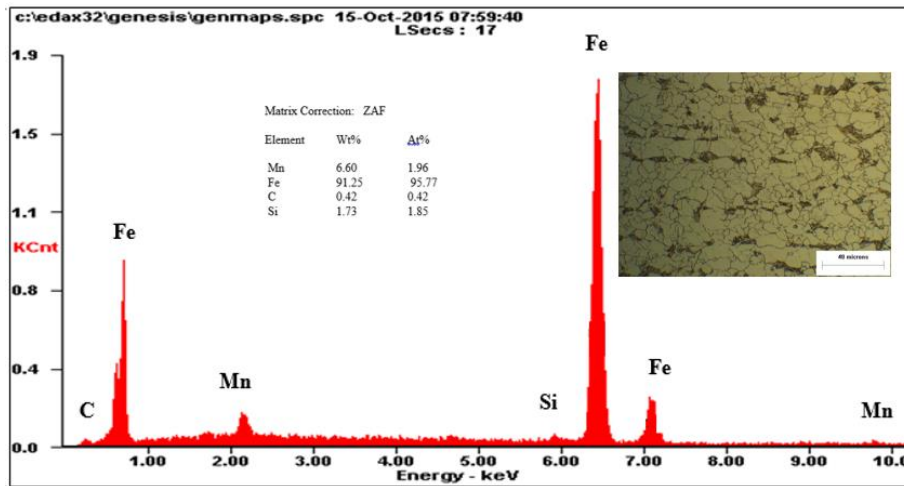


Figure 87 The EDS (analysis on the SEM) spectrum analysis at Base zone2 (4140 & EH36)

Usually, initial EDS analysis involves the generation of an X-ray spectrum from the scan area of the SEM or also call this method the EDS analysis on the SEM. They consist of the Y-axis which shows the result of counts (number of X-rays received and processed by the detector) and the X-axis shows the energy level of those counts. Figure 83 and Figure 84 illustrates the microstructures and EDS results of the base zone1 and HAZ1. The results show enriched amounts of Mn, Cr, C, Mo, Si and Fe. At the weld zone, the thermal from welding resulting in a number of element found that changes in the base zone1 and the results in Figure 85 were shown Mn, Cr, C, Mo, S and Fe. At HAZ2 found that Cr, C, P, Mn, S, Si and Fe. At base zone2 found that Mn, Fe, C and Si. However, another reason for the increased amounts of elements possibly from mixing between the welding electrode and base metal such as HAZ1, HAZ2 and the weld zone. They found similar element but the differences in them are the value of the element (Wt %) and the percentage of Fe decreases respectively from base zone1, base zone2 to weld zone.

4.4. Finite element method

The validation of a specimen model should be carried out in simple reproducible geometries that require a low computational cost in the FEA (Finite Element Analysis) software. One material model validation method consists of modelling the same uniaxial tensile test from which the stress-strain data points have been recorded.

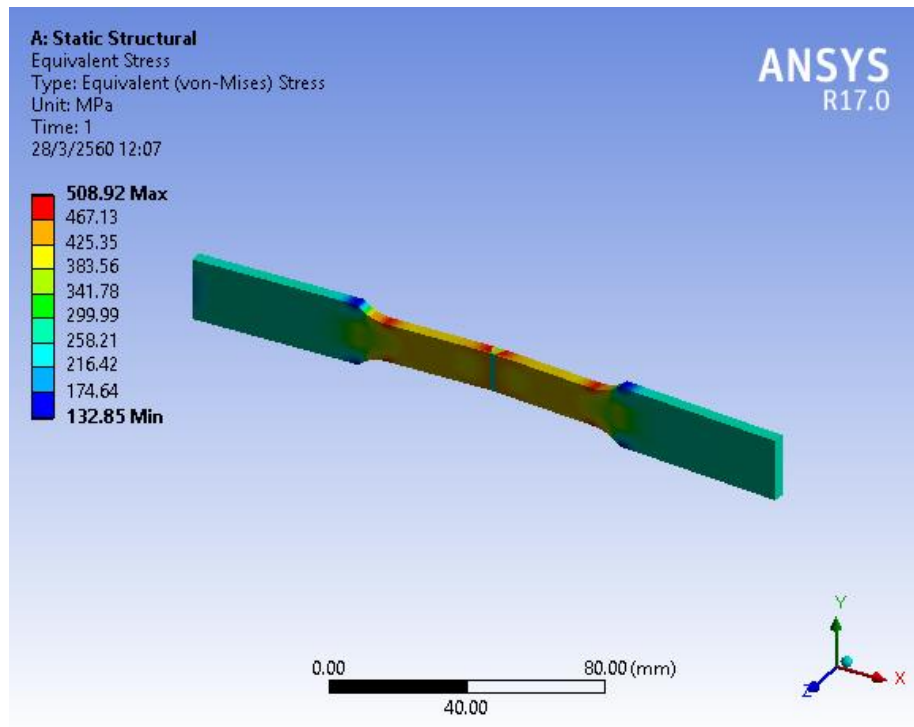


Figure 88 The result in ANSYS simulation (EH36 & EH36)

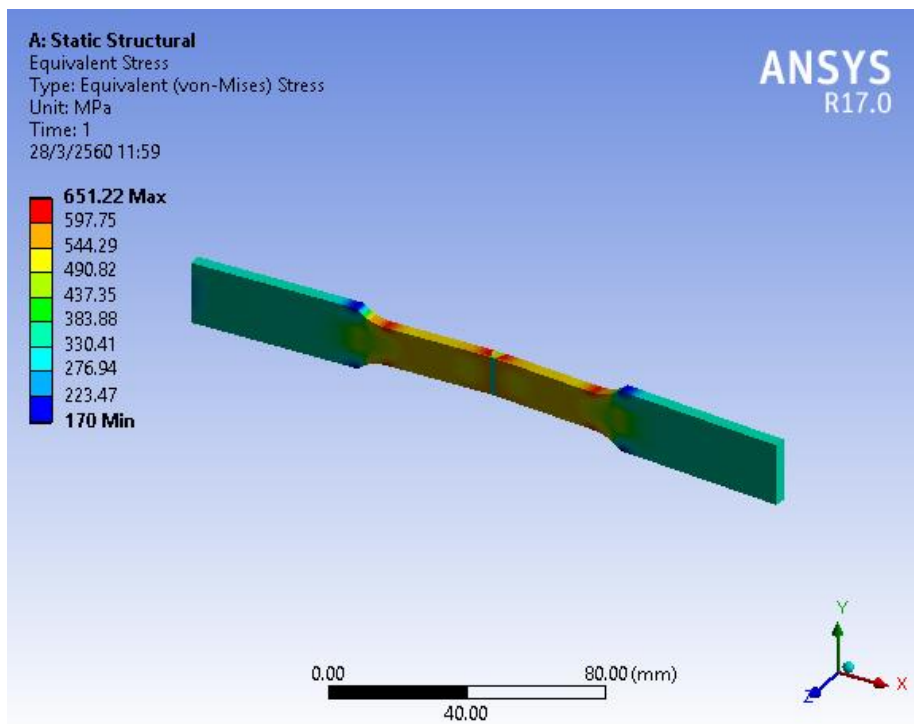


Figure 89 The result in ANSYS simulation (4140 & 4140)

