

**EFFECT OF SHIELDING GASES ON
MECHANICAL AND CORROSION PROPERTIES
OF STEEL 316L USING FCAW**

**By
Engineer \ Mostafa Abdelhamid Abdelazim Abdelmotteleb**

**A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of**

**MASTER OF SCIENCE
in
METALLURGICAL ENGINEERING**

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2015**

EFFECT OF SHIELDING GASES ON MECHANICAL AND CORROSION PROPERTIES OF STEEL 316L USING FCAW

By
Engineer \ Mostafa Abdelhamid Abdelazim Abdelmotteleb

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE
in
METALLURGICAL ENGINEERING

Under the Supervision of

Prof. Dr. Mohamed R. El-Koussy
Faculty of Engineering
Cairo University

Prof. Dr. Nahed A. Abdel Raheem
Faculty of Engineering
Cairo University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2015

EFFECT OF SHIELDING GASES ON MECHANICAL AND CORROSION PROPERTIES OF STEEL 316L USING FCAW

By
Engineer \ Mostafa Abdelhamid Abdelazim Abdelmotteleb

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE
in
METALLURGICAL ENGINEERING

Approved by the Examining Committee:

Prof. Dr. Mohamed R. El-Koussy, Thesis Main Advisor
Metallurgy Engineering Department
Faculty of Engineering- Cairo University

Prof. Dr. Nahed A. Abdel Raheem, Thesis Main Advisor
Metallurgy Engineering Department
Faculty of Engineering- Cairo University

Prof. Dr. Ahmed M. ElSheikh, Member, Internal Examiner
Metallurgy Engineering Department
Faculty of Engineering- Cairo University

Prof. Dr. Samir A. Ibrahim, Member, External Examiner
Faculty of Petroleum and Mining Engineering
Suez University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2015

Engineer: Mostafa Abdelhamid Abdelazim Abdelmotelieb
Date of Birth: 14 / 08 / 1983
Nationality: Egyptian
E-mail: m-abdelhamid@hotmail.com
Phone: (0020) 1224380080
(0049) 15733855733
Address: Elmataria, Cairo, Egypt
Registration Date: 01 / 10 / 2010
Awarding Date: / /
Degree: Master of Science
Department: Mining, Petroleum and Metallurgy



Supervisors: Prof. Dr. Mohamed Raafat El-Koussy
Prof. Dr. Nahed Ahmed Abdel Raheem

Examiners: Prof. Dr. Mohamed Raafat El-Koussy
Prof. Dr. Nahed Ahmed Abdel Raheem
Prof. Dr. Ahmed Mohammed ElSheikh
Prof. Dr. Samir Abdel-Hakim Ibrahim - Suez University

Title of Thesis:
Effect of Shielding Gases on Mechanical and Corrosion Properties of Steel 316L Using FCAW

Key Words: **Flux Cored Arc Welding, Shielding Gases, Stainless Steel 316L, Corrosion Resistance, Microstructure, Strength**

Summary:

In this study, the influence of variation in the shielding gas composition on the mechanical properties and corrosion resistance of steel 316L was investigated. Seven different shielding gas compositions in addition to pure CO₂ were studied in this work using flux cored arc welding (FCAW) process. For bead-on-plate specimens, all the specimens appeared satisfactory under x-ray. It showed less spatter except using Ar/N 97/3 and Ar/CO₂/N 82/15/3 shielding gases which resulted in higher number of spatter. Furthermore, for complete real welded joints, conditions 100% CO₂, Ar/CO₂ 75/25, Ar/CO₂ 80/20 and Ar/O₂ 98/2 showed low porosity beside success by tensile test. Increase of carbon dioxide percentage lead to increase the depth of penetration. It led also to decrease in hardness, impact values and ferrite content. All specimens showed near values in corrosion resistance. So, it is recommended to use 100% CO₂, Ar/CO₂ 75/25, Ar/CO₂ 80/20 and Ar/O₂ 98/2 for welding steel 316L by flux cored arc welding.

