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It is certified that the work contained in the thesis titled ***"FRICTION STIR PROCESSING OF GAS METAL ARC WELDED FERRITIC STAINLESS STEEL"*** by ***"*SANJAY KUMAR GUPTA*"*** has been carried out under my/our supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy, and SOTA for the award of Ph.D. Degree.

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I, ***"Sanjay Kumar Gupta"*** certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of **"*Dr. Mohd Zaheer Khan Yusufzai*** and ***Dr. Meghanshu Vashista",*** from ***"July 2016*** to ***June 2021",*** at the ***"Department of Mechanical Engineering",*** Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma.

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Date: 08/06/2021

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ACKNOWLEDGEMENTS

I am using this opportunity to express my sincere thanks and gratitude beyond words to my supervisors, **Dr. Mohd Zaheer Khan Yusufzai** and **Dr. Meghanshu Vashista,** for their consistent help, encouragement, and valuable discussions during the entire period of my research work. I would not have been able to complete the thesis without their utmost involvement and invaluable efforts. They motivated me to pursue research problems and the need for persistent effort to accomplish the goal. I am truly indebted to them. They are the real definition of the best teacher, being friendly and behind for all problems of not only mine but all the students.

Besides my supervisors, I would like to thank my RPEC members **Dr. U. S. Rao** and **Dr. Kaushik Chattopadhayay,** for their insightful comments and encouragement. I sincerely thank **Prof. Santosh Kumar**, Head of the Department of Mechanical Engineering, and the former heads Prof. A. P. Harsha and Prof. A. K. Jha for providing all the research facilities to successfully accomplish my research in the department. I have deep sense of gratitude to all the faculty members, office staff, and technical staff from idea development centre, main workshop, CIFC lab and production lab. I would like to thank specially Mr. Rajendra Prasad, Mr. Hari Shankar, Mr. Ganesh, Mr. Barmeshwar Rai, Mr. Ravi Shankar Singh, Mr. Bilu Guria, Mr. J. K. Sinha, Mr. Akash Mishra and Mr. V. P. Srivastava for their cooperation and inspiration.

I am thankful to my all friends Akash, Anupam, Ravi Soni, Ravi Prakash, Umesh, Jitendra, Abhishek and my seniors Avinash Sir, Harikishor Sir, Ashish Sir, Manidipto Mukherjee, Pritish Da, Vinayak Sir, Parshant Sir, Ravindra sir, Ashutosh Sir for their constant encouragement, making joyful and memorable life being with my moments of happiness and troubles at IIT (BHU), Varanasi. I would also thank my juniors Mithlesh, Adrash, Abhimanyu, Ashwani, Varsha, Vinayak, Deepak, Atul and Baljinder, for their support.

I have no words to express my deepest gratitude to my parents **Shri. Chaturbhuj Gupta** and **Smt. Kalawati Devi**, for giving my life in the first place, for educating me, for their unconditional support and encouragement to pursue my interest. A special word of thanks to my wife Smt. Shalini, younger brother Satyam, my sisters (Poonam and Pooja) and all family members for their support.

Last but certainly not the least, my sincere gratitude to **Pt. Madan Mohan Malviya** and **GOD,** for providing me with excellent academic environments (IIT, BHU) where one feels motivated for learning.

Sanjay Kumar Gupta

TABLE OF CONTENTS

List of figures

List of Tables

LIST OF SYMBOLS

1. Notations

A_{UR}	Upper reinforcement
A_{LR}	Lower reinforcement
A_{FBM}	Fused base metal
A_{RG}	Area of root gap
PD	Percentage dilution
Cr_{eq}	Chromium equivalent
Ni_{eq}	Nickel equivalent
A	Ampere
V	Volt
mV	Millivolt
M	Magnetisation
H	Applied magnetic field intensity
χ	Magnetic susceptibility
B	Magnetic flux density
V_{rms}	Root mean square voltage
V_{peak}	Peak voltage
δ	Skin depth
σ	Conductivity of the conductor
f	Frequency of the current
μ	Permeability of the conductor

