CHARACTERIZATION OF HEAT AFFECTED ZONE FOR TIG TORCH WELDED HIGH STRENGTH LOW ALLOY STEEL WITH MICROALLOYING ELEMENTS ADDITION

BY

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ABSTRACT

High strength low alloy (HSLA) steels possess an excellent combination of strength and toughness obtained by suitable alloying design and thermo-mechanical controlled processing. However, the strength and toughness combination are deteriorated by the welding parameters and the thermal cycles that the steel experiences during welding. Since welding is an unavoidable stage in HSLA steel manufacturing, it is essential to produce welded sections with as low heat energy as possible, while preserving an appropriate joint geometry and properties. Heat affected zone, particularly adjacent to the weld pool region, has higher hardness and lower fracture toughness compared with the substrate material. The deterioration of heat affected zone (HAZ) mechanical properties are attributed to the formation of martensite-austenite (M-A) constituents and local brittle zones (LBZ). Therefore, the main aim of this research is to improve the HAZ mechanical properties such as tensile strength, hardness and impact toughness of welded high strength low alloy (HSLA) steel using TIG torch melting at different welding process parameters with and without microalloying elements addition (Ti and V). The research investigation was conducted in three-phases. The first phase involves the experimental designs by Taguchi method and producing the welding track under different welding parameters such as welding current, welding voltage, welding speed and gas flow rate with and without microalloying element addition (Ti and V) using powder preplacement and TIG torch welding process. Secondly, optimization the input parameters with the responses to the heat affected zone properties of hardness, tensile strength, and impact toughness. In the last phase, characterization and evaluation of the welded HSLA steel specially HAZ in terms of microstructure, microhardness, tensile strength, and impact toughness. The HAZ microstructural characterization was performed using OM, SEM-EDX, and XRD analyzer. The results showed that the highest tensile strength achieved was 692.85 MPa and 729.80 MPa with Ti and V microalloying element additions, respectively. The impact toughness was 81 J and 76 J for Ti and V addition, and the hardness attained was 202 Hv for both Ti and V microalloying additions. The different ferrite phases formed in the HAZ including acicular ferrite and ferrite with secondary phase aligned along with the bainitic microstructure due to the enhancement of the grain refinement in the HAZ morphology. The best-optimized welding parameters achieved by Taguchi S/N ratio analysis were current, 100 A; voltage, 40 V; speed, 1.5 mm/s; and argon flow rate 20 L/min. The validation of the Taguchi predictive model and optimal parameters for HAZ responses shows that their prediction accuracy error is within the acceptable limit. The improvement of tensile strength value for the HAZ was ≈ 4.20 % for Ti addition and ≈ 5.20 % for V addition, and the average increment of impact toughness value was ≈ 30.36 % for Ti addition and ≈ 37.46 % for V addition. However, the reduction of hardness value for the HAZ was ≈14.5% for Ti addition and ≈19% for V addition compared to the TIG welded sample without the additions of microalloying elements. Due to the positive outcome on the mechanical properties and metallurgical characteristics of the HAZ obtained using the addition of microalloying elements (Ti and V), it can be said that this technique is suitable for improving the welded HAZ mechanical and microstructural performance of HSLA steel.