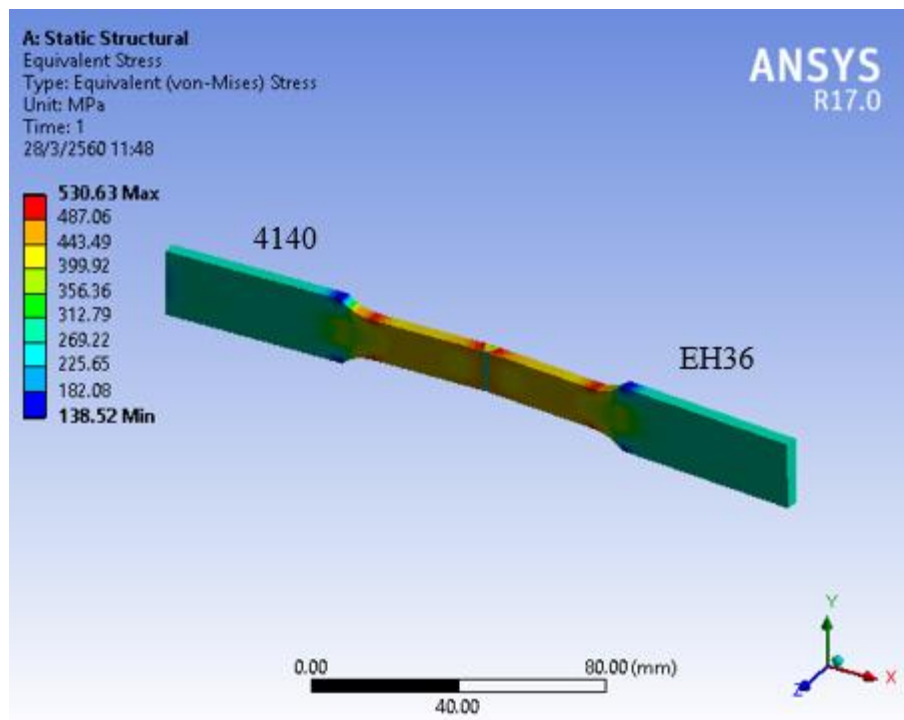


Figure 90 The result in ANSYS simulation (4140 & EH36)

Figure 88 to 90 illustrates the result in ANSYS simulation and shown specimen suffered considerable "necking" and influence to deformation of specimen (Beginning to be fracture point). The maximum value (Ultimate tensile strength) of Figure 88 was 509MPa and the evolution of necking point that nearby between Base zone and HAZ. The maximum value (Ultimate tensile strength) of Figure 89 was 651MPa and the evolution of necking point that look like Figure 88. The maximum value (Ultimate tensile strength) of Figure 90 was 530MPa and the evolution of necking point that nearby between Base zone and HAZ of EH36 side.

4.5. Comparisons between Mechanical Tests and Finite element method

Tensile tests were performed to determine the correlation level obtained between the experimental tests and the simulation results in ANSYS model-ing. Both utilize the same test samples and test conditions. The comparisons between Mechanical Tests and Finite element method was shown at table 15 and the comparisons of both method by tensile strength was shown at Figure 92

Table 15 Comparisons between Mechanical Tests and Finite element method

Specimen	Area / Method	Mechanical Tests		Finite Element Method
		Grain size analysis	Tensile test	Tensile test
		the yield stress $\sigma_y (MPa)$	Tensile strength $\sigma_{TS} (MPa)$	Tensile strength $\sigma_{TS} (MPa)$
EH36 & EH36	Base zone	371		
	HAZ	414	552	509
	Weld zone	NA		
4140 & 4140	Base zone	441		
	HAZ	494	563	651
	Weld zone	NA		
4140 & EH36	Base zone 1	476		
	HAZ 1	404		
	Weld zone	389	532	530
	HAZ 2	387		
	Base zone 2	368		

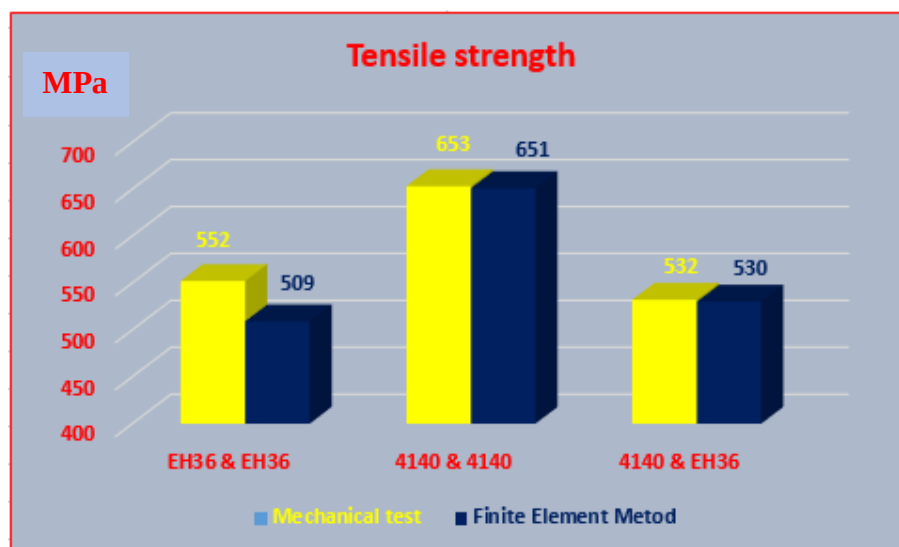


Figure 91 Comparisons between Mechanical Tests and Finite element method by tensile strength

5. Discussions

In mechanical properties were found that Chromium-Molybdenum steel (AISI: 4140) have the strength more than High Strength Low Alloy steel (ABS EH36). The minimum value of the hardness test is 239.95 HV and tensile strength is 653 MPa. This results have been confirmed by finite element method with similar direction. Tensile strength of 3 specimen model and simulation be ANSYS were found that most value at 651 MPa from AISI 4140 weld with AISI 4140. 532 MPa from AISI 4140 weld with EH36 and minimal values is 509 MPa from EH36 weld with EH 36. This study was analyze the strength of welding joint that will be changed at the welding joint between high strength low alloy steel (HSLA Steel) and Chromium-Molybdenum steel. Therefore, the strength of them were shown in the result (at AISI: 4140 and ABS EH36). The SHAW process used for the experimental procedure and the result of them consisted of a hardness test and tensile test. The minimum value of the hardness test is 155.95 HV at the base zone2 and maximum value is 235.59 HV at the base zone1. It was assumed that the synchronization of material (ABS EH36 and welding electrodes AWS-A 5.1 E7016) and the thermal influence the surface of the weld zone hardness greater than the surface of the base zone, respectively. But the synchronization of material (AISI: 4140 and welding electrodes AWS-A 5.1 E7016) was opposite effect. The base zone1 was hardness greater than another zone. However, in tensile test, the fracture point is nearby between base zone1 and HAZ1. The yield point is 477.79 MPa and tensile strength is 531.92 MPa and which is approximate to the standard (at the base zone1).

In the microstructure, the result of EDS analysis on SEM found that the differences of them are the value of element (Wt%) and the percentage of Fe decreases respectively from base zone2 to HAZ2. The reason for the increased or decreased amounts of elements possibly from mixing between materials (AISI: 4140 and ABS EH36) and welding electrodes AWS-A 5.1 E7016. Another microstructure, the optical microscope (OM) used the figure to find the grain size number with the intercept method and applied to use the value to find the yield stress with the Hall-Petch relationship. 476 MPa at base zone1 is the maximum value and 368 MPa at base zone2 is the minimum value of the yield stress. The weld zone was calculated difficult the yield stress because the shape of ferrite grain size being sharpened also known as acicular ferrite and affect to find the grain size number. They are very small and a barrier to count the grain size. The reason for the yield stress could be described as it could possibly be from the thermal and cooling rate from the welding process changed the structure of ferrite grain size.

CHAPTER 5

CONCLUSIONS AND SUGGESTIONS

5.1. Conclusions

The following conclusions were drawn from the result in this paper which probative involved about ferrite grain size and mechanical properties and at the welding joint between high strength low alloy steel (HSLA Steel) and Chromium-Molybdenum steel

5.1.1. Base zone1 has a maximum value of hardness test. It was the hardest zone and greater than HAZ1, HAZ2, Weld zone and the base zone2 respectively.

5.1.2. In the tensile test, the result has similar values with the standard and certificate of AISI: 4140 and ABS EH36. The weakness point (the fracture point) is the central area between base zone2 and HAZ2

5.1.3. The element found by EDS analysis on SEM have similar values with the composition and standard. They are the result from element of ABS EH36 and welding electrodes AWS-A 5.1 E7016

5.1.4. The yield stress at the base zone1 is a maximum value more than another zone.

5.1.5. Considering the result from those methods can know that a High-Strength Low-Carbon Micro alloyed Steel (AISI: 4140) has a higher strength than Chromium-molybdenum steel (ABS EH36). From the reasons mentioned above can prove assumption about the strength at welding joint and used to predict the strength of the material for use before the starting process.