Acknowledgements

I would like to express my gratitude and appreciation to my parents for their patience, love, help and support along all my life.

I wish to express my sincere thanks and deep gratitude to my supervisors, Prof. Dr. Eng. Mohamed R. El-Koussy (FECU), Prof. Dr. Eng. Nahed A. Abdel Raheem (FECU), and Dr. Eng. Hamed A. Abdelaleem (CMRDI) for their continuous support, their valuable guidance, and their helpful advices.

My great thanking to Eng. Salem Elhawawshy (manager of Alsalem Group) for his great help.

My great thanking to Eng. Said Hafez (General Manager of SLV Egypt-German Egyptian Welding Center) for his great help.

My great thanking to Dr. Eng. Hamed Ahmed Abdel-Aleem for his great help and supervision for conducting the experimental work.

My great thanking to Eng. Moataz Issa (Air Liquide, Egypt Branch) for his great help.

Table of Contents

	Page
ACKNOWLEDGEMENTS	I
TABLE OF CONTENTS	II
LIST OF TABLES	III
LIST OF FIGURES	IV
NOMENCLATURE	V
ABSTRACT	VI
CHAPTER 1 :INTRODUCTION	2
CHAPTER 2 :LITERATURE SURVEY	5
2.1 Basic Properties of a Shielding Gas	8
2.2 Introduction and Definition of Stainless Steel	10
2.3 Classification of Stainless Steel and their Applications	11
2.3.1 Austenitic stainless steels	11
2.3.2 Ferritic stainless steels	15
2.3.3 Duplex stainless steels	18
2.3.4 Martensitic and precipitation hardening stainless steels	21
2.4 Effect of Alloying Elements	24
2.5 Effect on Microstructure	26
2.6 Common Stainless Steel Welding Processes	29
2.6.1 Shielded metal arc welding: SMAW	29
2.6.2 Gas metal arc welding: GMAW	30
2.6.3 Gas tungsten arc welding: GTAW	32
2.6.4 Flux cored arc welding: FCAW	33
2.6.5 Submerged arc welding: SAW	34
2.6.6 Plasma arc welding: PAW	36
2.6.7 Laser Beam Welding: LBW	38
2.6.8 Electron Beam Welding: EBW	38
2.7 Weldability of Stainless Steels	39
2.7.1 Austenitic stainless steels: Fe-Cr-Ni (Mo)-(N)	39
2.7.2 Ferritic stainless steels: Fe-Cr-(Mo-Ni-V)	40
2.7.3 Duplex stainless steels: Fe-Cr-Ni (Mo)-N	40
2.7.4 Martensitic stainless steels: Fe-Cr-(Mo-Ni-V)	40
2.8 Chemical reactions in welding	40
2.8.1 Effect of Nitrogen, Oxygen, and Hydrogen	40
2.8.2 Techniques for Protection from Air	41
2.8.3 Gas–Metal Reactions	42
2.8.3.1 Nitrogen	42
2.8.3.2 Oxygen	44
2.8.3.3 Hydrogen	46
2.9 Effect of shielding gases and benefits of using	47
2.10 How Different Gases Affect the Welding Application	49
2.11 Effect of Nitrogen in Argon as a Shielding Gas	51
2.12 Effect of Oxygen in Argon as a Shielding Gas	53
2.13 Effect of Carbon Dioxide in Argon as a Shielding Gas	53
2.14 Properties of Shielding Gases	54