2. Abbreviations

GMAW	Gas metal arc welding
GTAW	Gas tungsten arc welding
TIG	Tungsten inert gas
MIG	Metal inert gas
PAW	Plasma arc welding
SMAW	Shielded metal arc welding
FCAW	Flux cored arc welding
SAW	Submerged arc welding
EBW	Electron beam welding
USW	Ultrasonic welding
RSW	Resistance spot welding
FSW	Friction stir welding
FSP	Friction stir processing
EBSD	Electron backscattered diffraction
BCC	Body centred cubic
FCC	Face centred cubic
HCP	Hexagonal closed packing
CVD	Chemical vapor deposition
PVD	Physical vapor deposition
LDR	Limited drawing ratio
AR	As rolled
HP	Horse power
SD	Shoulder diameter
BM	Base metal

BMZ	Base metal zone
WMZ	Weld metal zone
HAZ	Heat affected zone
PR	Processed region
TMAZ	Thermo-mechanically affected zone
HAZ (FSP)	Heat affected zone in the friction stir processing operation
RS	Rotational speed
PS	Processing speed
CDRX	Continuous dynamic recrystallization
DDRX	Discontinuous dynamic recrystallization
XRD	X-ray diffraction
SEM	Scanning electron microscope
MBN	Magnetic Barkhausen noise
MHL	Magnetic hysteresis loop
RMS	Root mean square
PCBN	Polycrystalline cubic boron nitride
CV	Constant voltage
Fe	Iron
Cr	Chromium
Al	Aluminium
Mo	Molybdenum
V	Vanadium
Ti	Titanium
W	Tungsten
C	Carbon

Si	Silicon
Ni	Nickel
O	Oxygen
N	Nitrogen
Mg	Magnesium
Mn	Manganese
Co	Cobalt
CO_2	Carbon dioxide
SiO_2	Silicon dioxide
TiO_2	Titanium dioxide
Cr_2O_3	Chromium oxide
$CuAl_2$	Copper aluminide
NbC	Niobium carbide
TiC	Titanium carbide
ZrC	Zirconium carbide
WC	Tungsten carbide
NaCl	Sodium chloride
AISI	American iron and steel institute
PRE	Pitting resistance equivalent
ASTM	American society for testing and materials
MFI	Magnetic field intensity
AMFD	Average maximum flux density
Hz	Hertz
Oe	Oersted

Preface

AISI 409L ferritic stainless steel is a widely used engineering material owing to its low cost in spite of its corrosion resistance properties. It possessed high thermal conductivity and lower thermal expansion coefficient compared to the austenitic stainless steel. Although its corrosion resistance is inferior to austenitic stainless steel, it better resists stress corrosion cracking in a chloride environment. Its oxidation resistance at high temperature is also higher; therefore, it is widely used in automotive exhaust systems such as mufflers, tail pipe, catalytic converter and exhaust manifold.

Ferritic stainless steels, including AISI 409L, are generally welded using gas metal arc welding process. However, grain coarsening of the weld metal zone and the heat affected zone is a major drawback in the welding of ferritic stainless steel. The grain coarsening can be eliminated to some extent using filler wire of austenitic grades such as austenitic grades ER304L, ER308L and ER316L, but the heat affected zone still possesses coarser grains.

Friction stir processing is a new technique based on friction stir welding that can be used to refine the grains of a material.

In this study, efforts have been made to initially optimize the process parameters to produce gas metal arc welding butt welds in plates of AISI 409L using ER304L (austenitic grade) filler material. Butt welds were produced on plates of 3 mm thickness using different heat input conditions by varying the welding current, welding voltage and welding speed. Other process parameters like root gap, shielding gas flow rate and stand-off distance were kept constant. The weldments were tested for the hardness, tensile strength, residual stress and Charpy impact toughness. The effect of heat input on the percentage dilution, microstructure, hardness, tensile strength, residual stress and Charpy impact toughness of the welded plates have been investigated.

