

**SURFACE MODIFICATION ASSISTED DIFFUSION
BONDING OF PURE COPPER, AA6082 AND WIRE ARC
ADDITIVELY MANUFACTURED COMPONENTS**

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**DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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ADDITIVELY MANUFACTURED COMPONENTS**

by

DIPIN KUMAR R

DEPARTMENT OF MECHANICAL ENGINEERING

Submitted

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

to the



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Dedicated to
My Family & eternal Nidhi

Certificate

This is to certify that the thesis entitled, “**Surface modification assisted diffusion bonding of pure copper, AA6082 and wire arc additively manufactured components**” submitted by **Mr. Dipin Kumar R** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** in Mechanical Engineering is a bonafide record of original research work carried out by him under my supervision in the conformity with the rules and regulations of the Institute.

The results presented in this thesis have not been submitted, in part or full, to any University or Institute for the award of any degree or diploma.

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ABSTRACT

Diffusion bonding (DB) processes are usually performed in a vacuum furnace, which makes the process and equipment costly and leads to high cycle time. Attempts are made in this work to perform diffusion bonding in non-vacuum conditions, leading to reduced cycle time and improved productivity. The various surface modification techniques employed for the diffusion bonding of pure Cu, AA6082, dissimilar bonding of Al and Cu, wire arc additively manufactured (WAAM) Al alloy, and WAAM Mg alloy AZ31 are discussed.

Low-cost friction stir process (FSP) surface modification was proposed to achieve grain refinement of the faying surfaces and to facilitate the DB of Cu in the Ar environment. Grain growth of fine grains produced by FSP near the interface and grain boundary migration were observed to be the major mechanisms by which bonding has been achieved. Single point diamond turning (SPDT) of Cu has resulted in the generation of nano-level surface roughness, brought the bonding surfaces in close contact, and facilitated low-pressure bonding. The bonding ratio and shear strength were observed to increase with the rise in bonding temperature from 600°C to 800°C in accordance with the Arrhenius relationship.

Solid state diffusion bonding of Al alloys is challenging owing to the formation of a tenacious oxide layer that acts as a barrier for the diffusion of atoms and results in poor metallurgical joint. A novel liquid Ga treatment of the faying surfaces was employed to isolate the polished surface from ambient conditions and to prevent reoxidation, which has facilitated diffusion bonding of highly reactive Al alloys and Mg alloys in a non-vacuum furnace. The dispersion of Ga is limited only to the diffusion-reaction zone. The dispersion of Al at the interface is the same as that of the base metal (BM), indicating the effectiveness of surface treatment that has resulted in enhanced diffusion of Al across the interface in ambient conditions.

Direct bonding of AA6082 with Cu has resulted in the formation of deleterious intermetallic compounds (IMCs) and cracks are observed in the bonded region. DB with electrodeposited Ni interlayer has prevented the interdiffusion of Al and Cu atoms, and the formation of brittle IMCs is avoided. Thus, successful Al-Cu bond formation could be achieved.

The joining of additively manufactured (AM) components by solid-state joining is gaining significant research attention these days as the industry wants to produce large components through AM. It is significant to join/repair AM components without inducing fusion defects such as heat-affected zone (HAZ), porosity, cracking, warpage, etc. Diffusion bonding is a suitable joining process for a homogeneous joint microstructure that resembles the parent metal owing to the void closure and grain boundary (GB) growth across the contact. High-integrity diffusion bonded joint of WAAM Al-Si alloy and AZ31 is achieved in a non-vacuum furnace with a special interface treatment. The uniform elemental distribution at the interface, like the parent metal, emphasizes the enhanced interdiffusion of atoms across the joint line and the formation of a void-free joint.

Microwave hybrid heating (MWHH) was proposed as an energy-efficient and rapid post-process heat treatment (PPHT) method for the WAAM AZ31 Mg alloy. Non-uniform microstructure in the build direction, owing to the prevailing thermal history during the WAAM process, is a major drawback and leads to anisotropic mechanical properties. PPHT is generally employed to improve the mechanical properties of WAAM components. Homogeneous grain size distribution was achieved through MWHH post-processing, and uniform microhardness could be observed from the bottom to the top layer.