خلاصة البحث

يمتاز الفولاذ العالي المقاومة (HSLA) بمزيج ممتاز من القوة والمتانة التي تم الحصول عليها من خلال التصميم المناسب والتحكم في المعالجة الحرارية الميكانيكية لهذه السبائك. ومع ذلك ، يمكن لهذه الخصائص أن تتدهور من خلال المدخلات الحرارة العالية والدورات الحرارية التي يتعرض لها الفولاذ أثناء عمليات اللحام والتي لا يمكن تجنبها خلال مرحلة تصنيع هذا الفولاذ (HSLA) بواسطة اللحام، فمن الضروري إنتاج مقاطع ملحومة مع طاقة حرارية منخفضة قدر الإمكان ، مع الحفاظ على الخصائص الهندسية المشتركة بين المعدن الأصلي والمنطقة الملحومة. المنطقة المتأثرة بالحرارة، وبصورة خاصة المتاخمة لمنطقة حمام اللحام عادة ما يكون لها صلابة أعلى ومتانة كسر أقل مقارنة بمنطقة المعدن الغير ملحومة. يعزى تدهور الخواص الميكانيكية للمنطقة (HAZ) إلى تكوين طور المارتنسيت - الأوستينيت (M-A) والمناطق الهشة (LBZ) المصاحبة. لذلك ، فإن الهدف الرئيسي من هذا البحث هو تحسين خصائص HAZ ، المتمثلة في خاصية قوة الشد ، الصلادة ، طاقة الصدمات والبنية المجهرية لل HAZ. في هذا البحث ، تم إجراء التحقيق على ثلاث مراحل. تتضمن المرحلة الأولى التصميمات التجريبية التي تم تبنيها باستخدام طريقة تاجوتشي وإنتاج مسار اللحام وفقًا لمعايير اللحام المختلفة مثل تيار اللحام، جهد اللحام، سرعة اللحام ومعدل تدفق الغاز مع وبدون إضافة عنصري التيتانيوم والفانديوم باستخدام تقنية إلصاق المسحوق على المعدن ومن ثم عملية اللحام بالشعلة TIG. ثانياً ، تحسين معلمات الإدخال بالاستجابات لخواص المنطقة المتأثرة بالحرارة (HAZ) ،الصلادة، قوة الشد ، وطاقة الصدم. في المرحلة الأخيرة ، توصيف وتقييم لحام HSLA الصلب، خاصة HAZ من خلال نتائج الصلادة الدقيقة ، قوة الشد ، وطاقة الصدم. أخيرًا ، يتم توصيف خصائص البنى الدقيقة HAZ باستخدام OM و SEM-EDX و XRD. أظهرت النتائج، أن أعلى قوة شد تم تحقيقها كانت 692.85 ميجا باسكال و 729.80 ميجا باسكال للعينات المضاف إليها Ti و V على التوالي. إلى جانب ذلك ، كان التحسن في صلابة الصدمات 81 J و 76 J للعينات المضاف إليها Ti و V ، وكان أدنى صلادة هو 202 Hv لكليهما (Ti وV). كانت أفضل المعلمات المحسّنة التي حققها تحليل (Taguchi S/N ratio) مع إضافات مساحيق Ti وV هي 1.5 مجم/مم^2 ، التيار 100 أمبير، الجهد 40 فولت ، السرعة 1.5 ملم/ثانية ، ومعدل تدفق الأرجون 20 لتر/دقيقة. يظهر التحقق من صحة نموذج تنبؤ Taguchi والمعلمات المثلى لأستجابات (الخصائص) HAZ أن خطأ دقة التنبؤ الخاص به يقع ضمن الحد المقبول. علاوة على ذلك، كان تحسين قيم مقاومة الشد القصوى ≈ 4.20٪ للعينات المضاف إليها ال Ti وبنسبة ≈ 5.20٪ للعينات المضاف إليها ال V ، ومتوسط الزيادة لقيم طاقة الصدم في HAZ كان ≈ 30.36٪ للعينات المضاف إليها ال Ti و ≈ 37.46٪ للعينات المضاف إليها ال V، بينما كان الأنخفاض في قيم الصلادة في منطقة ال HAZ ≈14.5٪ للعينات المضاف إليها ال Ti و ≈ 19٪ للعينات المضاف إليها ال V مقارنة مع عينات TIG الملحومة دون إضافة عنصري التيتانيوم والفانديوم للمنطقة الملحومة. نظرًا للنتائج الإيجابية للخواص الميكانيكية والخصائص المجهرية لمنطقة HAZ التي تم الحصول عليها باستخدام إضافة عنصري (Ti و V)، يمكن التوصية باستخدام هذه التقنية لتحسين أداء منطقة لحام فولاذ HSLA الملحوم.

APPROVAL PAGE

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Musa Moh. H. Abdullrhman

Signature.. Date.......................................