2.15 Shielding Gases for MIG/MAG Welding	55
2.16 Choosing a Shielding Gas for FCAW	55
CHAPTER 3 :MATERIALS AND EXPERIMENTAL WORK	58
3.1 Materials	60
3.2 Welding Technique	62
3.2.1 Welding machine	62
3.2.2 Shielding gases	63
3.2.3 Welding wire	63
3.2.4 Welding parameters	64
3.2.5 X-ray	64
3.2.6 Porosity counting	64
3.2.7 Spatter counting	64
3.3 Weld Metal Characterization	64
3.3.1 Mechanical properties characterization	65
3.3.1.1 Tension test	65
3.3.1.2 Impact test	65
3.3.1.3 Hardness test	66
3.3.2 Metallurgical characterization	67
3.3.2.1 Examination of weld bead profile	67
3.3.2.2 Metallographic examination	67
3.3.2.3 Macrostructure examination	67
3.3.2.4 Chemical analysis for weld metal	67
3.3.2.5 Ferrite number measurement	68
3.3.3 Corrosion test	68
CHAPTER 4 :RESULTS AND DISCUSSION	71
4.1 Visual Inspection	71
4.1.1 Visual appearance	71
4.1.2 X-ray	73
4.1.3 Porosity counting	75
4.1.4 Spatter counting	76
4.2 Chemical Analysis for Weld Metal	77
4.3 Ferrite Number Measurement	81
4.4 Mechanical Properties	82
4.4.1 Tensile test results	82
4.4.2 Vickers hardness test results	83
4.4.3 Impact test results	86
4.5 Microstructure	88
4.6 Macrostructure	91
4.7 Corrosion Test Results	94
CONCLUSIONS	98
REFERENCES	100

LIST OF TABLES

		Page
Table 2.1	Properties of shielding gases used for welding	8
Table 2.2	Effect of Nitrogen, Oxygen, and Hydrogen on Weld Soundness	40
Table 2.3	Protection Techniques in Common Welding Processes	41
Table 2.4	Benefits of using gas blends	47
Table 2.5	Properties of the shielding gases recommended for FCAW of stainless steel 316L	56
Table 3.1	Chemical compositions for stainless steel 316L (wt %)	61
Table 3.2	Mechanical properties for stainless steel 316L	61
Table 3.3	Main characteristics of the used FACW machine	62
Table 3.4	Shielding gases used in the present study	63
Table 3.5	Typical chemical composition of all-weld-metal (%)	64
Table 4.1	Spatter counting for bead on plate condition	77
Table 4.2	Spatter counting for complete joint penetration welds	77
Table 4.3	Chemical analysis of complete joint penetration welds	78
Table 4.4	Nickel and Chromium equivalent for welds	80
Table 4.5	Tensile test results	83
Table 4.6	Microstructure using different shielding gases	89
Table 4.7	Corrosion rate calculations for bead on plate condition	97
Table 4.8	Corrosion rate calculations for complete joint penetration welds	97

LIST OF FIGURES

		Page
Figure 2.1	Master Chart of Welding and Allied Processes	7
Figure 2.2	Austenitic microstructure showing equiaxed grains and characteristic annealing twins. Normal presence of small inclusions can be observed	12
Figure 2.3	Family Tree of Austenitic Stainless Steels	14
Figure 2.4	Ferritic microstructure showing equiaxed grains. Some presence of small inclusions and Ti(CN) can be observed	15
Figure 2.5	Family Tree of Ferritic Stainless Steels	17
Figure 2.6	Duplex microstructure showing an elongated lamella structure of darker etched ferritic regions and brighter austenitic regions	18
Figure 2.7	Family Tree of Duplex Stainless Steels	20
Figure 2.8	Martensitic microstructure showing fine-scale martensite which has formed within the prior austenite grains. Smaller dark carbides can also be observed	21
Figure 2.9	Family Tree of Martensitic Stainless Steels	23
Figure 2.10	Modified (by Outokumpu) Schaeffler DeLong diagram showing the different microstructures in welds	27
Figure 2.11	Shielded metal arc welding: (a) overall process; (b) welding area enlarged	30
Figure 2.12	Gas-metal arc welding: (a) overall process; (b) welding area enlarged	31
Figure 2.13	Gas-tungsten arc welding: (a) overall process; (b) welding area enlarged	33
Figure 2.14	Gas-shielded flux-cored arc welding	34
Figure 2.15	Submerged arc welding: (a) overall process; (b) welding area enlarged	35
Figure 2.16	Keyhole plasma welding	37
Figure 2.17	Principle of CO ₂ (CO ₂ , N ₂ , He) laser used for welding	38
Figure 2.18	Principle of electron beam welding	39
Figure 2.19	Oxygen and nitrogen levels expected from several arc welding processes	41
Figure 2.20	Effect of nitrogen partial pressure in Ar-N ₂ shielding gas on nitrogen content in welds of duplex stainless steel	43
Figure 2.21	Iron nitride in a ferrite matrix (X500)	43
Figure 2.22	Effect of nitrogen on the room temperature mechanical properties of mild steel welds	44
Figure 2.23	Effect of the oxygen content on the mechanical properties of mild steel welds	45
Figure 2.24	Effect of shielding gases on weld metal hydrogen content: (a) GMAW; (b) FCAW	46