सारांश

डिफ्यूजन बॉन्डिंग (DB) प्रक्रिया आमतौर पर वैक्यूम फर्नेस में की जाती है, जिससे यह प्रक्रिया और उपकरण महंगे हो जाते हैं और चक्र समय (सायकल टाइम) अधिक हो जाता है। इस कार्य में डिफ्यूजन बॉन्डिंग को गैर-वैक्यूम परिस्थितियों में करने के प्रयास किए गए हैं, जिससे चक्र समय में कमी और उत्पादकता में सुधार प्राप्त हुआ है। इस अध्ययन में शुद्ध तांबा (Cu), एए6082 एल्यूमीनियम मिश्रधातु, एल्यूमीनियम और तांबे का विषम बॉन्डिंग, वायर आर्क एडिटिव मैनुफैक्चरिंग (WAAM) एल्यूमीनियम मिश्रधातु, और WAAM मैग्नीशियम मिश्रधातु AZ31 की डिफ्यूजन बॉन्डिंग के लिए विभिन्न सतह संशोधन तकनीकों पर चर्चा की गई है।

कम लागत वाली फ्रिक्शन स्टिर प्रोसेसिंग (FSP) सतह संशोधन तकनीक का प्रस्ताव किया गया है, जिससे संपर्क सतहों का ग्रेन रिफाइनमेंट किया जा सके और आर्गन वातावरण में तांबे की डिफ्यूजन बॉन्डिंग संभव हो सके। FSP से उत्पन्न महीन दानों की इंटरफेस के पास ग्रेन ग्रोथ और ग्रेन बाउंड्री माइग्रेशन जैसी क्रियाएं प्रमुख तंत्र के रूप में पाई गईं, जिनसे बॉन्डिंग सफल हुई। सिंगल पॉइंट डायमंड टर्निंग (SPDT) से तांबे की सतह पर नैनो-स्तरीय खुरदरापन प्राप्त हुआ, जिससे संपर्क सतहों को निकट लाया गया और कम दबाव में बॉन्डिंग संभव हो सकी। बॉन्डिंग तापमान 600°C से 800°C बढ़ाने पर बॉन्डिंग अनुपात और शीयर स्ट्रेंथ में वृद्धि देखी गई, जो आरहेनियस संबंध के अनुसार है।

एल्यूमीनियम मिश्रधातुओं की सॉलिड स्टेट डिफ्यूजन बॉन्डिंग एक चुनौतीपूर्ण प्रक्रिया है, क्योंकि सतह पर बनने वाली सख्त ऑक्साइड परत परमाणुओं के प्रसार में बाधा बनती है और इससे कमजोर धात्विक जोड़ बनता है। इस समस्या के समाधान के लिए फेथिंग सतहों पर एक नवीन तरल गैलियम (Ga) उपचार किया गया, जिससे पॉलिश की गई सतह को वातावरण से अलग किया जा सके और पुनः ऑक्सीकरण को रोका जा सके। इस तकनीक ने अत्यधिक प्रतिक्रियाशील एल्यूमीनियम मिश्रधातुओं और

मैग्नीशियम मिश्रधातुओं की डिफ्यूजन बॉन्डिंग को गैर-वैक्यूम फर्नेस में संभव बनाया है। गैलियम का प्रसार केवल डिफ्यूजन-रिएक्शन क्षेत्र तक सीमित पाया गया। इंटरफेस पर एल्यूमीनियम का प्रसार मूल धातु (BM) के समान पाया गया, जो सतह उपचार की प्रभावशीलता को दर्शाता है और यह इंगित करता है कि सामान्य वातावरण में भी एल्यूमीनियम का प्रसार इंटरफेस के पार बेहतर रूप से हुआ है।

AA6082 और Cu के प्रत्यक्ष बॉन्डिंग में हानिकारक इंटरमेटालिक यौगिक (IMCs) बने और बॉन्डेड क्षेत्र में दरारें देखी गईं। इलेक्ट्रोडिपोजिटेड निकेल (Ni) इंटरलेयर के साथ DB करने से एल्यूमीनियम और तांबे के बीच परस्पर प्रसार रोका गया और भंगुर IMCs बनने से बचा गया। इस प्रकार सफल Al-Cu बॉन्डिंग संभव हुई।

