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MICROSTRUCTURAL FEATURES AND PROPERTIES OF TIG MELTED AISI 430 FERRITIC STAINLESS STEEL WELDS

BY

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ABSTRACT

Extensive grain growth in ferritic stainless steel welds causes severe loss of ductility and other properties which limits the usage of this low cost stainless steel in many structural applications. While a low energy input and faster heat dissipation conditions have been suggested for grain growth control, the range of the process parameters that falls within these conditions is not well identified. Therefore, it has not been possible to optimize the microstructure and properties of ferritic stainless steel welds. In this work, the microstructural features of AISI 430 ferritic stainless steel welds produced using TIG torch melting at different process parameters were studied and developed a relationship between process parameters and mechanical properties. Furthermore, two new schemes were employed to refine grain structures and their influences on chromium carbide precipitation in the weld are discussed. The investigation was conducted in three phases. In the initial phase, the low energy input conditions were identified for welding the 1.5 mm thick AISI 430 ferritic stainless steel used in this work. Arc currents in the range of 70-110 A and welding speeds in the range of 2.5 - 3.5 mm/s were identified as safe welding conditions for this material. Within these process parameters, the ductility of the weld was up to 45% of the base metal which is higher than the values reported in the literature. In the second phase, the new schemes to refine grain structures by the incorporation of elemental metal powders into the melt pool and cryogenic cooling of the weld were studied. These new schemes for refining the weld microstructure offered dual benefits of grain refinement and constriction in weld dimensions. The constriction in weld geometry is found to be very significant and it is beyond the range reported in any of the existing grain refinement strategies. However, the addition of metal powder provided greater benefits in terms of grain refinement and constriction in weld geometry, but it precipitated hard intermetallic particles in the microstructure resulting in low ductility. The precipitation of such hard particles was absent in the cryogenic cooling technique. The mechanical properties of welds are influenced by both the grain size and the phases present in the microstructure. In the final phase, chromium carbide precipitation in the welds under different grain refinement conditions was evaluated and found that the precipitation of carbide could be prevented when the weld was processed with an energy input less than 500 J/mm. The addition of metal powder such as a mixture of aluminum and titanium or cryogenic cooling did not facilitate carbide precipitation; however, the addition of aluminum powder into the melt pool facilitated carbide precipitation and increased sensitization in the welds. The present investigation achieved over 80% improvement in weld ductility via cryogenic cooling without affecting the sensitization resistance of the steel. This level of ductility is significantly higher than the maximum of 65% achieved with existing grain refinement techniques in fusion welding and is only comparable to those of the friction stir welding which generates ductility of over 90% of the base metal in AISI 430 ferritic stainless steel welds. Furthermore, the work developed an innovative parameter, *the grain refinement index*, for the evaluation of the degree of grain refinement for a given treatment condition relative to the base metal, not to the weld metal, which is the common practice in existing grain refinement techniques.

