FRICTION STIR WELDING OF 5052 ALUMINIUM ALLOY

RATNESH KUMAR RAJ SINGH

DEPARTMENT OF APPLIED MECHANICS

INDIAN INSTITUTE OF TECHNOLOGY DELHI

APRIL 2017

FRICTION STIR WELDING OF 5052 ALUMINIUM ALLOY

by

RATNESH KUMAR RAJ SINGH

DEPARTMENT OF APPLIED MECHANICS

Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

NEW DELHI, INDIA

APRIL 2017

CERTIFICATE

This is to certify that the thesis entitled "**Friction Stir Welding of 5052 Aluminium Alloy**" being submitted by Mr. **Ratnesh Kumar Raj Singh** to the Indian Institute of Technology Delhi is worthy of consideration for the award of the degree of **Doctor of Philosophy** and is a record of the original bonafide research work carried out by him. Mr. **Ratnesh Kumar Raj Singh** has worked under our supervision for the submission of this thesis, which to our knowledge has reached the requisite standard. To the best of my knowledge, this work in part or full has not been presented to any other university or institute for the award of any degree/diploma.

Prof. Rajesh Prasad

Professor

Department of Applied Mechanics

Indian Institute of Technology Delhi

Hauz Khas, New Delhi – 110016, India

Prof. Sunil Pandey

Professor

Department of Mechanical Engineering

Indian Institute of Technology Delhi

Hauz Khas, New Delhi – 110016, India

Date:

Place: New Delhi

ACKNOWLEDGEMENTS

I am extremely grateful to the God for the blessings, which of course have been with me always, and giving me the strength and dedication to complete my work to the best of my ability. I pay my exceptional gratitude to Professor Rajesh Prasad (Department of Applied Mechanics, IIT Delhi) and Prof. Sunil Pandey (Department of Mechanical Engineering, IIT Delhi), whose mere presence as my supervisors, consciously and subconsciously, always gave me support and strength. I have been able to complete this work only by virtue of the knowledge that I received from them during my PhD.

The experiment based research work requires availability of adequate research infrastructure. I am thankful to my supervisors, who are indeed, my mentors, Prof. Rajesh Prasad and Prof. Sunil Pandey to help me to get access to all the necessary facilities in IIT Delhi. I am privileged to work under the supervision of them and owe all thanks to them for supporting, advising and guiding me from time to time during course of experimentation and throughout my research studies.

My special thanks are also to Prof. Suhail Ahmad, Department of Applied Mechanics, IIT Delhi for his constant help and support. Being the chairman of student research committee (SRC), he always advised me with his valuable suggestions and expert opinions. I acknowledge the help and support that I received from Prof. Puneet Mahajan, Department of Applied Mechanics, IIT Delhi, during my research as the member of SRC. I also deeply thank Dr. P.M. Pandey, Associate Professor, Department of Mechanical Engineering for being the member of my SRC and for his advices and expert opinions related to my research. I am indebted to Dr. S.

Aravindan, Associate Professor, Department of Mechanical Engineering, for their help, support and valuable suggestions during my research.

I am also thankful to my fellow scholars Dr. Dinesh Rathore, Mrs. Deepti Jaiswal, Mr. Dinesh Shetti, Mr. Saurabh Shukla, Mr. Gaurav Singh, Mr. Anuj Jindal, Mrs. Shaksi Chauhan, Mrs. Shanta Mohapatra, Prof. Arshad Noor Siddiquee, Prof. Hariom Choudhary, Dr. Zaheer Khan, Mr. Abhishek Pandey, Mr. Aryajyoti Goswami, Mr. Mohd. Awol Habib and Mr. Siddharth Tamang. The support extended by them during the critical stages of this research work is gratefully acknowledged and I am also thankful for their interest and involvement in the technical discussions.

The help provided by staff of the Mechanical Engineering and Applied Mechanics Division Laboratories especially Mr. Ayodhya Prasad, Mr. Anil Kumar, Mr. Tulsiram, Mr. Ramchandar and Mr. Bhavar Singh is appreciated. The help extended on personal fronts by Mr. Ayodhya Prasad and Mr. Anil Kumar is gratefully acknowledged.

I am most grateful to my family. I express my deepest gratitude's to my parents, wife, and brother. I love them with all of my heart. I am thankful to my parents for the principles they instilled in me as a young man and for their continued support, guidance, and love for our family. It would have been impossible to complete this work without my family's understanding, patience, and sacrifices.

