

EXPERIMENTAL INVESTIGATION OF AZ31B MAGNESIUM ALLOY WELDMENTS FOR AUTOMOTIVE APPLICATIONS

Submitted in partial fulfillment of the requirements for the award of
**Bachelor of Engineering Degree in
Mechanical Engineering**

By

SAHAS S (39150113)

MURALIDHARAN S (39150088)



**DEPARTMENT OF MECHANICAL ENGINEERING
SCHOOL OF MECHANICAL ENGINEERING**

SATHYABAMA

**INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)**

**Accredited with Grade "A" by NAAC | 12B Status by UGC | Approved by AICTE
JEPPIAAR NAGAR, RAJIV GANDHI SALAI, CHENNAI - 600 119**

APRIL - 2023



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Jeppiaar Nagar, Rajiv Gandhi Salai, Chennai – 600 119
www.sathyabama.ac.in

DEPARTMENT OF MECHANICAL ENGINEERING

BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work of **SAHAS S (39150113)** and **MURALIDHARAN S (39150088)** who carried out the project entitled "**EXPERIMENTAL INVESTIGATION OF AZ31B MAGNESIUM ALLOY WELDMENTS FOR AUTOMOTIVE APPLICATIONS**" under our supervision from December 2022 to April 2023

Internal guide

Dr. V. K. BUPESH RAJA

Head of the Department

Dr. G. ARUN KUMAR

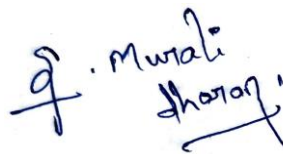
Submitted for Viva voce Examination held on **10-05-2023**

Internal Examiner

External Examiner

DECLARATION

I **SAHAS S** hereby declare that the Project Report entitled “**EXPERIMENTAL INVESTIGATION OF AZ31B MAGNESIUM ALLOY WELDMENTS FOR AUTOMOTIVE APPLICATIONS**” done by me under the guidance of **Dr. V.K. BUPESH RAJA** at SATHYABAMA INSTITUTE OF SCIENCE AND TECHNOLOGY, CHENNAI-600119 is submitted in partial fulfillment of the requirements for the award of Bachelor of Engineering degree SATHYABAMA INSTITUTE OF SCIENCE AND TECHNOLOGY.



DATE:10-05-2023

PLACE: CHENNAI

SIGNATURE OF THE CANDIDATE

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ABSTRACT

AZ31B is a magnesium alloy with desirable properties like ductility combined with corrosion resistance and weldability. Magnesium is 35% lighter than aluminium, so lighter weight results in an increased power-to-weight ratio. Magnesium alloy becomes stronger than aluminium alloy after heat treatment. However, due to a low melting temperature, magnesium has relatively poor mechanical properties at intense heat, making it unsuitable for automotive applications. In this project, 2mm thick sheets of AZ31B alloy were butt welded using the laser beam welding technique (LBW). LBW being a high-intensity heat, fusion welding technique is prone to thermal stress, cracking and loss of properties hence the weldments were subjected to post-weld heat treatment in order to improve the properties of the weldment. This project investigates the mechanical and metallurgical properties of the weldments before and after the aging process. The LBW weldments were subjected to mechanical tests such as tensile strength, impact strength and microhardness; and characterizations such as scanning electron microscopy, Electron dispersive microscopy, X-ray diffraction spectroscopy and Transmission electron microscopy.

Keywords: AZ31B, LBW, Aging PWHT, mechanical properties and characterization

TABLE OF CONTENTS

CHAPTER NO.	TITLE	PAGE NO.
	ABSTRACT	v
	LIST OF FIGURES	ix
	LIST OF TABLES	x
		xii
	LIST OF ABBEREVIATIONS	
1	INTRODUCTION	1
	1.1 MAGNESIUM AND ITS ALLOYS	1
	1.2 AZ31B	1
	1.3 TYPES OF WELDING TECHNIQUES	2
	1.4 LASER BEAM WELDING OF AZ31B	2
	1.5 POST-WELD HEAT TREATMENTS OF AZ31B	2
2	LITERATURE SURVEY	5
3	AIM AND SCOPE	7
	3.1 AIM	7
	3.2 SCOPE OF THE WORK	7
4	EXPERIMENTAL METHODS	8
	4.1 PARAMETERS IDENTIFICATION	8
	4.2 PARAMETERS LIMITS IDENTIFICATION	8
	4.3 LASER BEAM WELDING	8
	4.4 ANNEALING	10
	4.4.1 Tool	10
	4.4.2 Experimental Procedure	11
	4.4.3 Test Specimens	12
	4.5 ELECTRIC DISCHARGE MACHINING	12
	4.5.1 Tool	12

CHAPTER NO.	TITLE	PAGE NO.
	4.5.2 Experimental Procedure	13
	4.5.3 Test specimens	14
4.6	TENSILE TESTING	14
	4.6.1 Testing Machine	15
	4.6.2 Experimental Procedure	16
	4.6.3 Test Specimens	16
4.7	IMPACT TESTING	17
	4.7.1 Testing Machine	17
	4.7.2 Experimental Procedure	18
	4.7.3 Test specimen	18
4.8	MICROHARDNESS SURVEY	19
	4.8.1 Testing Machine	19
	4.8.2 Experimental Procedure	20
4.9	X-RAY DIFFRACTION SPECTROSCOPY	20
	4.9.1 X-ray Diffraction Spectroscopy	21
	4.9.2 Experimental Procedure	21
4.10	FRACTOGRAPHY	22
	4.10.1 Experimental Procedure	22
	4.10.2 Test Specimens	23
4.11	TRANSMISSION ELECTRON MICROSCOPY	23
	4.11.1 Transmission Electron Microscope	23
	4.12.2 Experimental Procedure	24
5	RESULTS, ANALYSIS AND DISCUSSION	26
	5.1 LASER BEAM WELDING	26
	5.2 ANNEALING	26
	5.3 ELECTRIC DISCHARGE MACHINING	27
	5.4 TENSILE TESTING	27
	5.5 IMPACT TESTING	30
	5.6 MICROHARDNESS SURVEY	32
	5.7 X-RAY DIFFRACTION SPECTROSCOPY	34