خلاصة البحث

النموالواسع في الخلايا نتيجه لحام الحديد الصلب الذي لا يصدأ يسبب خسارة فادحة في اليونة والخصائص الأخرى التي تحد من استخدام هذه الفولاذ المقاوم للصدأ منخفضة التكلفة في تطبيقات هيكلية كثيرة. استخدام منخفض للطاقة وتبديد الحرارة سريع يوفر الظروف للسيطرة على نمو الخلايا ، الشروط التي تحدد ذلك غير معروفه تماما. لذلك ، فإنه لم يكن من الممكن تعظيم الخواص المجهرية لحديدالصلب المقاوم للصدا. في هذا العمل، أنتج التركيب الدقيق (430 AISI) الفولاذ المقاوم للصدأ حديدي اللحامات باستخدام ذوبان الشعلة TIG في عملية مختلفة المعلمات ودراستها ووضع العلاقة بين المعلمات العملية والخواص الميكانيكية. وعلاوة على ذلك ، اقترحت خطتين تستخدم لاول مره لتحسين هياكل الخلايا وتأثيراتها على كربيد الكروم في اللحام. وأجري العمل على ثلاثه مراحل. في المرحلة الأولى ، يتم التعرف على مدخلات الطاقة منخفضة على ظروف اللحام 1.5 مم (430 AISI) الفولاذ المقاوم للصدأ من الحديد المستخدمة في هذا العمل التيار الكهربائي لقوس اللحام في نطاق 70-110 ألف وبسرعة في حدود 2.5 - 3.5 ملم /ثانيه ووضعت قواعد امنه للحام بهذه الظروف. ضمن ظروف اللحام هذه لايمكن للمطوعيه ان تصل إلى 45 ٪ من المعدن الأساسي و التي هي أعلى من القيم الموجوده في البحوث الحاليه لهذا الصلب. في المرحلة الثانية ، تمت دراسة المخططات الجديدة لتحسين هياكل الخلايا عن طريق دمج عنصري مساحيق المعادن تذوب في منطقه اللحام مع التبريد المستمر اثناء عملية الذوبان. هذه مخططات جديدة للتكرير والمجهرية لحام تقدم فوائد مزدوجة من صقل الخلايا وانقباض في أبعاد اللحام. تم تاشير على ان انقباض شكل الخلايا كان مؤثر و غير موجود في اي من الطرق المستخدمه الحاليه. ومع ذلك ، فإن إضافة مسحوق المعادن ويوفر المزيد من الفوائد من حيث صقل الحبوب وانقباض في هندسة اللحام ، ولكن معالجة اللحامات مع مسحوق المعدن اعادت تركيب و عجلت تداخل الجزيئات الصلبة في المجهرية مما أدى إلى انخفاض ليونة. ان ترسب الجزيئات الصلبة غير موجود في تقنية التبريد. العمل الحالي كشف على تاثر الخواص الميكانيكية للحام من قبل كل من حجم الخلايا والمراحل موجودة في المجهرية. في التركيب النهائي تم تقييم كمية الرواسب كروميم كاربايد في ظل مختلف الظروف وجدت أنه يمكن منع ترسب كربيد عند معالجة اللحام مع مدخلات الطاقة أقل من J/mm 500. ان إضافة مسحوق المعادن مثل خليط من الألمنيوم والتيتانيوم أو مساحيق التبريد المبردة لا يسهل ترسيب كربيد ، إلا أن إضافة مسحوق الألمنيوم في مجال اللحام سهلت ترسب كربيد وزيادة التوعية في اللحامات. التحقيق الحالي اثبت تحسن بنسبة 80 ٪ في ليونة لحام عبر التبريد المبردة دون التأثير على المقاومة توعية الصلب. هذا المستوى من ليونة هو أعلى بكثير من حوالي 65 ٪ التي تحققت مع التقنيات الموجودة في صقل الحبوب لحام الانصهار وقابلة للمقارنة فقط لتلك التي تثير الاحتكاك الذي يولد لحام ليونة اكثر من 90 ٪ من المعادن الأساسية في ايسي 430 الفولاذ المقاوم للصدأ حديدي اللحامات. وعلاوة على ذلك، هذا العمل طورطريقه مبتكرة وهي (مؤشرصقل الخلايا) لتقييم درجة صقل الخلايا كشرط المعاملة الممنوحة بالنسبة إلى المعادن الأساسية، وليس لحام المعادن، وهي ممارسة شائعة في القائمة تقنيات صقل الخلايا.

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 or part for any other degrees at IIUM or other institution(s) anywhere else in the world.

Muhammed Olawale Hakeem Amuda

Signature…………………….. Date……………

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Affirmed by Muhammed Olawale Hakeem Amuda.

………………………… ………………
Signature Date

Dedicated to...

The memory of my beloved late parents:
Alhaji (Chief) & Mrs. Amuda Yusuf Odugate Shalasoro
May Allah bless their souls and place them among His Servants, Amin.

My siblings and extended family members.

My Wife, Kafilah Olasunmbo Abike-Ade Badmus-Oreekan.

The next generations of scholars who would strive for the betterment of humanity.