(**Ratnesh Kumar Raj Singh**)

ABSTRACT

Friction Stir Welding (FSW) is a solid state welding process which involves stirring the material by a non consumable rotating tool to generate frictional heating that soften the base material and produces the joint. FSW is commonly used for welding of aluminium alloys. Owing to solid state nature, and reduced dependence on skills, FSW has numerous advantages over fusion welding processes. Consequently, researchers have shown increasing interest in the application of FSW to aluminium alloys to achieve better mechanical properties.

In the present research, friction stir welding of 5052-H32 aluminium alloy has been performed using conventional robust vertical milling machine (VMM). This VMM has been modified to work as a FSW machine and fitted with an indigenously developed setup which is capable of firmly clamping the 6 mm thick 5052 aluminium plates and is also capable for measuring downward and traverse welding forces. The different attachments have also been fitted with VMM for measurement of temperature distribution and power consumption during welding. A tool holder interface has also been developed which is able to effectively clamp the various size of FSW tool. The hot die steel (H13) tool with a cylindrical threaded pin has been used for the welding.

Numerous trial experiments have been performed to establish the principal FSW process parameters. The tool pin and shoulder diameter, tool rotation and welding speed have been selected as the FSW process parameters and experimentation have been performed in accordance with the response surface methodology (RSM). Mechanical and metallurgical tests have been performed for each welded specimen. The weld quality has been analyzed though tensile, impact,

fatigue and fracture toughness tests along with microstructural examination. The effect of individual process parameter on each weld properties has been analyzed in detail.

It has also been found that the external cooling also affects the quality of welds produced by FSW. To see the effect of external cooling three cooling media such as natural air, water and liquid nitrogen have been used for welding and welds have been examined based on mechanical and metallurgical properties. The water has been found a suitable cooling media for batter mechanical properties.

To achieve best mechanical properties, it is necessary to optimize the process parameters based on suitable cooling media. So the FSW process parameters have been optimized again for the best suited cooling media. In this experiment FSW process parameter has been studied through a separate set of experiments using Taguchi's L9 orthogonal array. The effect of process parameter in cooling media on weld quality characteristics such as strength, elongation, impact strength, fatigue and fracture toughness have been analyzed.

Analysis of results has revealed significant effect of all these FSW parameters and cooling media on mechanical and metallurgical properties of the weld. The FSW process parameters have also significantly affected the welding force generated, power consumed and temperature distributed during welding. The metallurgical test results have revealed occurrence of considerable grain refinement in the stir zone owing to dynamic recrystallization mechanism.

सार

घर्षण घूर्णन वेल्डिंग (एफएसडब्लू) एक ठोस अवस्था वाली वेल्डिंग प्रक्रिया है जिसमें गैर-उपभोज्य घूर्णन उपकरण द्वारा घुलनशील ताप उत्पन्न करने के लिए सामग्री को तेजी से घुमाया जाता है, जो आधार सामग्री को नरम करते हैं और संयुक्त जोड़ बनाता हैं। एफएसडब्लू आमतौर पर एल्यूमीनियम मिश्र धातुओं के वेल्डिंग के लिए उपयोग किया जाता है। ठोस अवस्था की प्रकृति और कौशल पर निर्भरता में कमी के कारण एफएसडब्ल्यू के फ्यूजन वेल्डिंग प्रक्रियाओं से ज्यादा फायदे हैं। नतीजतन, शोधकर्ताओं ने बेहतर यांत्रिक गुणों को प्राप्त करने के लिए एल्यूमीनियम मिश्र धातु को जोड़ने के लिए एफएसडब्ल्यू के उपयोग में बढ़ती रुचि दिखाई है।

वर्तमान शोध में, 5052-एच 32 एल्यूमीनियम मिश्र धातु के घर्षण घूर्णन वेल्डिंग के लिए पारंपरिक रूप से मजबूत ऊर्ध्वाधर मिलिंग मशीन (वीएमएम) का उपयोग किया गया है। इस वीएमएम को एफएसडब्लू मशीन के रूप में काम करने के लिए संशोधित किया गया है और श्वतः विकसित सेटअप के साथ लगाया गया है जो 6 मिमी मोटी 5052 एल्यूमीनियम प्लेटों को मजबूती से जोड़ने में सक्षम है और वे नीचे की तरफ लगने वाली वेल्डिंग बलों को मापने में भी सक्षम है। वेल्डिंग के दौरान तापमान वितरण और बिजली की खपत के माप के लिए विभिन्न उपकरण भी वीएमएम के साथ लगाए गए है। उपकरण धारक अंतरफलक भी विकसित किया गया है जो कि प्रभावी रूप से विभिन्न आकार के धातु के चादरों को दबाने में सक्षम है। वेल्डिंग के लिए गर्म मरने वाले स्टील (एच 13) से बनी एक बेलनाकार पेचदार पिन का उपयोग किया गया है।

