

# **CERTIFICATE**

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.

## **Supervisor**

**Dr. Mohd Zaheer Khan Yusufzai**

(Associate Professor)

Department of Mechanical Engineering,  
Indian Institute of Technology,  
(Banaras Hindu University)  
Varanasi – 221005, INDIA

## **Co-Supervisor**

**Dr. Meghanshu Vashista**

(Associate Professor)

Department of Mechanical Engineering,  
Indian Institute of Technology,  
(Banaras Hindu University)  
Varanasi – 221005, INDIA

## DECLARATION BY THE CANDIDATE

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.

I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports dissertations, theses, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

Date: 08/06/2021

Place: Varanasi

**Sanjay Kumar Gupta**  
(Candidate)

## CERTIFICATE FROM THE SUPERVISORS

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

**Supervisor**

**Dr. Mohd Zaheer Khan Yusufzai**

(Associate Professor)

**Co-Supervisor**

**Dr. Meghanshu Vashista**

(Associate Professor)

**Professor and Head**

Department of Mechanical Engineering,  
Indian Institute of Technology (BHU), Varanasi- 221005

# **COPYRIGHT TRANSFER CERTIFICATE**

**Title of the Thesis:** *Friction Stir Processing of Gas Metal Arc Welded Plate Ferritic Stainless Steel*

**Name of the Student:** Sanjay Kumar Gupta

## **Copyright Transfer**

The undersigned hereby assigns to the Indian Institute of Technology (Banaras Hindu University) Varanasi all rights under copyright that may exist in and for the above thesis submitted for the award of the ***“DOCTOR OF PHILOSOPHY”***.

Date: 08/06/2021

Place: Varanasi

(Sanjay Kumar Gupta)

**Note:** However, the author may reproduce or authorize others to reproduce material extracted verbatim from the thesis or derivative of the thesis for author's personal use provided that the source and the Institute's copyright notice are indicated.

## 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 Chattopadhyay**, 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, CIFIC 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

Certificate	
Acknowledgements	
Table of contents	i
List of figures	v
List of tables	xi
List of symbols	xiii
Preface	xvii

## **CHAPTER 1: INTRODUCTION ..... 1**

### **1.1 Background ..... 3**

### **1.2 Objectives of the current research work ..... 9**

### **1.3 Format of the thesis ..... 10**

## **CHAPTER 2: LITERATURE REVIEW ..... 13**

### **2.1 Introduction ..... 15**

### **2.2 Stainless steel ..... 15**

### **2.3 History of stainless steel ..... 16**

### **2.4 Types of stainless steel ..... 17**

#### **2.4.1 Martensitic stainless steel ..... 18**

#### **2.4.2 Duplex stainless steel ..... 19**

#### **2.4.3 Precipitation hardened stainless steel ..... 19**

2.4.4	Austenitic stainless steel.....	20
2.4.5	Ferritic stainless steel .....	21
<b>2.5</b>	<b>Mechanical and physical properties.....</b>	<b>28</b>
2.5.1	Crystal structure .....	28
2.5.2	Physical properties .....	28
2.5.3	Mechanical properties .....	29
<b>2.6</b>	<b>Welding of ferritic grades .....</b>	<b>29</b>
2.6.1	Electric resistance welding.....	29
2.6.2	Electron beam welding .....	31
2.6.3	Laser beam welding .....	32
2.6.4	Friction welding .....	32
2.6.5	Electric arc welding.....	34
<b>2.7</b>	<b>Welding of ferritic stainless steel AISI 409 (SS409).....</b>	<b>36</b>
2.7.1	Gas tungsten arc welding of SS409.....	37
2.7.2	Friction stir welding of SS409.....	40
2.7.3	Gas metal arc welding of SS409 .....	42
<b>2.8</b>	<b>Friction stir processing.....</b>	<b>45</b>
2.8.1	Friction stir processing of aluminium and its alloys.....	47
2.8.2	Friction stir processing of magnesium and its alloys.....	49
2.8.3	Friction stir processing of carbon steels .....	51
2.8.4	Friction stir processing of stainless steels .....	53
<b>2.9</b>	<b>Literature gap .....</b>	<b>55</b>
 <b>CHAPTER 3: EXPERIMENTATION .....</b>		 <b>57</b>
<b>3.1</b>	<b>Gas metal arc welding of ferritic stainless steel .....</b>	<b>59</b>
3.1.1	Introduction .....	61