CHAPTER NO.	TITLE	PAGE NO.
	5.8 FRACTOGRAPHY	36
	5.9 TRANSMISSION ELECTRON MICROSCOPE	38
6	CONCLUSION	41
	REFERENCES	42

LIST OF TABLES

TABLE NO	TITLE	PAGE NO
4.1	(a) Chemical Combinations (wt%) of AZ31B MG Alloy	9
4.2	Tool Specifications	11
4.3	Tool Specifications	13
4.4	Machine Specifications	15
4.5	Machine Specifications	18
4.6	Machine Specifications	19
4.7	XRD specification	21
4.8	TEM specification	24
5.1	Tensile Test Results	27
5.2	Joint Efficiency	28
5.3	Impact Test Results	30
5.4	Microhardness Test Results	32

LIST OF FIGURES

FIGURE NO	TITLE	PAGE NO
4.1	Dimensions of welding specimen	9
4.2	Welding specimen dimension	9
4.3	Welding joints	10
4.4	Muffle furnace	10
4.5	Before heat treatment	12
4.6	After heat treatment	12
4.7	Electric discharge machine	12
4.8	Before machining	14
4.9	After machining	14
4.10	Universal testing machining	15
4.11	Before testing	16
4.12	After testing	17
4.13	Charpy impact test setup	17
4.14	Before testing	18
4.15	After testing	19
4.16	Vicker's microhardness tester	19
4.17	X-ray Diffractometer	21
4.18	Test specimens	23
4.19	Transmission Electron Microscope	23
5.1	Stress strain graph of parent metal	28
5.2	Stress strain graph of as welded alloy	28
5.3	Stress-strain graph of post-weld heat-treated alloy	29
5.4	Load-Displacement graph of AW and PWHT	29
5.5	Impact Test results on bar graph	31
5.6	Microhardness survey	33
5.7	XRD of As Welded AZ31B	34
5.8	XRD of Post-Weld Heat-Treated AZ31B	35
5.9	SEM image of fractured As welded AZ31B	36

FIGURE NO	TITLE	PAGE NO
5.10	SEM image of fractured Post-Weld Heat-Treated AZ31B	37
5.11	TEM image of As Welded AZ31B	38
5.12	TEM image of Post-Weld Heat-Treated AZ31B	39

LIST OF ABBREVIATIONS

AS	-	As Welded
FSW	-	Friction Stir Welding
FZ	-	Fusion Zone
GMAW	-	Gas Metal Arc Welding
GTAW	-	Gas Tungsten Arc Welding
HAZ	-	Heat Affected Zone
LBW	-	Laser Beam Welding
PT	-	Parent Metal
PWHT	-	Post Weld Heat Treated

CHAPTER 1

INTRODUCTION

MAGNESIUM AND ITS ALLOYS

Magnesium is an alkaline earth metal with an atomic weight of 24.305 amu and is the lightest of the structural metals. It has a relatively low specific gravity of 1.74 g/cm³ and a low elastic modulus (42 GPa). Magnesium properties such as thermal and electrical conductivity and its melting point are very similar to that of aluminium, making it a lightweight alternative to aluminium. However, because the pure metal lacks some properties, such as tensile strength and hardness, magnesium is mainly used in the form of alloys. Magnesium is often mixed with aluminium, zirconium, zinc, manganese and rare earth metals. Aluminium enhances ductility and facilitates casting; Zinc improves strength at room temperature; manganese improves the corrosion resistance to saltwater; zirconium refines grains in the alloy, and rare earth metals increase the creep resistance and also reduce weld cracking and porosity. However, due to a low melting temperature, magnesium has relatively poor mechanical properties at intense heat which makes it not suitable for the engine body and its components (Kulekci, 2008). ZE, AM, and AZ are significant series of magnesium alloys, and A, E, M, and Z represent the main constituents of magnesium alloys, namely aluminum, earth metals, manganese, and zirconium, respectively.

AZ31B

AZ magnesium alloy series are widely used in the electronic industry to produce laptop and mobile phone cases.

AZ31B also possesses some desirable properties like weldability, castability and machinability (Yan et al., 2017a). Magnesium alloy is one of the most

popular non-ferrous materials for casting. The mechanical and metallurgical properties of alloys vary with their chemical composition. Adding different alloying elements gives different properties under different conditions

TYPES OF WELDING TECHNIQUES

Different types of welding techniques are used for welding magnesium alloys such as Friction Stir Welding (FSW) and Laser Beam Welding (LBW) are extensively used welding techniques for magnesium alloy. The advantage of FSW technology is the ability to control heat generation, low distortion, excellent metallurgical properties and response time (Bayazid et al., 2018; Dorbane et al., 2016).

LASER BEAM WELDING OF AZ31B

LBW appears to be the preferred technique for welding magnesium alloys due to its low heat input, high accuracy, high welding speed and small heat-affected zone (Commin et al., 2011). Joint strength is weakened in fusion welding techniques such as LBW because of dendritic structure formation in the fusion zone (George et al., 2020). When welding magnesium alloy, uneven heating and cooling cause HAZ to have residual stress, become harder, and make the weld joint susceptible to cold cracking (Kumar Srivastava & Prakash, 2010). Post-weld heat treatment enables us to triumph over those problems.

POST-WELD HEAT TREATMENTS OF AZ31B

PWHT is a heat treatment process for weldments after welding to achieve the desired characteristics. The process of relieving residual stress with the help of PWHT is known as stress relieving. Annealing is a heat treatment process that consists of three main stages; Recovery, Recrystallization, and Grain growth. The recovery stage of the annealing process alters the microstructures of a material which helps to achieve stress relief in the weldment. In the recrystallization process, the material is heated above the recrystallization temperature, but below the melting temperature, as a result, new grains are formed without existing stress. New grains fully develop in the grain growth stage. The grain growth rate can be manipulated