प्रमुख एफएसडब्ल्यू प्रक्रिया मापदंडों को स्थापित करने के लिए कई प्रयोग परीक्षण किए गए। उपकरण पिन और कंधे का व्यास, उपकरण रोटेशन और वेल्डिंग की गति का चयन एफएसडब्ल्यू प्रक्रिया मापदंडों

के रूप में किया गया है और प्रयोग की प्रतिक्रिया सतह पद्धति (आरएसएम) के अनुसार किया गया है। प्रत्येक वेल्डेड नमूने के लिए यांत्रिक और धातुविक गुणों के टेस्ट जैसे की तन्यता, प्रभाव, फटीग और फ्रैक्चर परीक्षणों के साथ-साथ सूक्ष्म-संरचनात्मक परीक्षा के साथ वेल्ड गुणवत्ता का विश्लेषण किया गया है। प्रत्येक वेल्ड गुणों पर अलग-अलग प्रक्रिया मापदंडों के प्रभाव का विश्लेषण किया गया है।

यह भी पाया गया है कि बाहरी शीतलन एफएसडब्ल्यू द्वारा उत्पादित वेल्ड्स की गुणवत्ता को भी प्रभावित करती है। बाहरी शीतलन के प्रभाव को देखने के लिए प्राकृतिक वायु, जल और तरल नाइट्रोजन जैसे शीतलन माध्यमों का इस्तेमाल वेल्डिंग के लिए किया गया है और यांत्रिक और धातु संबंधी गुणों के आधार पर वेल्ड की जांच की गई है। अच्छे यांत्रिक गुणों की वजह से जल को एक उपयुक्त माध्यम पाया गया है।

सर्वश्रेष्ठ यांत्रिक गुण प्राप्त करने के लिए, उपयुक्त बाहरी शीतलन पर आधारित प्रक्रिया मापदंडों को अनुकूलित करना आवश्यक है। इसलिए एफएसडब्ल्यू प्रक्रिया मापदंडों का अनुकूलतम शीतलन माध्यम के लिए फिर से अनुकूलित किया गया है। इस प्रयोग में एफएसडब्ल्यू प्रक्रिया मापदंडों का इस्तेमाल तागुची एल 9 ऑर्थोगोनल सरणी के प्रयोग के एक अलग सेट के माध्यम से किया गया है। शीतलन माध्यमों में प्रक्रिया मापदंडों का प्रभाव वेल्ड गुणवत्ता विशेषताओं जैसे कि शक्ति, बढ़ाव, प्रभाव शक्ति, फटीग और फ्रैक्चर का विश्लेषण किया गया है।

परिणामों के विश्लेषण ने इन सभी एफएसडब्ल्यू मापदंडों और शीतलन माध्यमों के वेल्ड के यांत्रिक और धातुविक गुणों पर महत्वपूर्ण प्रभाव दिखाया है। एफएसडब्ल्यू प्रक्रिया मापदंडों ने वेल्डिंग के दौरान उत्पन्न वेल्डिंग बल, बिजली का सेवन और तापमान को भी प्रभावित किया है। धातुविक गुणों के परिछण के नतीजे ने गतिशील पुनर्रचना तंत्र के चलते अस्थिर क्षेत्र में काफी ग्रेन शोधन की घटना का पता चला है।

TABLE OF CONTENTS

Appendices

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

R	Shoulder radius
r	Pin radius
t	Pin height
S	Welding Speed
T	Total spindle torque
τ	Shear flow stress
T_s	Torque on shoulder
T_{ps}	Torque on the lateral surface of pin
P_t	Traverse power
T_{pb}	Torque at pin bottom
F_t	Traverse force
F_1	Flow force
F_2	Frictional force
S	Welding speed
N	Tool rotational speed
d	Pin Diameter
D	Shoulder Diameter
υ	Poisson's ratio
a	Original crack length
K_I	Stress Intensity Factor
v_p	Plastic component of COD
W	Width of sample
B	Thickness of sample
S	Spam of the sample
δ_p	Plastic part of CTOD
δ_e	Elastic Part of CTOD
δ_c	Total CTOD
σ_{ys}	Yield Strength of the material
Q_s	Heat generation
A_S	Shoulder contact area
q_v	Volumetric heat source
F_N, F_P	Normal and traverse forces
T	Torque
H	Sheet thickness
YS	Yield strength of Weld
μ	Friction coefficient
UTS	Ultimate tensile strength