5.1.6. When mentioning Finite Element Method, The simulations performed show good agreement with the analytical and experimental results. The tensile strength of AISI: 4140 & AISI: 4140 is higher than more AISI: 4140 & ABS EH36 and ABS EH36 & ABS EH36 respectively.

5.1.7. After comparisons Finite Element Method with mechanical test and found that similar direction of the result for the strength. They confirmed by the computational simulations and can be considered as confirm the strength of material (With specimen at welding joint).

5.2. Suggestion

The following areas are worthy for further research in the light of this work.

5.2.1. The study of strength on welding joint are a continuously evolving field of research. On base zone is major specimen because manufacturing methods materials, new difference can emerge of other failure.

5.2.2. The shape of welding joint is important for the strength such as Lap joint, Conner joint or T-joint

5.2.3. Most of the processes for fusion welding and for solid-state welding are discussed in the present section

5.2.4. Finite element methods of investigation and study can be conducted on any stress with all elements in the simulation including difference of material such as ABS EH36 and AISI4140

5.2.5. After comparisons between mechanical test, Grain size analysis and Finite element method found that similar direction of the result for the strength. They confirmed by the computational simulations and can be considered as confirm the strength of material



REFERENCE

REFERENCE

- S.D. Bhole (2005) *"Effect of nickel and molybdenum additions on weld metal toughness in submerged arc welded HSLA line-pipe steel"*
- Bravo Ivan Mendoza, Zepeda Cuauhtemoc Maldonado, Hernandez Apolinar Albiter, Piedras Eduardo Robles (2010) *"Dissimilar Welding of Super duplex Stainless Steel/HSLA Steel for Offshore Applications Joined by GTAW"*
- S. Ravi, V. Balasubramanian; S. Babu; S. Nemat Nasser (2003) *"Assessment of some factors influencing the fatigue life of strength mis-matched HSLA steel weldments"*
- Shu Xu (2011) *"Thermal Stress Analysis of dissimilar welding joints by Finite Element Method"*
- Yashar Javadi; Mehdi Ahmadi Najafabadi (2013) *"Comparison between contact and immersion ultrasonic method to evaluate welding residual stresses of dissimilar joints"*
- Wisconsin Department of Administration Division of State Facilities *"WELD FILLER METAL SELECTION GUIDELINE FOR SMAW OF VARIOUS METAL COMBINATIONS"*
- Lei Zhang; Thomas Kannengiesser; (2014) *"Austenite grain growth and microstructure control in simulated heat affected zones of microalloyed HSLA steel"*
- An American National Standard *"Structural Welding Code-Steel"*
- An American National Standard *"Standard Methods for Mechanical Testing of Welds"*
- Valery Marinov, Manufacturing Technology *"FUSION WELDING"*
- High Strength Low Alloy (HSLA) Steel, from <http://www.imoa.info/molybdenum-uses/molybdenum-grade-alloy-steels-irons/high-strength-low-alloy-steel.php> (5/12/2014)
- Classification-of-Metals, from <http://fe.rmutl.ac.th/2012/wp-content/uploads/07-Classification-of-Metals.pdf>(6/11/2014)
- Chromium molybdenum—its uses and fabrication requirements, form <http://www.thefabricator.com/article/metalsmaterials/chromium-molybdenum-its-uses-and-fabrication-requirements> (14/12/2014)
- AISI 4140 Chrome-Molybdenum High Tensile Steel, from <http://www.azom.com/article.aspx?ArticleID=6116> (14/12/2014)
- Guide to Welding Electrodes <http://www.weldguru.com/welding-electrode.html> (14/12/2014)
- Welding Electrodes AWS E7016, from http://stonebridge.diytrade.com/sdp/1316212/4/pd-5716738/9237931-2347282/WELDING_ELECTRODES_AWS_E7016_J506.html (15/12/2014)
- Welding of HSLA Steels, from <http://www.twi-global.com/technical-knowledge/job-knowledge/welding-of-hsla-steels-098/> (12/12/2014)

Use and weldability of high-chromium molybdenum steels, from <http://www.thefabricator.com/article/metalsmaterials/use-and-weldability-of-high-chromium-molybdenum-steels> (14/12/2014)

Fusion Welding, from me.emu.edu.tr/me364/ME364_combining_fusion.pdf (12/12/2014)

Mechanical testing - Tensile testing Part I, from <http://www.twi-global.com/technical-knowledge/job-knowledge/mechanical-testing-tensile-testing-part-1-069/> (15/12/2014)

Mechanical testing - Tensile testing Part II, from <http://www.twi-global.com/technical-knowledge/job-knowledge/mechanical-testing-tensile-testing-part-2-070/> (15/12/2014)

Mechanical testing - Hardness testing Part I, from <http://www.twi-global.com/technical-knowledge/job-knowledge/hardness-testing-part-1-074/> (15/12/2014)

Mechanical testing - Tensile testing Part II, from <http://www.twi-global.com/technical-knowledge/job-knowledge/hardness-testing-part-2-075/> (15/12/2014)

ASTM Designation: E92 – 82 (Reapproved 1997) Standard Test Method for Vickers Hardness of Metallic Materials

ASTM Designation: E8/E8M Standard Test Methods for Tension Testing of Metallic Materials

M Kazeminezhad, A Karimi Taheri (2004) *"Prediction of ferrite grain size and tensile properties of a low carbon steel"*

ASTM Designation: E 112 – 96e3 Standard Test Methods for Determining Average Grain Size1,

Grain Size Analysis, from <http://www.olympus-ims.com/en/applications/grain-size-analysis/> (20/8/2016)

ASM Metals HandBook Volume 09 Metallography and Microstructures 1985

Metalog Guide (Fourth revised and updated edition 2002)

Daryl L. Logan: *"A first course in the finite element method"*, Fourth edition, Thomson, 2007



APPENDIX



APPENDIX A

LIST OF SYMBOLS

LIST OF SYMBOLS

Symbol		Description	Unit
A_0	=	Original cross-sectional area	cm^2
$\bar{A}$	=	Average Grain Area	mm^2
A_f	=	Cross sectional area at site of the fracture	cm^2
CE_v	=	Carbon equivalent	-
d	=	Average grain diameter	m
E	=	Designates an Electrode	-
E	=	Young's modulus	Pa
$El\%$	=	Percentage elongation	%
G	=	ASTM Grain Size	mm^{-2}
k	=	Materials constant for the strengthening coefficient	$MPa.m^{1/2}$
ℓ	=	Mean lineal intercept length	mm
L	=	Total test line length	mm
L_0	=	Gauge length	mm
L_f	=	Gauge length at fracture	mm
M	=	Magnification	-
N	=	Quantity of grains	$inch^2$
$\bar{N}_L$	=	Grains/Unit Area	$No./mm^2$
N_A	=	Number of grains	mm^{-2}
N_s	=	Shape function matrix	-

$N_{\text{intercept}}$	=	Number of grains that intercept the test circle	mm^{-2}
N_{inside}	=	Number of grains completely inside the test circle	mm^{-2}
P_{max}	=	Maximum load	N
P_{yp}	=	Load at the yield point	N
ν	=	Poisson's ratio	-
σ_0	=	Materials constant for the starting stress	MPa
σ_x	=	Stress in the x direction	N / mm^2
$\sigma_x, \sigma_y, \sigma_z$	=	Shear stresses act in the faces (planes) of the element	N / mm^2
σ_y	=	Yield point	N / mm^2
σ_y	=	Yield stress	MPa
σ_{max}	=	Maximum Stress	N / mm^2
ϕ	=	Electrode Diameter	mm
ϵ_x	=	Strain (Define the strain / Displacement)	-
τ	=	Normal strain	N / m^2
γ	=	Shear strains	$Radian$
α	=	Coefficient of thermal expansion	-