by changing the cooling rate. This results in enhanced microhardness and tensile strength (KUMAR & KUMAR, 2021). The alteration in microstructure also results in a change in mechanical properties such as ductility and hardness. Aging is a heat treatment process in which a material's temperature is maintained high for a very long time period. During the aging process, supersaturated alloying elements within the metal alloy form so-called metallic precipitates. These precipitates are responsible for dislocations in a block of metal, and an increase in the strength and hardness of the material. The Aging results in a high yield point and light profile for a high load capacity, high brittle fracture resistance, low transition temperature and high degree of weldability (Mujahid et al., n.d.). Aging PWHT is also used to increase hardness by precipitation method. Quenching is a heat treatment process in which the material is heated above the recrystallization temperature and rapidly cooled down which stops the grain growth. During the quenching process, hot parts are cooled to room temperature immediately by immersion, spraying or pouring liquid. Liquids such as water, oils and aqueous polymer solutions can be quenching mediums. Changes in material properties depend only on the cooling rate (Mackerle, 2003). Quenching PWHT yields high tensile strength and ductility. The optimal subsequent aging PWHT on laser welded Al-Cu-Mg (Al₂CuMg) caused a little effect on mechanical strength, but amplified yield strength by 20 MPa (Malikov et al., 2021). The subsequent artificial aging heat treatment on WE43 Mg alloy resulted in enhanced strength and elongation under tension with significantly improved alloy fatigue life (Ghorbanpour et al., 2019). Aging heat treatment on AZ80 magnesium alloy was found to be much more efficient in reducing tension-compression yield asymmetry than solution treatment of extruded AZ80-Mg alloy (Lv et al., 2012). The annealing PWHT (300 °C – 1 hour) on stir welded AZ31 Mg alloy was found to be more beneficial than other heat treatments in relieving the compressive transverse and longitudinal stress and improving mechanical properties such as yield and tensile strength and microstructure properties such as homogenizing grain size and improved fatigue life (G. Wang et al., 2017). The annealing heat treatment on (180 s at 400 °C) Al-Si-Mg alloys results in rapid growth at the expense of small grain, after annealing at 400 °C for 1800 s, a transition from the main texture component to the <11 $\bar{2}$ 0> component occurs (Hitzler et al., 2020). The effects of annealing PWHT on hybrid laser arc welded AA5754 Mg alloy are improved mechanical strength by reduction of the segregation and significantly enhanced microhardness.

(Leo et al., 2016). The quenching heat treatment on extruded ZK60 magnesium alloy leads to undesirable effects such as developed compressive and tensile residual stresses at the surface and center (C. Wang et al., 2018). The effects of quenching heat-treated Al-Si-Mg alloys are reduced corrosion resistance, no significant change in tensile strength but improved elongation which is caused by the change in grain boundary precipitates.(Hitzler et al., 2020)

CHAPTER 2

LITERATURE SURVEY

Balasubramanian V, Padmanaban G, Sarin sundar et al (2010): The AZ31B Alloy materials are more beneficial when compared to the conventional materials of (iron, steel etc.) because of their light weight, good fatigue performance and increased life of the materials. All industries are researching for the betterment for them the best alternative is the material. It is highly used in the area of automobile body parts, marine application and civil structures etc. In this paper we are investigated AZ31B Mg Alloy material are used for light weight and Marine applications.

Cotler C, Munitz A, Stern A, Kohn G et al (2001): Mechanical properties and microstructure of GTAW magnesium AZ91D plates. The alloy materials is studied with help of weld joints. The grain structure of the material joint heat zone and fusion zone is investigated to check the mechanical properties and corrosion act on the joints. Weld quality of the joints is fully inspected before that weld bead plate is tested to get the fine grain structure to obtain strong mechanical properties. Study also states that when the laser power increased too high which causes the microstructure grain as coarse. Mechanical properties have improved using the LBW of surface hardness thus caused the black color coating in the surface.

Niemeyer M, H Haferkamp, Diltthey U, Trager G et al (2000): LBW and EBW of magnesium. In this study the Laser beam welding was activities were observed and recorded for the future use. When the laser touches the specimen surfaces and other important parameters are recorded. Welding flaws on the magnesium material was analysed clearly in this journal. Before welding multiple trails has been implements as RSM and constrained the variables to many changes and build the matrix design for the purpose of the optimization of parameters

Bach Fr-W, Haferkamp H, Burmester I, Kreutzburg K, Niemeyer M et al (2010): LBW of magnesium creations were clearly understood and recorded he welded butt joints and tried to get the maximum out of the good visible looking inspection method in the welded area. He used Laser CO₂ type laser beam welding and used argon of 20 L/min to avoid any oxidation-based problem in the weld. The bead on plate is tested and used for the penetration check by cutting the fusion zone. Then mould is prepared for the checking of the microstructure of the fusion and heat affected zone.

Li Lin, Zhu Jinhong, Liu Zhu et al (2005): CO₂ and diode laser welding (LW) of AZ31 Mg alloy studied about the difference between the most popular and available type of laser welding technology. Investigation has been carried out between the CO₂ and diode laser welding and address their limitation in welding. Using the available resources and welding strength has been improved by the change in parameters and correlation of the parameters are created to find the betterment of the welding in AZ31 magnesium alloy.

CHAPTER 3

AIM AND SCOPE

AIM

The aim of the project is to investigate the effect of post-weld heat treatment (PWHT) on the mechanical and metallurgical properties of AZ31B magnesium alloy weldments. The project will focus on the changes in microstructure, hardness, and tensile strength of the weldments before and after PWHT.

SCOPE OF THE WORK

Conducting a literature review on AZ31B magnesium alloy weldments and the effects of PWHT on their mechanical and metallurgical properties, with a specific focus on laser beam welding. Developing a welding procedure for AZ31B magnesium alloy using laser beam welding process.

To determine the suitable post-weld heat treatment process for the alloy magnesium AZ31B in order to make the alloy suitable for automotive application.

Performing microstructural analysis using optical microscopy and Scanning Electron Microscopy (SEM) to investigate the microstructure of the weldments before and after PWHT.

Conducting hardness tests on the weldments before and after PWHT to evaluate the changes in hardness. Analyzing the results and drawing conclusions on the effect of PWHT on the hardness of AZ31B magnesium alloy weldments produced by laser beam welding.

CHAPTER 4

EXPERIMENTAL METHODS

PARAMETERS IDENTIFICATION

Review of the literature, factors which have a substantial impact upon that tensile strength for laser beam welded joints been discovered. [10–13] and bit complicated. Overall focus position, laser power, and welding speed were its three variables.

PARAMETERS LIMITS IDENTIFICATION

Multiple trial run has been executed the using AZ31B Mg alloy 2 mm sheet to decide the possible operating boundaries of LBW parameters. Various parameters of LBW had been trailed. The weld trial, weld infiltration and excellent had been examined to discover operating welding's restrictions variables, main thus subsequent findings:

- (i) When any laser's output power was below 1.5 KW, seemed to be a dearth of fusion & partial infiltration. When the laser power is larger than 2 KW, poor weld quality.
- (ii) When any welding speed was below 10 mm/sec, poor weld. When any welding speed was above 15 mm/sec, poor weld.
- (iii) When any focal position is above the weld bead plate, Weld spatters.