Figure 2.25	Spatter produced by various gases	48
Figure 2.26	Fume formation by various gases	48
Figure 2.27	Depth of penetration by various gases	49
Figure 2.28	Travel speed by using various gases	49
Figure 2.29	Influence of the nitrogen content of the arc atmosphere on the pore formation	51
Figure 2.30	Possibilities of gas absorption during gas metal arc welding	52
Figure 3.1	Flow diagram for experimental procedure	59
Figure 3.2	Joint design	60
Figure 3.3	The Standard Tensile Specimen Cut from Plate According to ASME IX QW-462.1	65
Figure 3.4	Standard dimensions of Charpy V-Notch specimen according to ASTM E23-01	66
Figure 3.5	Hardness profile for bead on plate and complete weld	67
Figure 3.6	AUTOLAB electrolytic cell	68
Figure 3.7	Cyclic anodic polarization curve	69
Figure 4.1	Visual appearance for bead on plate and complete weld specimens	73
Figure 4.2	X-ray for bead on plate and complete weld conditions	75
Figure 4.3	Porosity counting for complete joint penetration welds	76
Figure 4.4	Porosity counting for complete joint penetration welds	76
Figure 4.5	Percentage of Carbon in complete joint penetration welds	79
Figure 4.6	Percentage of Chromium in complete joint penetration welds	79
Figure 4.7	Percentages of Silicon and Manganese in complete joint penetration welds	80
Figure 4.8	Ferrite number measurement for bead on plate condition	81
Figure 4.9	Ferrite number measurement for complete weld condition	82
Figure 4.10	Tensile test results	83
Figure 4.11	Hardness profile for bead on plate condition	84
Figure 4.12	Hardness profile for bead on plate condition	85
Figure 4.13	Hardness profile for complete weld condition	85

Figure 4.14	Hardness profile for complete weld condition	86
Figure 4.15	Average absorbed energy (impact toughness) values of weld metal at -196°C	87
Figure 4.16	Average absorbed energy (impact toughness) values of weld metal at -196°C	87
Figure 4.17	Base metal microstructure	88
Figure 4.18	Macrostructure of bead on plate condition	92
Figure 4.19	Macrostructure of complete joint penetration welds	93
Figure 4.20	Depth of penetration for bead on plate condition	94
Figure 4.21	Depth of penetration for bead on plate condition	94
Figure 4.22	Corrosion test results for bead on plate condition	96