3.1.2	Selection of base material and welding process.....	61
3.1.3	Selection of electrodes .....	62
3.1.4	Selection of backing plate.....	63
3.1.5	Joint configuration .....	65
3.1.6	Equipment used for experimentation .....	67
3.1.7	Welding trial runs for gas metal arc welding of SS 409L.....	75
3.1.8	Final welding runs at the selected parameters.....	86
3.1.9	Characterisation of welds.....	89
<b>3.2</b>	<b>Friction stir processing of gas metal arc welded ferritic stainless steel ...</b>	<b>109</b>
3.2.1	Introduction.....	111
3.2.2	Friction stir processing equipment.....	112
3.2.3	Selection of friction stir processing tool material .....	115
3.2.4	Tool grinder .....	118
3.2.5	Selection of tool profile .....	119
3.2.6	Processing trial runs on gas metal arc welded plate.....	120
3.2.7	Outcome of the trial runs .....	123
3.2.8	Final runs .....	124
3.2.9	Characterisation of the processed plates .....	126
	<b>CHAPTER 4: RESULTS AND DISCUSSION.....</b>	<b>131</b>
<b>4.1</b>	<b>Gas metal arc welding of ferritic stainless steel .....</b>	<b>133</b>
4.1.1	Introduction.....	135
4.1.2	Visual examination of the weld .....	136
4.1.3	X-ray radiography of the welds .....	137
4.1.4	Calculation of percentage dilution .....	139
4.1.5	Relation between heat input and percentage dilution.....	141
4.1.6	Variation of percentage dilution with the welding current.....	142
4.1.7	Variation of percentage dilution with the welding voltage .....	143
4.1.8	Variation of percentage dilution with the welding speed.....	145



4.1.9	Chemical composition of welds .....	146
4.1.10	Metallography study.....	151
4.1.11	X-ray diffraction analysis .....	159
4.1.12	Hardness of weld metal zone and heat affected zone .....	161
4.1.13	Tensile testing .....	163
4.1.14	Charpy impact testing.....	169
4.1.15	Residual stress measurement of the welded plate .....	171
4.1.16	Micro-magnetic characterisation of welds .....	172
<b>4.2</b>	<b>Friction stir processing of gas metal arc welded ferritic stainless steel ...</b>	<b>211</b>
4.2.1	Introduction .....	213
4.2.2	Visual examination of the processed plate .....	214
4.2.3	X-ray radiography of the processed plates .....	215
4.2.4	Metallography .....	216
4.2.5	Microhardness testing .....	228
4.2.6	Tensile testing .....	231
4.2.7	Charpy impact testing.....	233
4.2.8	Residual stress measurement of the processed plate .....	237
4.2.9	Micro-magnetic characterisation of processed plates .....	239
<b>CHAPTER 5: CONCLUSIONS .....</b>		<b>249</b>
<b>CHAPTER 6: SCOPE FOR FUTURE WORK.....</b>		<b>255</b>

# List of figures

Figure 2.1 Types of stainless steel.....	18
Figure 2.2 Different grades of ferritic stainless steel.....	22
Figure 2.3 Terminology used in FSP.....	46
Figure 3.1 Copper backing plate. ....	64
Figure 3.2 Different types of joints: (a) butt joint, (b) lap joint, (c) corner joint, (d) edge joint, and (e) tee joint. ....	65
Figure 3.3 Types of the butt joint. ....	66
Figure 3.4 GMAW machine setup along with its components: (a) shielding gas cylinder, wire feed rate controller, power source, and (b) welding gun, wire feeder, welding trolley, welding rail, welded plate. ....	67
Figure 3.5 Welding trolley: (a) controller components, (b) attachments to the welding trolley.....	72
Figure 3.6 Welding rail. ....	73
Figure 3.7 Job clamping setup.....	74
Figure 3.8 Schematic diagram of (a) stick out and electrode extension, (b) nozzle to workpiece distance and contact tip to workpiece distance.....	81
Figure 3.9 Trial runs with different root gaps. ....	83
Figure 3.10 Schematic diagram of root gap. ....	84
Figure 3.11 Trial runs at different rates of the shielding gas.....	85
Figure 3.12 Photographs of a few welded plates obtained at different welding process parameters. ....	88
Figure 3.13 X-ray radiography of welded plate. ....	90
Figure 3.14 Schematic diagram of extraction of different specimens for characterisations from the welded plates. ....	91
Figure 3.15 Transverse section of the welded plate (a) actual weld bead, and (b) schematic diagram. ....	95
Figure 3.16 Schematic diagram of locations for hardness measurement. ....	98