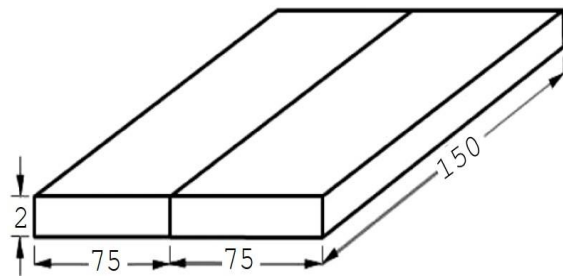
LASER BEAM WELDING

Sheets of 2 mm thick, AZ31B Mg alloy were made required dimension (L = 150 mm, B = 150 mm, T = 2 mm). The mechanical properties and chemical

combination of the specimen (AZ31B Mg alloy). Fig. 4.1 shows the fabricated joints used in the investigation. Produced CO₂ laser LBW joints (Rofin Slab: Laser CO₂). Mechanical clamps are used to position, and the joint primary was acquired by plates attaching. The rolling direction occurred usually to the welding path. Used single-pass welding. Argon pure-16 L/min was shielding gas.

Table 4.1 Chemical Combinations (wt%) of AZ31B MG Alloy

Al	Mn	Zn	Mg
2.7	0.19	0.9	Bal



All dimensions are in mm

Fig. 4.1: Dimensions of welding specimen

The welded joints were machined ASTM E8M-04 is a standard. (50 mm gauge length). Fig. 4.2 shows the tensile specimen dimensions. Specimens are ready to evaluate the tensile strength.

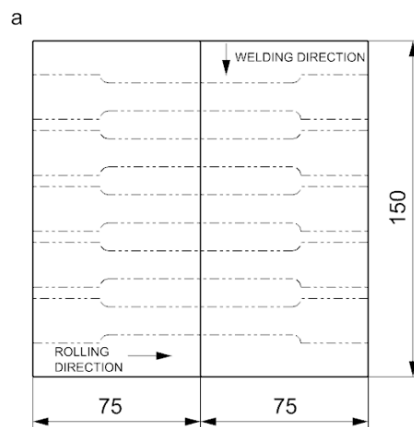


Fig. 4.2: Welding specimen dimension



Fig. 4.3: Welding joints

ANNEALING

Annealing is a heat treatment process used to improve the mechanical properties of a material by reducing its internal stresses, increasing its ductility, and refining its microstructure. The annealing heat treatment process performed at 300 degrees Celsius for one hour.

Tool



Fig. 4.4: Muffle furnace

Table 4.2: Tool specification

Furnace	Muffle furnace
Range	1-1100 ^{0c}
Temperature Control	RTT
K-type	Thermo couple
Control	Thermistor controlled

Experimental Procedure

1. Sample preparation: Magnesium alloy AZ31B was obtained in the form of a rectangular plate.
2. Annealing: The samples were annealed in a furnace at 300°C for one hour. The furnace was preheated to the desired temperature before the samples were placed inside.
3. Holding time: The specimen was held at the annealing temperature for one hour to ensure complete transformation.
4. Cooling: The specimen was cooled slowly to room temperature in the furnace to avoid sudden temperature changes that could affect the microstructure.
5. Post-treatment evaluation: The specimen was evaluated using various tests, such as hardness testing, microstructure analysis, and mechanical testing.

Test Specimens



Fig. 4.5: Before heat treatment



Fig.4.6: After heat treatment

ELECTRIC DISCHARGE MACHINING

Electrical discharge machining (EDM) is a process that uses electrical discharges to remove material from a workpiece. The EDM process was performed on a magnesium alloy AZ31B to create test specimens for mechanical testing.

Tool

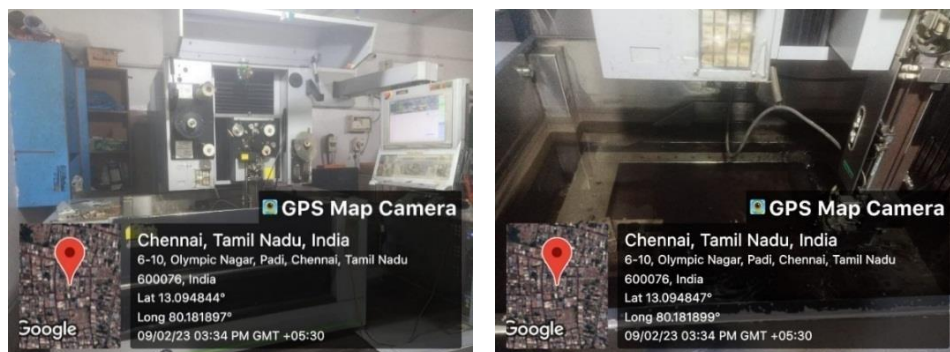


Fig. 4.7: Electric Discharge Machine

Table 4.3: Tool specifications

Name	Sodick VL400Q
X-Axis Travel	400 mm
Y-Axis Travel	300 mm
Z-Axis Travel	220 mm
U, V-Axis Travel	80 x 80 mm
Wire Diameter Range (min - max)	0.10 - 0.30 mm
Tank Inner Dimensions W x D	860 x 690 mm
Maximum Workpiece Weight	500 kg
Length from Floor to Table Top	900 mm
Machine Dimensions W x D x H	2,020 x 2,310 x 1,990 mm
Machine Weight	2,700 kg

Experimental Procedure

1. Material selection: A magnesium alloy AZ31B was selected for the EDM process.
2. Workpiece preparation: The material was cut or machined to a specific size and shape to form a workpiece suitable for the mechanical test.
3. Electrode preparation: The electrode was made of a conductive material, such as copper or graphite, and shaped to the desired geometry.
4. Set up: The workpiece and the electrode were set up in the EDM machine.
5. EDM parameters: The EDM parameters, such as voltage, current, and pulse duration, were adjusted to optimize the machining process.

6. Machining: The EDM machine was started, and the electrode was moved towards the workpiece to initiate the electrical discharge. The electrical discharge created a spark that removed material from the workpiece, creating the desired test specimen shape.