APPENDIX B

Properties of selected engineering material

MTEC3075/58

รายงานผลการวิเคราะห์ตัวอย่าง

วันที่รายงาน	:	9 กันยายน 2558
ตัวอย่างจาก	:	บริษัท อูธูรยา อินดัสเตรียลแก๊ส จำกัด 378 หมู่ 2 ตำบลคลองจิก อำเภอบางปะอิน จังหวัดพระนครศรีอยุธยา 13160 โทรศัพท์: 035 268 255 ต่อ106 โทรสาร : 035 268 257
ทดสอบโดย	:	ห้องปฏิบัติการโลหะวิทยาเชิงวิศวกรรม ศูนย์เทคโนโลยีโลหะและวัสดุแห่งชาติ
วันที่รับตัวอย่าง	:	21 สิงหาคม 2558
วันที่วิเคราะห์	:	8 กันยายน 2558
ตัวอย่าง	:	เหล็กกล้าคาร์บอน
การขึ้นรูปตัวอย่าง	:	1. HSLA (ดำ) และ 2. SCM440 (แดง)
เครื่องมือที่ใช้ทดสอบ	:	Emission Spectrometer (ARL 3460 Metals Analyzer)
เทคนิคในการทดสอบ	:	Emission Spectroscopy
สถานะการทดสอบ	:	อุณหภูมิห้อง
การเตรียมชิ้นงาน	:	ขัดเตรียมผิวบริเวณวิเคราะห์ให้เรียบ

รายละเอียดการวิเคราะห์

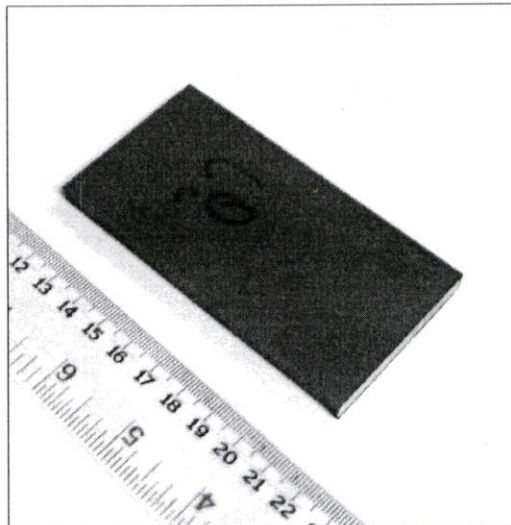
- วิเคราะห์ส่วนผสมทางเคมี

การแสดงผลการวิเคราะห์

- ผลการวิเคราะห์ส่วนผสมทางเคมีแสดงในตารางที่ 1 และ 2

ตารางที่ 1. ผลการวิเคราะห์ส่วนประกอบเคมีของตัวอย่าง (Emission Spectrometer)

ธาตุ	ปริมาณ (% โดยน้ำหนัก)
C	0.0704
Si	0.3220
Mn	1.4834
P	0.0102
S	0.0025
Cr	0.0247
Mo	0.0129
Ni	0.0569
V	0.0033
Al	0.0333
Cu	0.0772
Ti	0.0107
Nb	0.0174
Fe	Balance



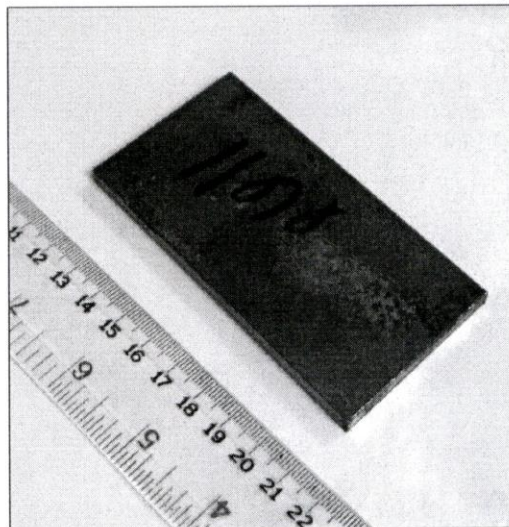
ภาพที่ 1. ตัวอย่างสำหรับการวิเคราะห์ 1. HSLA (ดำ)

หมายเหตุ

1. ผลวิเคราะห์ที่แสดงในตารางเป็นค่าเฉลี่ยจากการวิเคราะห์เพื่อยืนยันผลที่ใกล้เคียงติดต่อกันจำนวน 3 ครั้ง
2. ธาตุที่แสดงในตารางระบุด้วยการเทียบตัวอย่างมาตรฐานกลุ่มเหล็กกล้าคาร์บอน

ตารางที่ 2. ผลการวิเคราะห์ส่วนผสมทางเคมีของตัวอย่าง (Emission Spectrometer)

ธาตุ	ปริมาณ (% โดยน้ำหนัก)
C	0.3725
Si	0.2504
Mn	0.6115
P	0.0052
S	0.0025
Cr	0.9936
Mo	0.1911
Ni	0.0290
V	0.0030
Al	0.0296
Cu	0.0223
Ti	0.0022
Nb	0.0013
Fe	Balance



ภาพที่ 2. ตัวอย่างสำหรับการวิเคราะห์ 2. SCM440 (แดง)

หมายเหตุ

1. ผลวิเคราะห์ที่แสดงในตารางเป็นค่าเฉลี่ยจากการวิเคราะห์เพื่อยืนยันผลที่ใกล้เคียงติดต่อกันจำนวน 3 ครั้ง
2. ธาตุที่แสดงในตารางระบุด้วยการเทียบตัวอย่างมาตรฐานกลุ่มเหล็กกล้าคาร์บอน

ทดสอบโดย : 
(นายประภาส คุณนาม)
วิศวกร

ตรวจสอบโดย : 
(นายธนากรณ์ โกรษฤทธิ์)
หัวหน้าห้องปฏิบัติการ โลหะวิทยาเชิงวิศวกรรม

หมายเหตุ

1. ศูนย์ฯ ไม่อนุญาตให้มีการแก้ไข เพิ่มเติม หรือเปลี่ยนแปลงรายงาน หรือส่วนหนึ่งส่วนใดของรายงาน เว้นแต่จะได้รับอนุญาตเป็นลายลักษณ์อักษร จากศูนย์ฯ
2. ทางศูนย์ฯ ไม่สามารถรับผิดชอบต่อความเสียหายใดๆ ที่จะเกิดขึ้น ไม่ว่าโดยทางทางตรงหรือทางอ้อม ในกรณีที่น่าข้อมูลผลการวิเคราะห์ข้อสรุปหรือคำแนะนำฉบับนี้ไปใช้ในการออกแบบ การผลิต หรือเพื่อจุดประสงค์ใดก็ตาม
3. ผลการทดลองเป็นจริงเฉพาะตัวอย่างที่นำมาทดลองเท่านั้น



APPENDIX C

Kasem Bundit engineering journal

วิศวกรรมสารเกษมบัณฑิต

ISSN 2286-668X

KASEM BUNDIT

Engineering Journal



คณะวิศวกรรมศาสตร์ มหาวิทยาลัยเกษมบัณฑิต

ปีที่ 6 ฉบับที่ 2 กรกฎาคม - ธันวาคม 2559
Vol.6 No. 2 July - December 2016

วิศวกรรมสารเกษมบัณฑิต

ปีที่ 6 ฉบับที่ 2 กรกฎาคม - ธันวาคม 2559

Kasem Bundit Engineering Journal (KBEJ)

Volume 6 No.2 July - December 2016

คณะวิศวกรรมศาสตร์ มหาวิทยาลัยเกษมบัณฑิต

FERRITE GRAIN SIZE AND MECHANICAL PROPERTIES IN THE WELD HAZ OF A HIGH-STRENGTH LOW-CARBON MICROALLOYED STEEL

Nuttaporn Bungmek and Ganwarich Pluphrach

Department of Mechanical Engineering, Faculty of Engineering, Srinakharinwirot University
63 M.7 Rangsit-Nakhonnayok Rd., Khong 16, Ongkharak, Nakhonnayok 26120, Thailand

ABSTRACT

The process of Shielded Metal Arc Welding (SMAW) was used to join High-Strength Low-Alloy (HSLA) with AWS E7016 electrodes. The ABS EH36 steel was a part of HSLA grade. The testing forms of weld ability use to predict mechanical properties and microstructure. An investigation was carried out to determine mechanical properties in a hardness test (Vickers hardness tester) and tensile test. Microstructure as chemical composition analysis with a spectrometer, EDS analysis on the SEM with a scanning electron microscope and predicts the strength as the optical microscope (OM) that used the figure to find the grain size number by the intercept method and applied to use the value to find the yield stress with the Hall-Petch relationship. The result has a higher strength than HAZ and base zone respectively.