Figure 3.17 Schematic diagram of transverse tensile sample. ....	100
Figure 3.18 Schematic diagram of reduced section transverse tensile sample. ....	100
Figure 3.19 Steps followed to tensile sample preparation and performing the tensile testing operation. ....	101
Figure 3.20 Schematic diagram of Charpy impact testing sample. ....	102
Figure 3.21 Charpy impact testing process: (a) testing machine, (b) magnified view of the sample holding location, (c) testing sample and (d) fractured sample after performing testing. ....	103
Figure 3.22 Schematic diagram showing residual stress measurement points in the welded plates. ....	104
Figure 3.23 MBN analyser setup. ....	106
Figure 3.24 Schematic diagram of MBN analyser. ....	106
Figure 3.25 FSP machine setup. ....	112
Figure 3.26 Photographs of FSP tool profile preparation (a) tool grinding machine, (b) closure view of tool and grinding wheel, and (c) prepared FSP tool. ....	118
Figure 3.27 Photographs of the sequence of FSP of the welded plate: (a) welded plate after shaping operation, (b) performing FSP operation on the welded plate, and (c) FSPed welded plate. ....	120
Figure 3.28 Profile of FSP tool: (a) schematic diagram of FSP tool, and (b) actual FSP tool. ....	124
Figure 3.29 FSP of gas metal arc welded plate S7 at different processing parameters. ....	126
Figure 3.30 Schematic diagram of extraction of different specimens for characterisations from the processed plates. ....	127
Figure 3.31 Fractured transverse tensile sample after performing tensile testing. ....	129
Figure 3.32 Fractured reduced section tensile sample after performing tensile testing. ....	129
Figure 3.33 Schematic diagram showing residual stress measurement points in the processed plates. ....	130
Figure 4.1 Image of the trial run weld sample: (a) top surface, and (b) bottom surface. ....	136
Figure 4.2 Image of the final weld sample: (a) top surface, and (b) bottom surface. ....	137
Figure 4.3 X-ray radiography of welded plate. ....	138
Figure 4.4 Variation of percentage dilution at different heat input. ....	141

Figure 4.5 Plot of percentage dilution versus welding current at different values of welding speed. ....	142
Figure 4.6 Plot of percentage dilution versus welding voltage at different values of welding speed.....	144
Figure 4.7 Plot of percentage dilution versus welding speed at different values of welding voltage.....	145
Figure 4.8 Variation of ( $Cr_{eq}/Ni_{eq}$ ) ratio with the heat input. ....	150
Figure 4.9 Macrograph of the weld sample.....	151
Figure 4.10 Microstructure of different regions: (a)BMZ, (b) WMZ, (c) HTHAZ, (d) interface between HTHAZ and WMZ, (e) interface between LTHAZ and HTHAZ, (f) LTHAZ, and (g) interface between LTHAZ and BMZ. ....	152
Figure 4.11 Schaeffler diagram. ....	154
Figure 4.12 13% Cr pseudobinary phase diagram.....	156
Figure 4.13 Variation in the grain size of HAZ and WMZ with the heat input.....	158
Figure 4.14 XRD analysis of weld metal. ....	160
Figure 4.15 Variation of the average hardness of WMZ and HAZ at different heat input.....	161
Figure 4.16 Transverse tensile test specimen after testing: (a) base metal, and (b) welded plate. ....	163
Figure 4.17 Tensile stress-strain curve for (a) base metal SS409L, and (b) welded plate S7. ....	164
Figure 4.18 Fractographic surfaces of the transverse tensile sample of (a,b) base metal and (c,d) welded plate S7.....	165
Figure 4.19 Fractographic surfaces of reduced section tensile sample of (a,b) base metal and (c,d) welded plate S7.....	168
Figure 4.20 Charpy impact toughness test specimen after testing.....	169
Figure 4.21 Variation of Impact toughness of WMZ and HAZ at different heat input.....	169
Figure 4.22 Longitudinal residual stress measurements in the welded plate.....	171
Figure 4.23 Variation of AMFD. ....	175
Figure 4.24 Variation of AMFD in (a) low frequency range, and (b) high frequency range. ....	177
Figure 4.25 Magnetisation curve at the magnified view. ....	181