Test specimens



Fig. 4.8: Before Machining

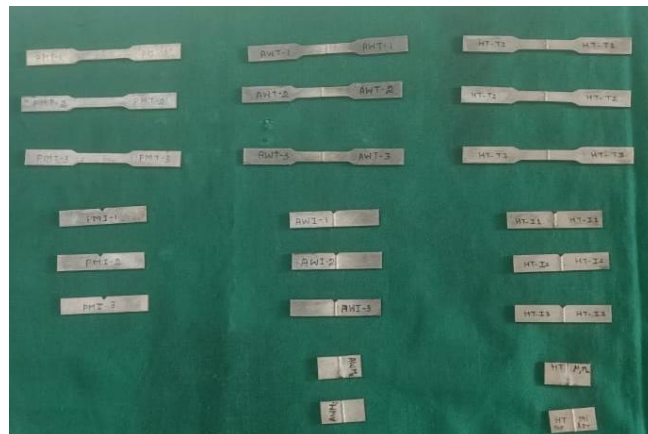


Fig. 4.9: After Machining

TENSILE TESTING

A tensile test, also known as a tension test, is a common mechanical test that measures the response of a material to a gradually applied axial load. This test is widely used in the industry to determine the tensile strength, yield strength, and elongation properties of a wide range of materials, including metals, plastics, composites, and ceramics.

Testing Machine



Fig. 4.10: Universal testing machine

Table 4.4: Machine Specifications

Name	Universal testing machine
Tensile load range	0.1 N - 50 KN
Load cell accuracy	0.01 Kg
Load cell gasket speed	0.01 – 500 mm/min
Control	Servo controlled with ball screw
Make	Made in india

Experimental Procedure

1. Specimen preparation: A rectangular-shaped specimen was prepared from the material under test according to the ASTM standard.
2. Mounting of the specimen: The specimen was mounted on the grips of the tensile testing machine, ensuring that it was properly aligned and centered.
3. Pre-loading of the specimen: A small load was applied to the specimen to ensure that it was properly secured in the grips.
4. Application of the tensile load: A gradually increasing load was applied to the specimen until it reached its maximum load-carrying capacity or fractured.
5. Data collection: During the test, the load and displacement were measured using load cells and displacement transducers, respectively.
6. Data analysis: The obtained data was analyzed to determine the tensile strength, yield strength, and elongation properties of the material under test.

Test Specimens



Fig. 4.11: Before testing



Fig. 4.12: After testing

IMPACT TESTING

The Charpy impact test is a standardized test used to measure the toughness of a material, which is its ability to absorb energy in the presence of a crack or notch. The test is widely used in the industry to determine the impact strength of materials such as metals, plastics, composites, and ceramics.

Testing Machine



Fig. 4.13: Charpy impact test setup

Table 4.5: Machine specifications

Impact test	Charpy impact test
Dead weight	10 Kg
Accuracy	0.01 Kgm
Angle inclination	270°
Arm length	250 mm

Experimental Procedure

1. Specimen preparation: A rectangular-shaped specimen with a notch was prepared from the material under test according to the ASTM standard.
2. Mounting of the specimen: The specimen was mounted on the support anvils of the Charpy impact testing machine, ensuring that it was properly aligned and centered.
3. Release of the pendulum: A pendulum with a known weight was released from a certain height to strike the specimen, causing it to break.
4. Data collection: During the test, the energy absorbed by the specimen was measured by recording the difference in the height of the pendulum before and after the impact.
5. Data analysis: The obtained data was analyzed to determine the impact strength of the material under test.

Test specimen



Fig. 4.14: Before testing



Fig. 4.15: After testing

MICROHARDNESS SURVEY

Microhardness survey is a commonly used technique to determine the hardness of small and/or thin materials that cannot be tested using conventional hardness testing methods. This test is widely used in the industry to evaluate the mechanical properties of materials such as metals, ceramics, and composites.

Testing Machine



Fig. 4.16: Vicker's microhardness tester

Table 4.6: Machine specifications

Microhardness	Vicker's microhardness
Load	1g – Kg
Least count	0.001 micrometer
Scales	HV, HRC, HRB
Make	China

Experimental Procedure

1. Specimen preparation: A small sample of the material under test was cut and polished to a smooth surface.
2. Mounting of the specimen: The sample was mounted on a microscope stage, ensuring that it was properly aligned and centered.
3. Application of the load: A small load was applied to the specimen using a diamond indenter, creating an indentation on the material's surface.
4. Measurement of the indentation: The indentation was measured using an optical microscope to obtain the diameter or diagonal length of the impression.
5. Calculation of the hardness: The hardness of the material was calculated using the load and the size of the indentation.
6. Data collection: The procedure was repeated at various locations on the sample surface to obtain a microhardness map of the material.

X-RAY DIFFRACTION SPECTROSCOPY

X-ray diffraction (XRD) is a common technique used to study the crystal structure and composition of materials. In the case of welded AZ31B magnesium samples, XRD can be used to investigate the microstructural changes that occur as a result of the welding process.

X-ray Diffraction Spectroscopy



Fig. 4.17: X-ray Diffractometer

Table 4.7: XRD specification

Scanning range	0°-120°
Goniometer type	Fixed goniometer system
Detector	Curved position-sensitive X-ray detector, CPS120
X-ray tube	Cu K α 1 radiation
Sample holders	Fixed (No realignment)

Experimental Procedure

1. Preparation of the samples: The samples must be prepared by cutting and polishing the welded area to remove any surface defects and ensure a smooth surface. The samples should be carefully handled to prevent any damage to the welded area.
2. Mounting the sample: The sample is mounted onto a sample holder, which can be made of various materials such as glass or quartz. The sample must be securely fastened to the holder to prevent any movement during the experiment.

3. X-ray source and detector setup: The X-ray source is positioned so that the X-rays are directed onto the sample surface. The detector is positioned at a specific angle relative to the source to capture the diffraction pattern produced by the sample.
4. Data collection: The X-ray beam is directed onto the sample and the detector records the diffraction pattern produced by the sample. The diffraction pattern is then analyzed to determine the crystal structure and composition of the sample.
5. Data analysis: The diffraction pattern is analyzed using software to identify the peaks and calculate the lattice parameters of the sample. The results can be compared to known crystal structures and compositions to determine the microstructural changes that occur as a result of the welding process

FRACTOGRAPHY

Fractography is a technique used to analyze the fracture surfaces of materials to understand the failure mechanism and the underlying reasons for the failure. The fractography of a magnesium alloy AZ31B to understand the failure mechanism and the factors that contributed to the failure.

Experimental Procedure

1. Sample preparation: The magnesium alloy AZ31B was selected, and samples were prepared according to ASTM E1823-16 standard.
2. Mechanical testing: The samples were subjected to mechanical testing, such as tensile testing, to induce fracture
3. Fracture surface analysis: The fractured samples were analyzed using a scanning electron microscope (SEM) to study the fracture surface.