KEYWORDS: Ferrite Grain Size, Mechanical Properties, Microstructure, High-Strength Low-Carbon Microalloyed Steel, Hall - Petch relationship

1. Introduction

High-Strength Low-Alloy (HSLA) or Micro alloyed Steel are widely used to provide many benefits over regular steel alloys [1]. In general, they are much stronger and tougher than ordinary plain carbon steels and used in shipbuilding, oil platform, cars and other structures that are designed to handle a lot of stress, often at very low temperatures. One typical benefit from micro alloyed steel is the grain refinement of ferrite due to the effect from fine micro alloy (Ti, Nb and V). When micro alloyed steels are fusion welded as Shielded Metal Arc Welding (SMAW), it is also of interest and significance to study the ferrite grain size and further phase transformation at HAZ. Accordingly, simulation of the welding process is to be more important for the welding industry. Therefore, it should be studied for strength from the manner and general use to be certain before applying them.

The ferrite grain size is an important fundamental physical property of steel. In particular, the strength of many steels such as micro alloyed steel [2, 3]. So that we can use the result in this paper to predict and analyze the ferrite grain size at the welding joint and HAZ.

The mechanical properties of materials have shown the microstructural dimensions. Based on Hall - Petch [2, 4], a relationship of yield strength was predicted between grain size and the mechanical properties of steel (HSLA) and formulated.

For HSLA [5],

$$\sigma_y = \sigma_0 + kd^{-1/2} \quad (1)$$

Where σ_y is the yield stress, σ_0 is the materials constant for the starting stress for dislocation movement and k is the materials constant for the strengthening coefficient, d is the average grain diameter. Normally the stress can be used or applied to the yield strength for division of plasticity and elasticity behavior. Hall - Petch [4], relationship was focused on the large variety of material properties more than the lower yield point and the stress of material such as hardness. Hall - Petch [4], relationship related to find or to measure the grain size for describe the microstructure. However the strength of different grain sizes was estimated by applying a weighting fact or equal to the volume of the grains [4] each area such HAZ. The grain size indicate the yield strength and can be explained by the grain boundary because they are also much more disordered than inside the grain. But several studies with the average grain diameter can be obtained from the experimental measurements.

In the calculation process the ASTM E112 standard was measured in accordance to the ferrite grain size in each material [5] and gives a value of grain size relationships computed for uniform, randomly oriented, equiaxed grains. It is validated for microstructure and the recommended measurement procedure for linear intercept length method coupled with used other measurement method such as optical microscope for comparing the results of the calculation. The ASTM commonly used included "Comparison method", "Planimetric method or Jeffries method" and "Intercept method".

1.1. Comparison method

Normally imaging microstructure or photomicrographs that extends at 100X. Then compare the grain size with standard microscopic structure and called "ASTM grain size number" This method is suitable for equiaxed grain [5]. The ASTM grain size number can be calculated by counting the number of grains in one square inch at the surface area which extends at 100X. Thus, calculated according to the equation as follow.

$$N = 2^{n-1} \quad (2)$$

Where the quantity of grains are N in per square inch and n is the ASTM grain size number.

1.2. Planimetric method or Jeffries method

In the "Planimetric method or Jeffries method" created a circle or rectangle on the area on the photomicrographs (usually $500mm^2$ to simplify the calculations) and the quantity of grains no less than 50 grains. Equation of Planimetric method or Jeffries method as follow

$$N_A = f(N_{inside} + \frac{N_{intercept}}{2}) \quad (3)$$

Where N is the number of grains per square millimeter at 1X, f is the Jeffries' multiplier [5], N_{inside} is the number of grains completely inside the test circle and $N_{intercept}$ is the number of grains that intercept the test circle

The ASTM Grain Size, G in unit N_A in mm^{-2} , using the following equations [5]

$$G = (3.321928 \log_{10} \bar{N}_A) - 2.954 \quad mm^{-2} \quad (4)$$

1.3. Intercept method

"Intercept method", is more convenient to use than the planimetric such as the Heyn lineal intercept procedure [5], or Circular intercept procedure. There is no direct mathematical relationship between the ASTM grain size number and the mean lineal intercept as follow

$$\ell = \sqrt{\frac{\pi}{4} \bar{A}} \quad (5)$$

Where ℓ is the mean lineal intercept, $\bar{A}$ is exact for circles. Therefore, the relationship between the ASTM grain size number and the mean lineal intercept has been defined. ASTM No.0 has a mean intercept size of precisely 32.00 mm for the macroscopically determined grain size scale and of 32.00 mm at 100X on a field of view magnification for the microscopically determined grain size scale.

$$G = 2 \log_2 \frac{\ell_0}{\ell} \quad (6)$$

Where ℓ_0 is 32 mm and $\bar{\ell}$ and $\bar{N}_L$ [5], are in millimetres at 1X or number of intercepts per mm for the macroscopically determined grain size numbers and in millimetres or number per mm on a field at 100X for the microscopically determined grain size numbers.

1.3.1 Heyn lineal intercept procedure

In the Heyn lineal intercept procedure, that use a several cross line through on a photomicrograph and count the number of grains which intercept the line to calculate the arithmetic average or mark a line on the surface of spacemen to measure grain size with a length of 0.005 inches and 3.75 inches at 750X. If number of grains about 8-12 grains it means rough grain but if the number of grains is about 8-12 grains it's called a fine grain and if more than 15 grains it's called very fine grain

1.3.2 Circular intercept procedure

In the circular intercept procedure, that use drawing of three circle on the photomicrograph to find the grain size and except that circles of known circumference are used instead of lines. Three circles with a diameter at 26.53 mm, 53.05 mm, and 79.58 mm respectively [5]. The circumference length of the three circles combined are 500 mm. Then count the amount of grain that was cut through the line. Every grain that was intercepted on the three circles is equivalent to 1, while the line of the circles that intercept through three

grain equivalent 1.5 and number of grain boundary intersections per unit length of test line as follows

$$\bar{\ell} = \frac{1}{N_i} = \frac{1}{P_i} \quad (7)$$

Where $\bar{N}_L$ and $\bar{P}_L$ [5], are number of grain boundary intersections per unit length of the test line, $\bar{\ell}$ is the mean linear intercept value for each field, L is the total test line length (500 mm) and M is the magnification. Therefore, they are used to calculate in (6), (7) and (8) or determine the microscopically measured ASTM grain [5].

2. Experimental Procedure

The scope of this research aims to study the strength at welding joint (Base zone, Heat affect zone (HAZ) and Weld zone) and the detail as follows:

- HSLA Steel (ABS EH36) in 4 mm thickness of steel plate.
- Welding process by Shielded Metal Arc Welding (SMAW).
- Welding electrodes standards AWS-A 5.1 E7016
- Mechanical properties in Vickers hardness test and tensile test
- Microstructure as chemical composition analysis, EDS analysis on the SEM, the strength as the optical microscope (OM) that used the figure to find the grain size number by the intercept method

The development and use of high strength low alloy (HSLA) steels has been driven by the need to reduce costs. The microstructure as chemical composition analysis with a spectrometer. ABS EH36 is a part of HSLA and the chemical composition of specimen and standard property details as shown at [6, 7]. Nowadays, the economic impact of the welding-related processes to use and the steel industries remain to solve the problems of welding. One of them is ABS EH36 steel and it is popular less than other steel grade such as SCM440 etc. It is difficult find to buy in local and the best price (cheap).