एडिटिव मैनुफैक्चरिंग (AM) से बने घटकों को सॉलिड-स्टेट जॉइनिंग से जोड़ना हाल के समय में अनुसंधान का प्रमुख क्षेत्र बन गया है, क्योंकि उद्योग बड़े घटकों को AM से बनाना चाहता है। इन AM घटकों को बिना फ्यूजन दोष जैसे कि HAZ, पोरोसिटी, क्रैकिंग, वॉर्पेज आदि के जोड़ा या मरम्मत किया जाना चाहिए। डिफ्यूजन बॉन्डिंग एक उपयुक्त प्रक्रिया है जिससे संपर्क पर वॉयड क्लोजर और ग्रेन बाउंड्री ग्रोथ के कारण पेरेंट मेटल जैसी समरूप माइक्रोस्ट्रक्चर प्राप्त होती है। विशेष इंटरफेस उपचार के साथ WAAM Al-Si मिश्रधातु और AZ31 का उच्च गुणवत्ता वाला बॉन्ड गैर-वैक्यूम फर्नेस में प्राप्त किया गया। इंटरफेस पर तत्वों का समान वितरण मूल धातु जैसा ही था, जो दर्शाता है कि परमाणुओं का इंटरडिफ्यूजन बढ़ा और वॉयड-रहित जॉइंट बना।

माइक्रोवेव हाइब्रिड हीटिंग (MWHH) को WAAM AZ31 Mg मिश्रधातु के लिए एक ऊर्जा-कुशल और तेज पोस्ट-प्रोसेस हीट ट्रीटमेंट (PPHT) के रूप में प्रस्तावित किया गया है। WAAM प्रक्रिया के दौरान उत्पन्न थर्मल हिस्ट्री के कारण बिल्ड दिशा में माइक्रोस्ट्रक्चर असमान होता है, जिससे यांत्रिक गुणों में असमानता आती है। PPHT का उपयोग इन गुणों में सुधार के लिए किया जाता है। MWHH

पोस्ट-प्रोसेसिंग से समान ग्रेन साइज वितरण प्राप्त हुआ और नीचे से ऊपर तक परतों में समान माइक्रोहार्डनेस देखी गई।

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ABBREVIATIONS

AA	Aluminium alloy
AM	Additive manufacturing
BL	Bond line
BM	Base metal
CG	Coarse grains
CMP	Chemical mechanical polishing
CMT	Cold metal transfer
CNC	Computer numerical control
CTWD	Contact tube to work distance
DB	Diffusion bonding
DDRX	Discontinuous dynamic recrystallization
DED	Directed Energy Deposition
DIR	Diffusion induced recrystallization
DRX	Dynamic recrystallization
DTM	Diamond turning machine
EBSD	Electron backscatter diffraction
EDM	Electric discharge machining
EDS	Energy Dispersive X – Ray Spectroscopy
EPMA	Electron probe microanalyzer
ETP	Electrolytic tough pitch
FCC	Face Centred Cubic
FESEM	Field emission scanning electron microscopy
FG	Fine grain
FSP	Friction stir processing
FSW	Friction stir welding
GB	Grain boundary
HAE	Heat accumulation effect

HAGBs	High-angle grain boundaries
HAZ	Heat affected zone
HCP	Hexagonal close packed
HIP	Hot isostatic pressing
HRTEM	High-resolution transmission electron microscope
IGB	Interfacial grain boundary
IMCs	Intermetallic compounds
IPF	Inverse pole figure
LAGBs	Low-angle grain boundaries
LAM	Local average misorientation
LBR	Linearized bond ratio
MMC	Metal matrix composite
MPD	Melting point depressant
MWHH	Microwave hybrid heating
NG	Nano grain
NPs	Nanoparticles
OM	Optical microscopy
PBF	Powder bed fusion
PBHT	Post-bond heat treatment
PCHE	Printed Circuit Heat Exchanger
PPHT	Post-process heat treatment
PVD	Physical vapour deposition
RF	Radiofrequency
RX	Recrystallized
SCFH	Standard cubic feet per hour
SG	Submicron grains
SiC	Silicon carbide
SLM	Selective laser melting
SN	Surface nanocrystallization

SPD	Severe plastic deformation
SPDT	Single point diamond turning
SPF	Superplastic forming
SPS	Spark plasma sintering
SSDB	Solid state diffusion bonding
SSW	Solid state welding
TJs	Triple junctions
TLP	Transient liquid phase
TR	Recrystallization temperature
UTM	Universal testing machine
UTS	Ultimate tensile strength
UW	Ultrasonic welding
WAAM	Wire arc additive manufacturing
WDS	Wavelength-dispersive spectrometry
XPS	X-ray photoelectron spectroscopy
XRD	X-Ray Diffraction