4. Microstructure analysis: The microstructure of the material was analyzed using optical microscopy or SEM to understand the microstructural features and their role in the failure.

Test Specimens

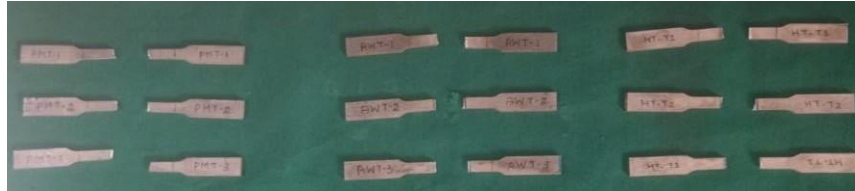


Fig. 4.18: Test specimens

TRANSMISSION ELECTRON MICROSCOPY

The transmission electron microscopy (TEM) analysis of materials requires the preparation of thin foils with a thickness of approximately 100 nm. In the case of AZ31B magnesium alloy, the preparation of thin foils can be challenging due to its high reactivity and low ductility. Therefore, the sample preparation process requires careful attention to detail to avoid damage to the material.

Transmission Electron Microscope

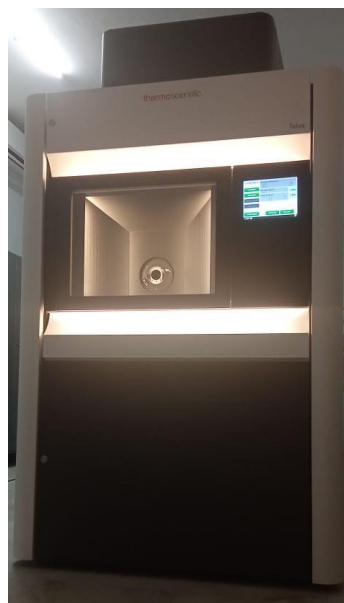


Fig.4.19: Transmission Electron Microscope

Table 4.8: TEM specification

HR STEM	TALOS F200S G2
Size, shape	TEM image
Crystal structure	Diffraction pattern
Interface studies	High-resolution TEM
Z(Atomic No) contrast	Scanning TEM
Chemical information	XEDS

Experimental Procedure

1. Sample cutting: AZ31B magnesium alloy was cut into small pieces with a thickness of approximately 1 mm using a low-speed diamond saw. The cut surfaces were then polished using 600-grit SiC paper to remove any visible scratches or deformation.
2. Mechanical polishing: The polished samples were then mechanically polished using a series of diamond paste with decreasing particle sizes (9, 6, 3, 1, and 0.25 μm) to obtain a mirror-like finish. The polishing process was performed on a rotating wheel with a cloth pad until a smooth, flat surface was achieved.
3. Electropolishing: To further reduce the thickness of the samples, electropolishing was performed using a solution of 10% perchloric acid in ethanol. The sample was first placed in the electropolishing solution, and a voltage of 15V was applied for 10-20 seconds while the sample was agitated. This process was repeated until a thin foil was obtained.
4. Ion milling: The final step in the sample preparation process was ion milling. This process was used to remove any remaining surface damage and to achieve a final thickness of approximately 100 nm. The sample was mounted on a sample holder and placed in an ion

milling system, and a low-energy argon ion beam was used to sputter away material from the surface.

5. TEM grid placement: the thin foils were removed from the sample holder using a pair of fine-tipped tweezers and placed onto a TEM grid. The samples were then ready for TEM analysis.

CHAPTER 5

RESULTS, ANALYSIS AND DISCUSSION

LASER BEAM WELDING

In order to achieve high productivity, quality, and cost-effectiveness in welding magnesium joints, it is essential to develop a welding process that is predictable, repeatable, consistent, and reliable. Industrial applications would benefit from wider welding operating windows. In the future, laser welding is expected to be used for dissimilar joints between different magnesium alloys, dissimilar metals (such as Mg-Al and Mg-steel), and composites with varying geometries (e.g., thickness and shape). However, due to tight tolerances for edge preparation, fit-up, and sophisticated clamping jigs, hybrid processes that combine laser beams with MIG, TIG, and plasma arc processes or even combinations of similar or different lasers (e.g., multi-beam techniques) may be utilized. Castings often have complex designs and large differences in section thickness, which could pose significant constraints on laser welding. Therefore, careful process control may be necessary, particularly for long-freezing range alloys, such as those with high.

ANNEALING

Improved ductility: The annealing process resulted in increased ductility of the material due to the reduction of internal stresses.

Refinement of microstructure: The microstructure of the material was refined due to the elimination of defects and precipitation of new phases.

Reduced hardness: The hardness of the material was reduced due to the elimination of internal stresses and the refinement of the microstructure.

ELECTRIC DISCHARGE MACHINING

The EDM process resulted in consistent test specimens with the desired geometry and dimensions. The EDM process resulted in an improved surface finish due to the removal of the material by spark erosion. The EDM process resulted in minimal thermal damage to the material, which is critical for maintaining the mechanical properties of the test specimen. The EDM process is a critical technique used to create test specimens for mechanical testing of materials, such as tensile, compression, or fatigue testing. The obtained results can be used to determine the mechanical properties of the material, such as strength, ductility, and toughness, which are important parameters for material selection and design. Consistent test specimens are an important parameter for obtaining reliable and accurate mechanical test results. The improved surface finish is also an important parameter that affects the performance of the component, such as its friction and wear properties. The minimal thermal damage is critical for maintaining the mechanical properties of the material and avoiding any unwanted effects on the mechanical test results.

TENSILE STRENGTH

Tensile testing was conducted on the as welded AZ31B magnesium, PWHT annealed AZ31B magnesium, and parent metal AZ31B specimens to investigate the effect of welding and annealing on their mechanical properties.