Often materials are calculated for stress, so when they are used and performing the test on the materials for strength such as mechanical properties (tensile test or harness test) and microstructures (OM, SEM and EDS) as a function of applied load, time, temperature

and other conditions or standards which are published by the ASTM. Thus, these processes are used for this experiment. Therefore the process is approximately as follows:

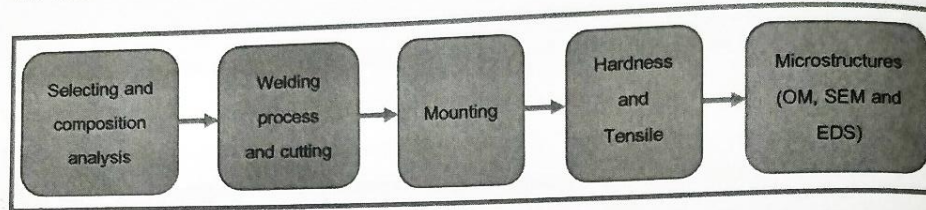


Figure 1 Metallography examination process

2.1 SMAW and Specimen

In SMAW Process or any process of welding, the important parameters for influence input an influence on the joint mechanical properties. By varying the input process parameters the combination of output would be different welded joints with significant variation in their mechanical properties. Accordingly, welding is usually done with the aim of getting a welded joint with excellent mechanical properties. To determine these welding combinations that would lead to excellent mechanical properties. Different methods and approaches have been used to achieve this aim. The following is a review of some articles that utilized these techniques for the purpose of optimizing the welding process in order to achieve the desired mechanical properties of the welded joint. This method used welding DC+ at 26.4 volt, 85 Amp and the speed is 120 mm/min. Welding electrodes AWS-A 5.1 E7016 2.4 mm was using for weld butt joint of two specimens shape V (In certificate of specimen (ABS EH36), the yield stress is 451 Mpa)

Welding electrodes AWS E7016 is a kind of electrode with low-hydrogen potassium type coating AC / DC. All position welding [8]. It has excellent welding performance, stable arc, fewer spatters and good slag detachability.

After the weld process, prepare the specimen for the test 2 kind method. They consist of the specimen for hardness and tensile test method and another one by cutting at the welding joint and nearby surface for microstructures the test method such as Optical Microscope (OM), Scanning Electron Microscope (SEM) and Energy Dispersive spectroscopy (EDS).

2.2 Hardness test

The specimen was then sectioned for a micro-hardness measurement. Micro-hardness was measured using ANTON PAAR model MHT-10 with diamond pyramid angle of 136° indenter and conditions Force 100 g. Pressing time 10 sec, Magnification 500x. A total of 11 points were measured to establish the hardness profile of the specimen by press throughout the axial of surface at left to right under ASTM E92-82 (Reapproved 1997) [9].

2.3 Tensile test

The tensile test use to study the relationship between stress and strain of specimen derived from the pull test and using a universal testing machine INSTRON MODEL 8801. [10]

2.4 Microstructures (OM, SEM and EDS)

The microstructures were examined for the small scale structure of the specimen using an optical microscope (OM) by OLYMPUS LEXT OLS4000 LASER SCANNING CONFOCAL MICROSCOPES. The structure of the grain size can use the optical microscope to analyze and apply to find grain size number such as the intercept method. Then scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS) is used to study the morphology and surface characteristics of a specimen and analyzed using SEM and EDS techniques. They are employed were HITACHI: S-3400N Energy Dispersive Spectroscopy microanalysis system. The modes of analysis used consist of point analysis, line scanning, and elemental mapping.

In all of the test methods, there will be testing at the three surfaces consisting of the base zone, heat affect zone (HAZ) and weld zone.

3. Result

Chemical composition of the ABS EH36 was analyzed using a spectrophotometer test machine (ARL 3640). ABS EH36 was made from low-alloyed steels. The average values of the chemical composition are shown in Table 1.

Table 1 Chemical composition of ABS EH36

C	Si	Mn	P	S	Cr	Mo	Ni	V	Al	Cu	Ti	Nb	Fe
0.0704	0.322	1.4834	0.0102	0.0025	0.0247	0.0129	0.0569	0.0033	0.0333	0.0772	0.0107	0.0174	Balance

3.1 SMAW and Specimen

The specimen of ABS EH36 had been welded by SMAW process and begins with the rough cutting of material to length on a saw or more refined cutting, closer to size and prepare for the test 2 kind method. After cutting is completed they are consist of the first specimen for tensile test method (figure 2 (a)) by the milling machine and another one by cutting at the welding joint and nearby surface and prepare by polishing etching mounting for hardness test method and microstructures the test method (figure 2 (b)).

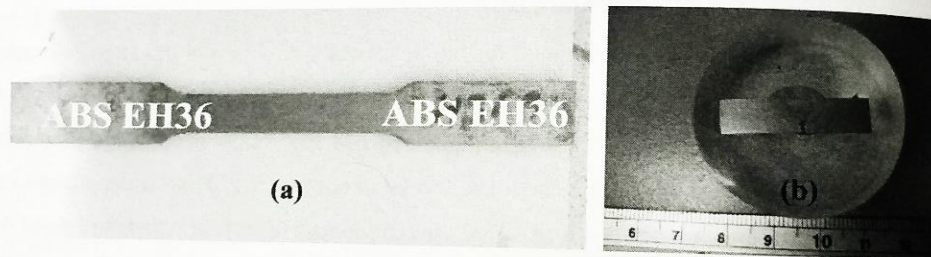


Figure 2 Specimen of ABS EH36 (a) for tensile test method (b) for hardness test method, OM, SEM and EDS

3.2 Hardness test

The hardness test used a press throughout the axial of surface at the left to right of the specimen was measured using a Vickers hardness tester force 100 g, pressing time 10 sec and magnification 500X. The results are shown Figure 3. The maximum hardness of approximately 192.61 HV occurred near the surface of weld zone and minimum hardness diminish with distance at about 150.06 HV of the base zone.

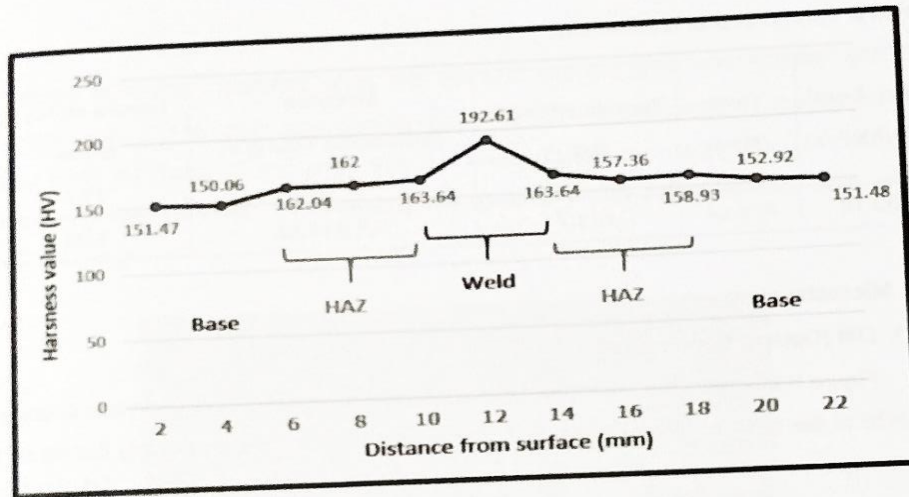


Figure 3 The hardness test used a press throughout the axial of surface at the left to right of the specimen.

3.3 Tensile test

The results in Table 2 from this testing was shown in the fracture point that nearby between the base zone and HAZ and they are indicated to be known that to reference from the standard [6, 7] with similar values.