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LIST OF ABBREVIATIONS

AC/DC	Alternating Current/Direct Current
Al	Aluminum
AOD/VOD	Argon Oxygen Decarburization/Vacuum Oxygen Decarburization
Ar	Argon
$Ar\text{-}CO_2$	Argon-Carbon dioxide gas mixture
$Ar\text{-}N_2$	Argon-Nitrogen gas mixture
BCC	Body Centred Cubic
BM	Base Metal
C	Carbon
CCT	Continuous Cooling Transformation
CET	Columnar-Equiaxed Transition
CPS	Count Per Second
Cr	Chromium
Cr_{eq}	Chromium equivalent
CTE	Coefficient of Thermal Expansion
Cu	Copper
CW	Conventional Weld
DCEN	Direct Current Electrode Negative
EDX	Energy Dispersive X-ray
ESW	Electroslag Welding
FCC	Face Centred Cubic
Fe	Iron
Fe-Cr	Iron – Chromium
Fe-Cr-C	Iron – Chromium – Carbon
FSS	Ferritic Stainless Steel
FSW/FSWed	Friction Stir Welding/Friction Stir Welded
FZ	Fusion Zone
GRI	Grain Refinement Index
GS	Grain size of the base metal (μm)
$H_2\text{-}Ar$	Hydrogen-Argon gas mixture
HAZ	Heat Affected Zone
$He\text{-}O_2$	Helium-Oxygen gas mixture
HTE	High Temperature Embrittlement
HTHAZ	High Temperature Heat Affected Zone
ICDD	International Centre for Diffraction Data
IGC	Intergranular Corrosion
IMT	Image and Microscope Technology
KFF	Kaltenhauser Ferrite Factor
LN	Liquid Nitrogen
LOM	Light Optical Microscope
LTE	Low Thermal Conductivity
$M_{23}C/M_7C_6/MC$	Metal Carbides
MAO	Magnetic Arc Oscillation
MIG	Metal Inert Gas
Mn	Manganese

Mo	Molybdenum
M_s	Martensite start
N	Nitrogen
Nb	Niobium
Ni	Nickel
Ni_{eq}	Nickel equivalent
NR	Not Reported
O	Oxygen
P	Phosphorus
PH	Precipitation Hardening
PVA	Polyvinyl Alcohol
S	Sulphur
SCCR	Stress Corrosion Cracking Resistance
SEM	Scanning Electron Microscopy
Si	Silicon
SMAW	Shielded Metal Arc Welding
SP	Straight Polarity/Reverse Polarity
Ta	Tantalum
Th	Thoria
Ti	Titanium
TIC	Titanium Carbide
TIG	Tungsten Inert Gas
V	Vanadium
VHN	Vickers Hardness Number
VPTIG	Variable Polarity Tungsten Inert Gas
W	Tungsten
WRC	Welding Research Council
WRD	Weld Relative Ductility
XRD	X-Ray Diffraction

LIST OF SYMBOLS

% El	Percent elongation
d	Mean grain size (µm)
$d_{\phi 0}$	Intercept of the residual stress plot (MPa)
$d_{\phi\psi}$	Lattice spacing
E	Modulus of elasticity (N/mm^2)
e	The base of natural logarithm
EI	Energy input (J/mm)
G	Thermal gradient (^{0}C/mm)
hkl	Diffraction planes
I	Arc current (A)
K	Strengthening coefficient
q	Heat flux (W)
R	Local solidification velocity (mm/s)
T	Temperature at any given point in the heat affected zone (^{0}C)
t	Instantaneous time (s)
T_0	Pre-weld temperature of the material (^{0}C)
$T'_{12/8}$	Cooling rate from 1200-800 ^{0}C (^{0}C/s)
T_p	Peak temperature of the thermal cycle (^{0}C)
TS	Tensile strength (MPa)
V	Arc Voltage (V)
v	Poisson’s ratio
x_1	Width of the fusion zone during sensitization (mm)
x_2	Location of the sensitized zone from the weld interface in the lateral direction (mm)
x_3	Width of the sensitized zone (mm)
X_{BM}	Grain size of the base metal (µm)
X_{CW}	Grain size of conventional weld (µm)
X_{ref}	Grain size due to grain refinement (µm)
y_1	Depth of the FZ during sensitization (mm)
y_2	Location of the sensitized zone from the weld interface in the transverse direction (mm)
y_3	Depth of the sensitized zone (mm)
YS	Yield strength (MPa)
α	Alpha ferrite
β	Martensite
γ	Austenite
δ	Delta ferrite
σ	Sigma phase
$\Delta t_{12/8}$	Cooling time from 1200-800 ^{0}C (s)
$\Delta t_{1500\text{-}800}$	Cooling time from 1500-800 ^{0}C (s)
$\Delta t_{8\text{-}5}$	Critical cooling rate from 800^0-500^{0}C (^{0}C/s)
η	Efficiency of TIG melting process (%)
θ_2	Dimensionless thermal gradient
Θ_2	Dimensionless parameter of temperature
λ	Thermal conductivity of material (J/s/m/^{0}C)