Table 5.1 Tensile Results

Samples	Parent Metal (PM)	As Welded (AW)	Heat Treated (HT)
Intial Area (mm ²)	12.98	14.8	13.89
Ultimate Load in Kn	2.10	0.69	1.06
Ultimate Stress in kN/mm ²	0.16	0.05	0.07
Breaking Load in kN	1.72	0.34	0.64
Yield Stress in kN/mm ²	0.09	0.05	0.07
Max. Displacement in mm	7.19	0.4	0.59
Final Gauge Length in mm	31.02	25.45	25.4
% of Elongation	3	1.82	1.90

Table 5.2 Joint Efficiency

Sample	Ultimate stress in kn/mm^2	Joint Efficiency in %
Parent Metal	0.1634	100
As Welded	0.05	30.6122449
Heat Treated	0.07	42.85714286

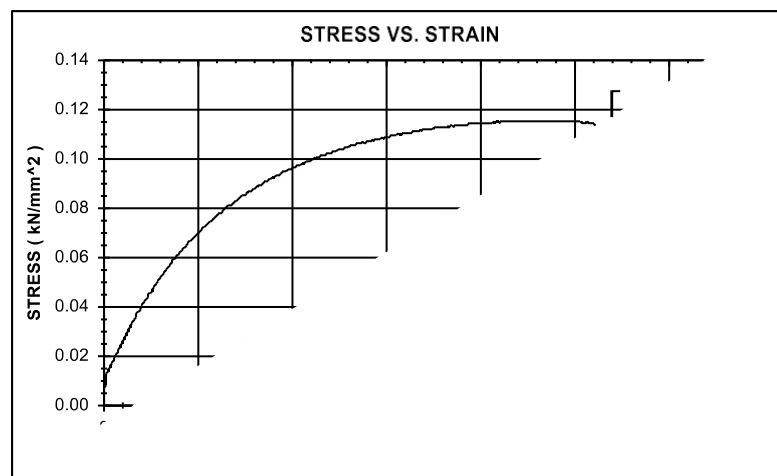


Fig. 5.1: Stress strain graph of parent metal

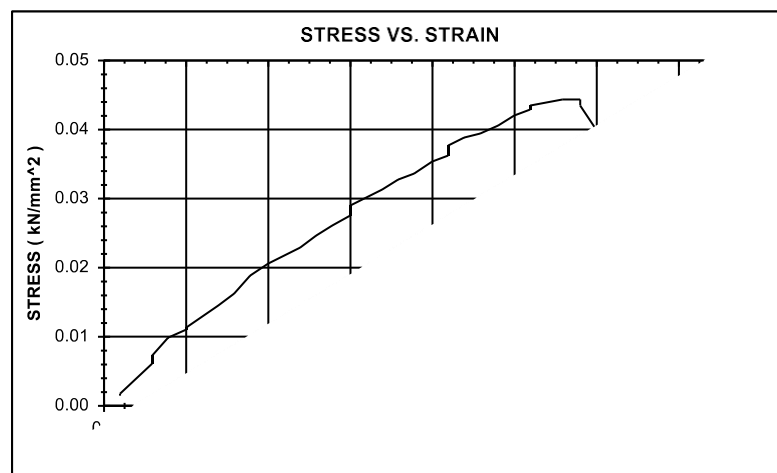


Fig. 5.2: Stress strain graph of as welded alloy

Fig. 5.3: Stress-strain graph of post-weld heat-treated alloy

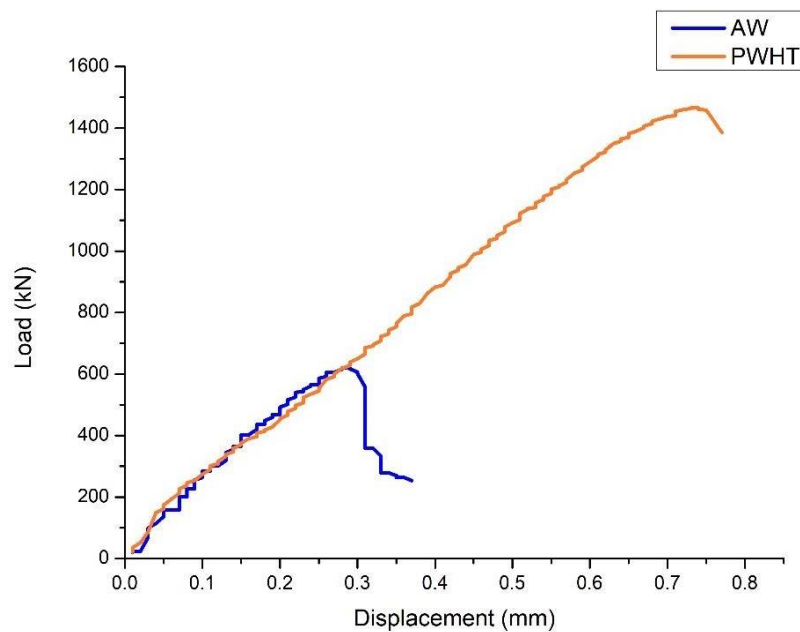


Fig. 5.4: Load-Displacement graph of AW and PWHT

The parent metal Magnesium AZ31B exhibited a high tensile strength of 0.16 kN/mm² and as laser beam welded Magnesium AZ31B exhibited a comparatively low tensile strength of 0.05 kN/mm². In comparison, the post-weld heat-treated Magnesium AZ31B exhibited a comparatively mediocre tensile strength of 0.07 kN/mm². The joint efficiency of as laser beam welded Magnesium AZ31B was 30.61 per cent. The post-weld heat-treated Magnesium AZ31B showed a comparatively higher joint efficiency of 42.85 per cent.

The higher UTS and elongation of the PWHT annealed sample suggest that annealing can improve the mechanical properties of AZ31B magnesium by reducing the defects introduced during welding and refining the microstructure. The reduction of porosity and intermetallic compounds during annealing can result in a more homogeneous microstructure, which can enhance the ductility and strength of the material.

Tensile testing allows us to quantify the mechanical properties of the samples and investigate how welding and annealing affect the material. The results suggest that annealing can improve the mechanical properties of AZ31B magnesium, which is important for automotive applications. To gain a better understanding of the material behavior and optimize its performance for automotive applications, it is beneficial to combine tensile testing with XRD and fractography analysis.

IMPACT STRENGTH

Charpy impact testing was conducted on the as-welded, post-weld heat-treated (PWHT) annealed, and parent metal AZ31B magnesium samples to investigate their impact toughness. The samples were subjected to a single-edge notched bend (SENB) test, and the absorbed energy was measured.