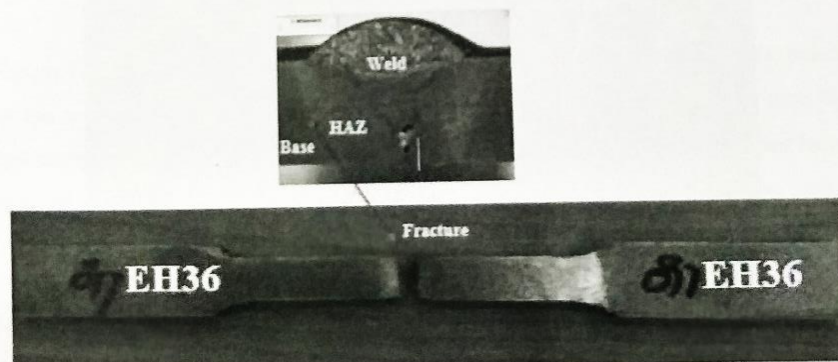


Figure 4 The tensile test was shown in the fracture point that nearby between the base zone and HAZ

Table 2 The result of tensile test

Max. Load (kN)	Yield (MPa)	Tensile strength (MPa)	Modulus (Automatic Young's) (MPa)	Tensile strain at Break (%)
33.18	474.04	511.71	101,919.12	9.93

3.4 Microstructure

3.4.1 OM (Optical Microscope)

Figure 5 illustrates the microstructures (OM) results shown original grain size boundary of EH36 at the base zone which consist of ferrite and pearlite. Therefore apply this figure to find the grain size number with the intercept method. The grain size number (G) = 11.41 and compared to the table from ASTM E112 [5] (Table 3) can know that the average grain diameter (d) = 0.006916mm. Considering the Hall-Petch relationship from equation (1) to determine the yield stress (σ_y) = 371Mpa

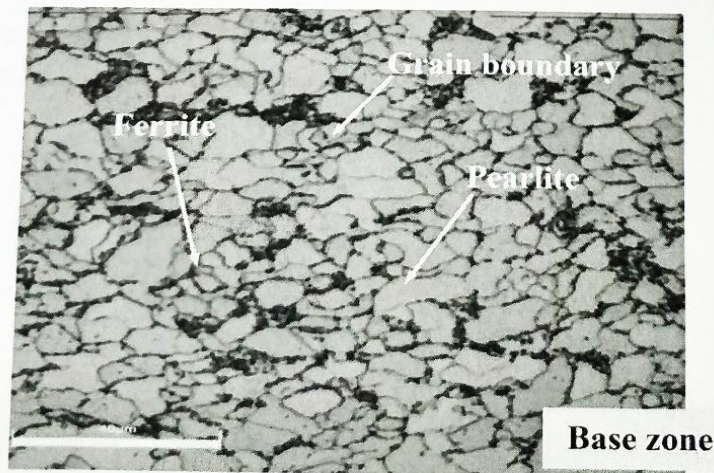


Figure 5 Varity of grain sizes at base zone and apply this figure to find the grain size number.

Figure 6 illustrates the microstructures (OM) results show the grain size boundary of EH36 at HAZ. They consist of ferrite and pearlite which are similar to the base zone. But the

differences of the both in the figure is the size of grain. Grain size at HAZ began to change the shape to smaller. Therefore apply this figure to find the grain size number with the intercept method. The grain size number (G) = 12.10 and compared to the table from ASTM E112 [5] (Table 3) can know that the average grain diameter (d) = 0.00542mm. Considering the Hall-Petch relationship from equation (1) to determine the yield stress (σ_y) = 414Mpa

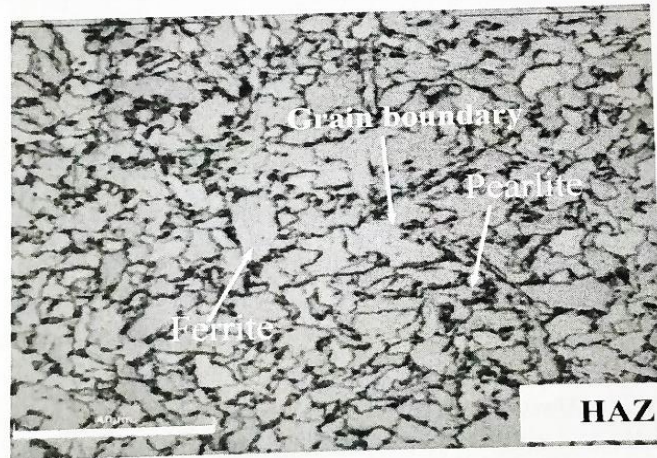


Figure 6 Varity of grain sizes at HAZ zone and apply this figure to find the grain size number.

Figure 7 illustrates the microstructures (OM) results shown the grain size boundary of EH36 at the weld zone. Ferrite grain size are smaller than in the base zone and HAZ and the shape being sharpened also known as acicular ferrite. In the case of acicular ferrite, they are very small and a barrier to count the grain size. They affect to find the grain size number and cannot calculated the yield stress.

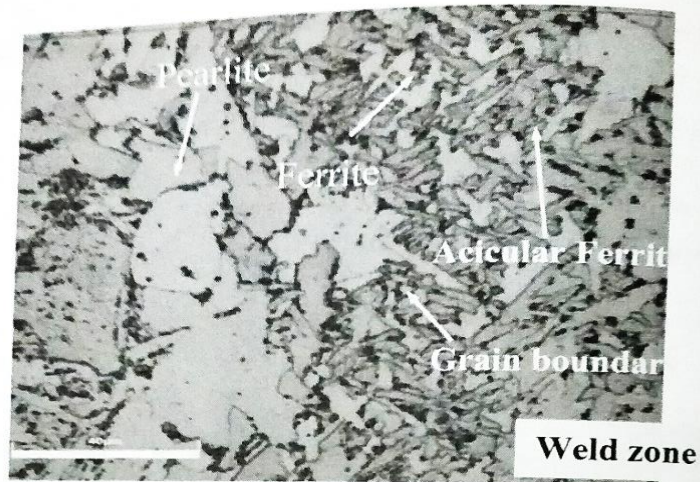


Figure 7 Varsity of grain sizes at weld zone and apply this figure to find the grain size number.

Table 3 The result of OM (Optical Microscope)

Area / Results	The grain size number, (G)	The average grain size number, $d(mm)$	the yield stress $\sigma_y (Mpa)$
Base zone	11.4	0.006916	371
Heat effect zone	12.1	0.00542	414
Weld zone	-	-	-

3.4.2 SEM and EDS (Scanning Electron Microscope and Energy Dispersive Spectroscopy or Energy Dispersive X-ray)

Usually, initial EDS analysis involves the generation of an X-ray spectrum from the scan area of the SEM or also call this method the EDS analysis on the SEM. They consist of the Y-axis which shows the result of counts (number of X-rays received and processed by the detector) and the X-axis shows the energy level of those counts. Figure 8 illustrates the microstructures and EDS results of the base zone. The results show enriched amounts of Mn, Fe, C, and Si. At HAZ and the weld zone, the thermal from welding resulting in a number of element found that changes in the base area and the results in Figure 9 and Figure 10

were shown C, Si, P, S, Mn, and Fe. However, another reason for the increased amounts of elements possibly from mixing between the welding electrode and base metal such as HAZ and the weld zone. They found similar element but the differences in them are the value of the element (Wt%) and the percentage of Fe decreases respectively from base zone to weld zone.

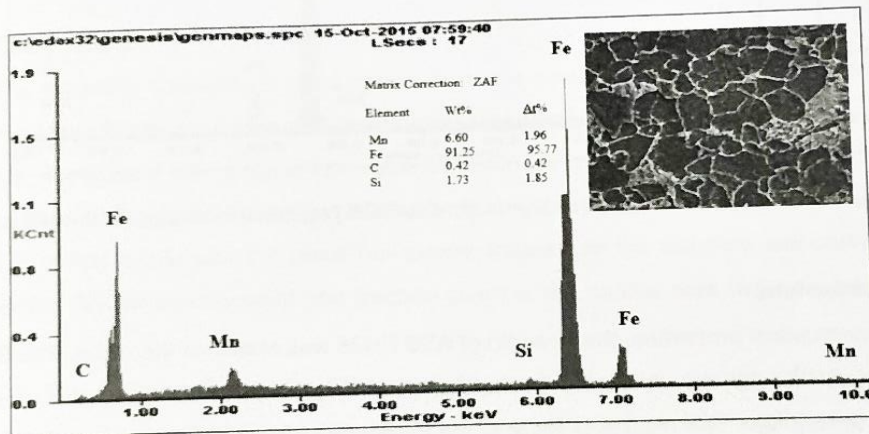


Figure 8 The result of EDS (analysis on the SEM) spectrum analysis at base zone.