The microstructure consisted of finer grains in the weld metal zone and coarser grains in heat affected zone. The applicability of the magnetic Barkhausen noise analysis and magnetic hysteresis loop has been demonstrated for both the welded plate as well as the processed plate. The testing was performed at each region of the welded plate, i.e. weld metal zone and heat affected zone, and processed region of the processed plate at different combination of magnetic Barkhausen noise process parameters. From this characterisation technique, it was found that the grain size affects the response parameters of the magnetic Barkhausen noise as well as the magnetic hysteresis loop.

The weldments with the best combination of mechanical properties obtained at optimized process parameters (sample S7) have been refined by using friction stir processing. The weld material and the heat affected zone on both sides were processed in a single pass. Friction stir processing has been carried out in such a way that the processing thickness was approximately half of the thickness of the welded plates. The friction stir processing tool material, tool geometry, and tool tilt angle to be used during friction stir processing were selected using extensive trial runs such that defects were prevented from occurring. The range of rotational speed and processing speed was found for the two different values of shoulder diameters. These process parameters (shoulder diameter, rotational speed and processing speed) were varied in a range of parametric window to perform the friction stir processing of the welded plate. The location of the friction stir processing tool has been kept above the centre of the weld metal zone such that the heat affected zone on both sides can be processed.

After performing friction stir processing on the welded plate, the plates were characterized to assess the mechanical and metallurgical properties. The processed region in the weld metal and the heat affected zone, both, consisted of refined grains of 3.0 microns and ferrite phases along with the austenite and martensite phases. The average grain size of the processed region decreased on an average from 164.0 micron of heat affected zone to 3.0 micron after friction stir processing.

The average hardness of the processed region was also found more than the other regions, which imply that the hardness of the heat affected zone of the welded plate has also been improved. On performing transverse tensile testing of the processed plates, all tensile specimens have been fractured in the base metal zone, reflecting the improvement in the strength of the heat affected zone of the welded plate.

The effect of shoulder diameter and ratio of rotational speed to the processing speed has also been studied. It was found that for a given shoulder diameter, on increasing the ratio of rotational speed to the processing speed, the grain size of the processed region and thermo mechanically affected zone is decreasing, whereas the grain size of the heat affected zone (friction stir processing) are increasing. For a given set of process parameters, it was found that friction stir processing tool with a higher shoulder diameter produced coarser grains in all regions of the processed plate than the smaller diameter.

Similarly, the effect of shoulder diameters and the ratio of rotational speed to the processing speed on the hardness of different regions were also analysed. These variations were opposite to the variation as observed in the case of grain size.

The longitudinal residual stresses were also measured at different locations in each region of the welded plate and processed plate. In the case of the welded plate, compressive residual stresses have been found in the heat affected zone, while tensile residual stresses have been found in the base metal zone as well as weld metal zone. In the case of the processed plate, the base metal zone was under the tensile residual stress, and the processed region was under the compressive residual stress whose magnitude is more than the compressive residual stress exists in the welded plate as well as the area of the plate under compressive residual stress is also more than the case of the welded plate. Therefore, the tensile residual stress of the weld metal zone was completely removed upon carrying out friction stir processing and get converted into the compressive residual stress.

Also, the micromagnetic analysis (magnetic Barkhausen noise and magnetic hysteresis loop) of the processed region of sample A has been carried out at magnetic field intensity of 800 Oe and magnetising frequency of 0.05 Hz. The obtained values of response parameters for different regions of the welded plate S7 and processed region of sample A have been compared to see the effect of friction stir processing on the micromagnetic response.

From the obtained results, it was concluded that friction stir processing might be used to refine the coarser grains of the heat affected zone, which in turn increases the strength of the heat affected zone. Thus the problems associated with the grain coarsening of the heat affected zone obtained in the gas metal arc welding of the ferritic stainless steel can be removed by using friction stir processing.