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……..…………………….. ………………………..
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Dedicated to…
To my beloved parents,
Alhaj Mohamed H. Abdullrhman,
And
Alhaaja Maryam A. Amen
For their love, encourage and care
May Almighty Allah continue to show His choicest mercy on them, and provide them with health and wellness…Amin?

My sweetheart wife (Munira)
And our children
(Marwa, Safa, Mohammed, Maryam, and Marh)
For their love, understanding and their sacrifices
The comfort of eyes...... forever and ever

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LIST OF ABBREVIATIONS

ABS	American Bureau of Shipping
AC	Alternating Current
ACC	Accelerated Cooling
AF	Acicular Ferrite
Al	Aluminum
API	American Petroleum Institute
Ar	Argon
ASM	American Society of Metals
ASTM	American Society for Testing of Material
B	Bainite
BBD	Box-Behnken Design
BCC	Body Centered Cubic
BM	Base Metal
Bs	Bainite Start
C	Carbon
Ca	Calcium
CCD	Central Composite Design
CCT	Continuous Cooling Transformation
CGHAZ	Coarse Grained Heat Affected Zone
Cr	Chromium
CTOD	Crack Tip Opening Displacement
Cu	Copper

CVN	Charpy V Notch
DBTT	Ductile Brittle Transition Temperature
DCEN	Direct Current Electrode Negative
DCEP	Direct Current Electrode Positive
DCRP	Direct Current Reverse Polarity
DCSP	Direct Current Straight Polarity
DOE	Design Of Experiment
DP	Dual Phase
DWTT	Drop Weight Tear Test
EL	Elongation
EDM	Electric Discharge Machining
EDX	Energy Dispersive X-ray Spectroscopy
EGS	Effective Grain Size
FCC	Face Centered Cubic
Fe-FeC$_3$	Iron-Iron Carbide
FGHAZ	Fine Grain Heat Affected Zone
FZ	Fusion Zone
GTAW	Gas Tungsten Arc Welding
HACC	Hydrogen Assisted Cold Cracking
HAGB	High Angle Grain Boundary
HAZ	Heat Affected Zone
HD	Hardness
HSLA	High Strength Low Alloy
HTB	Higher-The-Better

Hv	Vickers Hardness
HY	High Yield
ICCGHAZ	Intercritically Reheated Coarse Grained Heat Affected Zone
IIW	International Institute of Welding
IT	Impact Toughness
JCPDS	Joint Committee on Powder Diffraction Standards
LBZ	Local Brittle Zone
LM	Lath Martensite
LOM	Light Optical Microscope
LTB	Lower-The-Better
M	Martensite
M-A	Martensite-Austenite
Mn	Manganese
Ms	Martensite Start
MnS	Manganese Sulfide
Mo	Molybdenum
N	Nitrogen
Nb	Niobium
Ni	Nickel
NTB	Nominal-The-Best
OA	Orthogonal Arrays
OAW	Oxy-Acetylene Welding
P	Pearlite
PAG	Prior Austenite Grain

PF	Polygonal Ferrite
PVA	Polyvinyl Alcohol
PWHT	Post Weld Heat Treatment
QT	Quenching and Tempering
RT	Room Temperature
SAW	Submerged Arc Welding
SEM	Scanning Electron Microscope
SG	Shielded Gas
Si	Silicon
SMAW	Shielded Metal Arc Welding
SPF	Side Plate Ferrite
TEM	Transmission Electron Microscope
Ti	Titanium
TiC	Titanium Carbide
TIG	Tungsten Inert Gas
TMCP	Thermo-mechanical Controlling Process
TiN	Titanium Nitride
TiS	Titanium Sulfide
TS	Tensile Strength
UTS	Ultimate Tensile Strength
V	Vanadium
VC	Vanadium Carbide
VN	Vanadium Nitride
WF	Widmanstatten Ferrite

WM	Weld Metal
XRD	X-ray Diffraction
YS	Yield Strength
Zr	Zirconium
α	Alpha
γ	Gamma