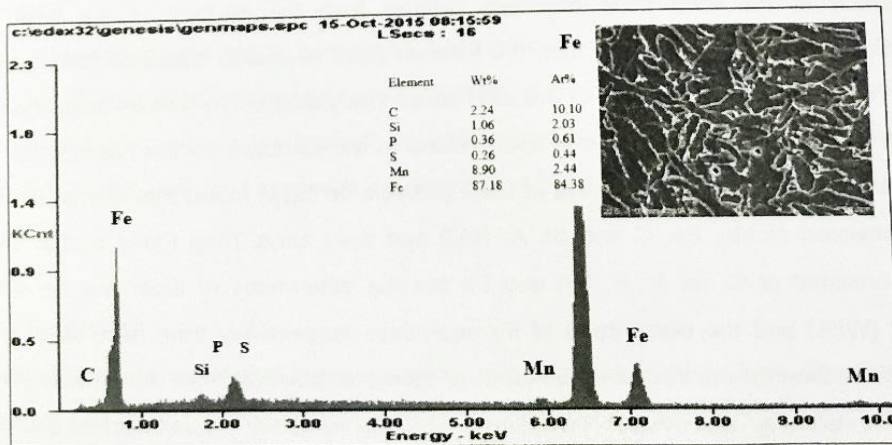


Figure 9 The result of EDS (analysis on the SEM) spectrum analysis at HAZ

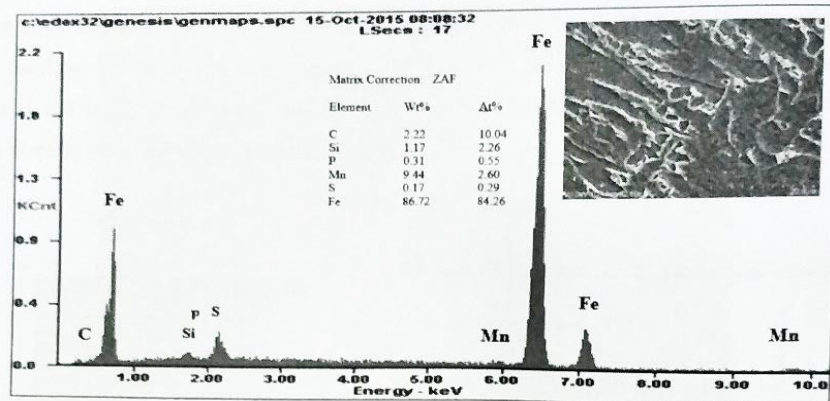


Figure 10 The result of EDS (analysis on the SEM) spectrum analysis at weld zone

4. Discussions

In mechanical properties, the strength of ABS EH36 was shown in the result. The SHAW process used for the experimental procedure and the result of them consisted of a hardness test and tensile test. The minimum value of the hardness test is 150.06 HV at the base zone and maximum value is 192.61 HV at the weld zone. It was assumed that the synchronization of material (ABS EH36 and welding electrodes AWS-A 5.1 E7016) and the thermal influence the surface of the weld zone hardness greater than the surface of the base zone, respectively. However, in tensile test, the fracture point is nearby between base zone and HAZ and it indicates the strength of the weld zone. The yield point is 474.04 Mpa and tensile strength is 511.71 Mpa and which is approximate to the standard (at the base zone).

In the microstructure, the result of EDS analysis on SEM found that elements at base zone consisted of Mn, Fe, C and Si. At HAZ and weld zone They found similar element which consisted of C, Si, P, S, Mn and Fe but the differences of them are the value of element (Wt%) and the percentage of Fe decreases respectively from base zone to weld zone. The reason for the increased amounts of elements possibly from mixing between ABS EH36 and welding electrodes AWS-A 5.1 E7016. Another microstructure, the optical microscope (OM) used the figure to find the grain size number with the intercept method and applied to use the value to find the yield stress with the Hall-Petch relationship. The result at the base zone is 371 Mpa, HAZ is 414 Mpa and the weld zone cannot calculated the yield

stress because the shape of ferrite grain size being sharpened also known as acicular ferrite and affect to find the grain size number. They are very small and a barrier to count the grain size. The many acicular ferrite can found at the weld zone more than HAZ. The reason for the yield stress could be described as it could possibly be from the thermal and cooling rate from the welding process changed the structure of ferrite grain size.

5. Conclusions

The following conclusions were drawn from the result in this paper which probative involved about ferrite grain size and mechanical properties

5.1 Weld zone has a maximum value of hardness test. It was the hardest zone and greater than HAZ and the base zone respectively.

5.2 In the tensile test, the result has similar values with the standard and certificate of ABS EH36. The weakness point (the fracture point) is the central area between base zone and HAZ

5.3 The element found by EDS analysis on SEM have similar values with the composition and standard. They are the result from element of ABS EH36 and welding electrodes AWS-A 5.1 E7016

5.4 The yield stress at the weld zone is a maximum value more than HAZ and the base zone.

5.5 Considering the result from those methods can know that at the weld zone has a higher strength than HAZ and base zone respectively and from the reasons mentioned above can prove assumption about the strength at welding joint (ABS EH36 and welding electrodes AWS-A 5.1 E7016) and used to predict the strength of the material for use before the starting process.

Acknowledgment

I would like to express sincere thanks to my advisor, Assoc. Prof. Dr. Ganwarich Phulphrach and Prof. Dr. Hadi Sutanto, for their valuable suggestions, attentive interest. I would like to express sincere thanks to Asst. Prof. Charnont Moolwan kind recommendations in my present study and I would like to express sincere thanks to Mr. Anuprong Pronpijit, Mr. Nirut Bunchoo, National metal and materials technology center

(M-Tech), for their help and guidance during my study and another recommendations. Lastly, I would like to thank my family for always helping me to remember what is important in life, their always supporting me in my good and bad times and for giving right suggestions to me, encouragement, endless love and understanding throughout my study program.

References

- [1] High - Strength Low - Alloy Steels - ASM International. (2001). [Online]. Available: <http://www.asminternational.org/documents/>
- [2] M.Kazerminezhad, A. Karimi Taheri. (2004). "Prediction of ferrite grain size and tensile properties of a low carbon steel". **Materials Science and Technology**. Vol.20: 106-110
- [3] Lei Zhang, Thomas Kannengiesser. (2014). "Austenite grain growth and microstructure control in simulated heat affected zones of micro alloyed HSLA steel". **Materials Science & Engineering**. A613: 326-335
- [4] Pauli Lehto, Heikki Remes, Tapio Saukkonen, Hannu Hänninen, Jani Romanoff. (2014). "Influence of grain size distribution on the Hall-Petch relationship of weld structural steel". **Materials Science & Engineering**. A592: 28 - 39
- [5] ASTM. (1996). **ASTM E112-96e3, Standard Test Methods for Determining Average Grain Size**. West Conshohocken, Pennsylvania, United States.
- [6] ABS EH36 shipbuilding steel plate - Bebon steel. Available: <http://www.bebonchina.com/pdf/ABS%20EH36.pdf>
- [7] ASTM. (1994). **ASTM A131/A131M - 94, Standard Specification for Structural Steel for Ships**. West Conshohocken, Pennsylvania, United States.
- [8] BASIC COATED - LOW HYDROGEN ELECTRODE CODING: AWS A 5.1 - E 7016. Available: <http://www.weldingelectrodesindia.com/pdf/euro-lh.pdf>
- [9] ASTM. (1982). **ASTM E92 - 82, Standard Test Method for Vickers Hardness of Metallic Materials**. West Conshohocken, Pennsylvania, United States.
- [10] ASTM. (2000). **ASTM E8/E8M Standard Test Methods for Tension Testing of Metallic Materials**. West Conshohocken, Pennsylvania, United States.

Author's Profile



Nuttapom Bungmek Maintenance Supervisor at Ayutthaya Industrial Gases Co., Ltd. Mobile: +66 (81) 8532690 / E-Mail: nuttapom.aig@gmail.com



Ganwarich Phulphrach Assoc. Prof. Dr. at Department of Mechanical Engineering, Faculty of Engineering, Srinakharinwirot University. Mobile: +66 (89) 1411135 / E-Mail: pganwarich@yahoo.com



CURRICULUM VITAE

Name	Act Sub Lt. Nuttaporn Bungmek
Date of Birth	April 26, 1975
Place of Birth	Lampang province
Address	426 Moo 6, Pongyangkok , Hangchat ,Lampang 52190
Position	Maintenance Supervisor
Workplaces	Ayutthaya Industrial Gases Co.,Ltd
Education	
1981-1987	Dontum Lampang School
1987-1990	Bunyawatwittayalai Lampang School
1990-1995	Lampang Technical, Diploma (Lathe man)
2005-2008	Srinakharinwirot University, Engineering (Mechanical)