ABBREVIATIONS

ABBREVIATIONS

Ar	: Argon
CO ₂	: Carbon dioxide
N ₂	: Nitrogen
O ₂	: Oxygen
HAZ	: Heat affected zone
SMAW	: Shielded metal arc welding
GMAW	: Gas metal arc welding
GTAW	: Gas tungsten arc welding
FCAW	: Flux cored arc welding
SAW	: Submerged arc welding
PAW	: Plasma arc welding
LBW	: Laser beam welding
EBW	: Electron beam welding
UTS	: Ultimate tensile strength
DC	: Direct current
ASME	: American Society for Mechanical Engineers
AWS	: American Welding Society
ASTM	: American Society for Testing and Materials
DIN	: Deutsches Institut für Normung “German Institute for Standardization”
EN	: European Norm
ISO	: International Organization for Standardization
UNS	: Unified numbering system

ABSTRACT

This work aimed at studying the effect of the shielding gases on the weld metal by studying the mechanical and corrosion properties of steel 316L using flux cored arc welding by determining the most appropriate welding conditions in terms of optimum current and voltage. Then, different ratios of shielding gases were used to determine the most suitable gas/gas mixture to reach the best mechanical and corrosion properties.

Steel 316L was used where surface preparation for welding had been done. Then applying welding using flux cored arc welding process with changing the shielding gases. Then, each weld condition was evaluated either by visual inspection and mechanical tests such as tension, hardness and impact whereas metallurgical evaluation was done by optical microscope examination for the heat affected zone and weld metal. This is beside the corrosion test. Then, a comparison was made for all the obtained results to reach the optimum conditions.

The results lead to that the most suitable gas/gas mixtures are 100% CO₂, Ar/CO₂ 75/25, Ar/CO₂ 80/20 and Ar/O₂ 98/2 which give the optimum mechanical and metallurgical properties for the weld.

Chapter (1)

Introduction

Chapter (1)

Introduction

This work is directed to study the effect of the shielding gases on the mechanical and corrosion properties of steel 316L using flux cored arc welding. FCAW is considered one of the most productive welding methods since it is used in the welding of metals with high thickness. For this reason it is used in the heavy industry and shipbuilding industry. Steel 316L is considered one of the most important kinds of austenitic steels which used in industry since it contains molybdenum, which gives it greater corrosion resistance in addition to its ability having high strength at low temperatures.

Stainless steel is one of the most versatile materials in today's society. It can be produced with a wide range of properties and is used in millions of applications. Stainless steels are used for their corrosion resistance. Stainless steels are those alloys of iron and chromium, with or without other elements, containing at least 11% chromium. This is the minimum amount of chromium necessary to form a stable, passive chromium oxide film. It is this film that is the basis for the corrosion resistance of all stainless, and most nickel base, corrosion-resistant alloys. [1]

Austenitic stainless steels represent the largest of the general groups of stainless steels and are produced in higher tonnages than any other group. They have good corrosion resistance in most environments. The austenitic stainless steels have strengths equivalent to those of mild steel's, approximately 210 MPa (30 ksi) minimum yield strength at room temperature, and are not transformation hardenable. Low-temperature impact properties are good for these alloys, making them useful in cryogenic applications. Service temperatures can be up to 760°C (1400°F) or even higher, but the strength and oxidation resistance of most of these steels are limited at such high temperatures. Austenitic stainless steels can be strengthened significantly by cold working. They are often used in applications requiring good atmospheric or elevated temperature corrosion resistance. They are generally considered to be weldable, if proper precautions are followed.

Elements that promote the formation of austenite, most notably nickel, are added to these steels in large quantities (generally over 8 wt%). Other austenite-promoting elements are C, N, and Cu. Carbon and nitrogen are strong austenite promoters. Carbon is added to improve strength (creep resistance) at high temperatures. Nitrogen is added to some alloys to improve strength, mainly at ambient and cryogenic temperatures, sometimes more than doubling it. [2]

Stainless steel 316L is used in several applications such as automotive industry, construction industry, chemical industry, decorative applications and kitchen fittings, food and beverage industries, mechanical engineering, aerospace applications, medical and pharmaceutical applications.

The “L” grades are used to provide extra corrosion resistance after welding. The letter L after a stainless steel type indicates low carbon (as in 304L). The carbon