Figure 4.26 Variation of coreloss. ....	182
Figure 4.27 Variation of core loss in (a) low-frequency range, and (b) high-frequency range.....	185
Figure 4.28 Variation of average permeability. ....	188
Figure 4.29 Variation of average permeability in (a) low-frequency range, and (b) high-frequency range. .....	190
Figure 4.30 Variation of remanence. ....	192
Figure 4.31 Variation of remanence in (a) low-frequency range, and (b) high-frequency range. ....	195
Figure 4.32 Variation of coercivity.....	198
Figure 4.33 Variation of coercivity in (a) low-frequency range, and (b) high-frequency range.....	200
Figure 4.34 Variation of the number of pulses with magnetizing frequency. ....	204
Figure 4.35 Variation of the number of pulses with MFI. ....	206
Figure 4.36 Variation of the RMS value with magnetizing frequency. ....	207
Figure 4.37 Variation of the RMS value with the MFI.....	209
Figure 4.38 Photographs of some of the processed plates. ....	214
Figure 4.39 X-ray radiography of processed plate.....	215
Figure 4.40 (a) Metallographic sample, (b) Macrostructure of processed plate, (c) Microstructure of PR, (d) Microstructure at the interface of PR and WMZ, and (e) microstructure showing PR, TMAZ and HAZ (FSP).....	217
Figure 4.41 XRD analysis of the processed plate. ....	221
Figure 4.42 Microstructure of different regions of friction stir processed plate taken by scanning electron microscope: (a) PR, (b) TMAZ and (c) HAZ (FSP). ....	223
Figure 4.43 Grain size of different zones of friction stir processed plate: (a) PR, (b) TMAZ and (c) HAZ (FSP).....	224
Figure 4.44 Comparative hardness profile of different regions of friction stir processed plate and gas metal arc welded plate. ....	229

Figure 4.45 Hardness of different zones of friction stir processed plate: (a) PR, (b) TMAZ and (c) HAZ (FSP). .....	230
Figure 4.46 Charpy impact toughness test specimen after testing.....	234
Figure 4.47 Variation of impact toughness $I_1$ with the RS to PS ratio. ....	236
Figure 4.48 Variation of impact toughness $I_2$ with the RS to PS ratio. ....	236
Figure 4.49 Longitudinal residual stress measurements in the processed plate. ....	237
Figure 4.50 Average permeability of various zones. ....	240
Figure 4.51 AMFD of various zones.....	241
Figure 4.52 Remanence of various zones.....	242
Figure 4.53 Coercivity of various zones. ....	244
Figure 4.54 Coreloss of various zones. ....	245
Figure 4.55 Number of pulses of various zones. ....	246
Figure 4.56 RMS value of various zones. ....	247



## List of Tables

Table 3.1 Chemical compositions of base metal (weight %) .....	62
Table 3.2 Chemical compositions of electrode wire (weight %).....	63
Table 3.3 Specifications of the power source.....	68
Table 3.4 Specification of the GMAW machine.....	75
Table 3.5 Different combinations of welding process parameters.....	86
Table 3.6 Specification of the FSP machine.....	115
Table 3.7 Process parameters of FSP on welded SS409L plate.....	125
Table 4.1 Results of the radiographic testing.....	138
Table 4.2 Percentage dilution calculated for welds produced using GMAW .....	140
Table 4.3 Chemical composition (weight %) of WMZ.....	147
Table 4.4 Reduced section tensile properties .....	167
Table 4.5 MBN response of different zones with different MFI at the constant magnetizing frequency (25 Hz).....	202
Table 4.6 MBN response of different zones with different magnetizing frequency at constant MFI (800 Oe).....	202
Table 4.7 Results of the radiographic testing.....	216
Table 4.8 Tensile properties of the processed region .....	232
Table 4.9 Charpy impact toughness of different regions of sample S7.....	234
Table 4.10 Charpy impact toughness of processed plates.....	234





# 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
$\chi$	Magnetic susceptibility
B	Magnetic flux density
$V_{rms}$	Root mean square voltage
$V_{peak}$	Peak voltage
$\delta$	Skin depth
$\sigma$	Conductivity of the conductor
$f$	Frequency of the current
$\mu$	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 <sub>2</sub>	Carbon dioxide
SiO <sub>2</sub>	Silicon dioxide
TiO <sub>2</sub>	Titanium dioxide
Cr <sub>2</sub> O <sub>3</sub>	Chromium oxide
CuAl <sub>2</sub>	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.