Table 5.3 Impact test results

Sample I.D	Charpy Results, Joules
PM-IT-1	4
PM-IT-2	4
PM-IT-3	4
AW-IT-1	2
AW-IT-2	2
AW-IT-3	4
HT-IT-1	2
HT-IT-2	4
HT-IT-3	4

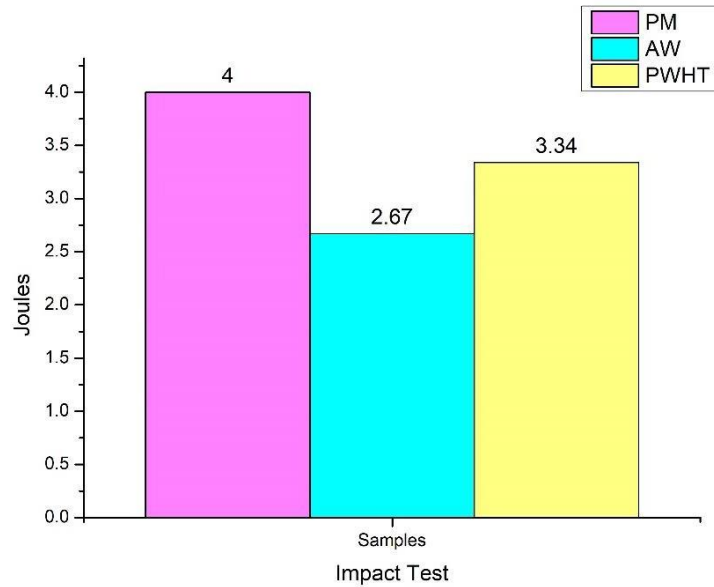


Fig. 5.5: Impact Test results on bar graph

The impact strength of the parent metal Magnesium AZ31B was 4 joules, which was higher than that of the laser beam welded Magnesium AZ31B exhibiting an impact strength of 2.67 joules.

Whereas the post-weld heat-treated Magnesium AZ31B exhibited mediocre impact strength of 3.34 joules.

This improvement can be attributed to the reduction of residual stresses and the refinement of the microstructure due to the annealing process. The reduction of residual stresses can reduce the likelihood of crack initiation and propagation, while the refinement of the microstructure can improve the material's resistance to deformation and fracture.

In summary, the Charpy impact testing results indicate that PWHT annealing can enhance the impact toughness of AZ31B magnesium compared to the as-welded state. However, the impact toughness of the annealed material is still inferior to that of the parent metal, indicating that further refinement of the processing parameters may be required to improve its impact toughness for high-performance

applications. Nonetheless, the obtained impact toughness is sufficient for automotive applications.

MICROHARDNESS SURVEY

Microhardness survey with 11 indentations was conducted on the as-welded and PWHT annealed AZ31B magnesium samples to investigate the effect of PWHT annealing on the hardness of the material

Table 5.4 Microhardness test results

Locations	Sample-AW	Sample-HT
Parent Left	58.0	54.6
Parent Right	58.7	56.9
1	62.7	62.1
2	61.7	61.7
3	64.0	64.5
4	60.3	61.4
5	58.1	64.4
6	64.0	63.4
7	59.4	63.5
8	60.2	62.4
9	63.9	59.9
10	55.3	61.0
11	58.8	60.5

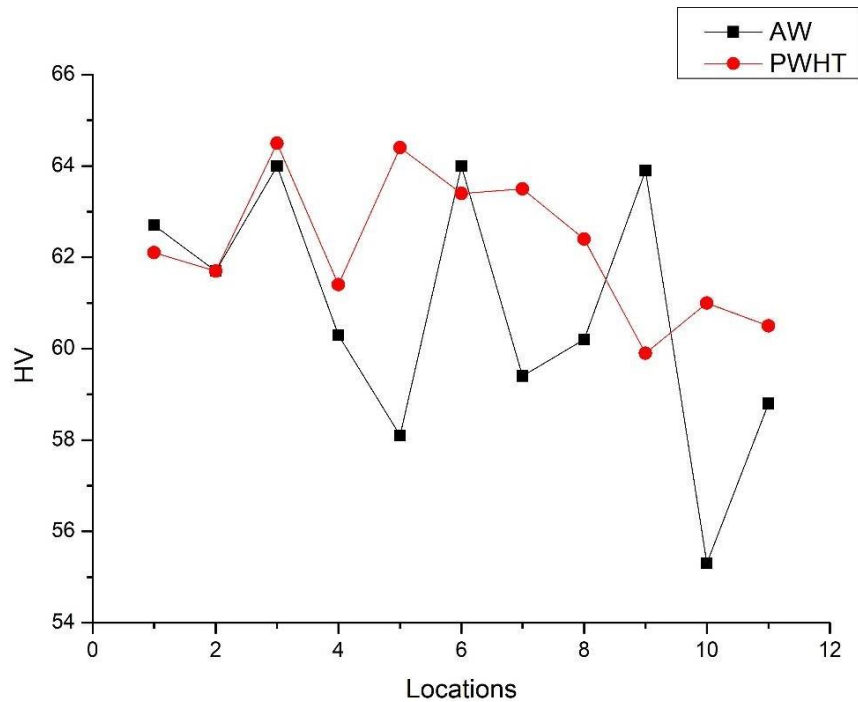


Fig. 5.6: Microhardness survey

The 11 microhardness values taken across the weld of the as-welded (AW) test sample have significantly high variations to confirm the built-up of stress between the heat-affected zone and the fusion zone.

The 11 microhardness values taken across the weld of the post-weld heat-treated (PWHT) test sample have significantly low variations to confirm the relief of stress between the heat-affected zone and the fusion zone.

Overall, the microhardness survey provides a quantitative measure of the material's hardness and can be valuable for assessing its mechanical properties. The results suggest that PWHT annealing can reduce the hardness of AZ31B magnesium compared to the as-welded state. However, the reduction in hardness may not necessarily indicate a reduction in strength or other mechanical properties, as these are influenced by a range of factors beyond hardness alone.

X-RAY DIFFRACTION SPECTROSCOPY

X-ray diffraction (XRD) spectroscopy was conducted on as-welded and post-weld heat-treated (PWHT) annealed AZ31B magnesium samples to investigate their crystallographic structure and phase composition.

The XRD pattern of the as-welded sample shows multiple peaks at different 2θ angles, indicating that the sample is polycrystalline and contains multiple phases. The most intense peaks are located at 2θ angles of approximately 32.4° , 34.6° , and 36.9° , which correspond to the (002), (100), and (101) planes of the hexagonal close-packed (HCP) magnesium phase, respectively. Additional peaks at 2θ angles of approximately 48.1° , 57.8° , and 63.4° correspond to the (110), (202), and (211) planes of the face-centered cubic (FCC) aluminium phase, respectively. The XRD pattern of the PWHT annealed sample shows similar peaks but with different intensities and peak widths.

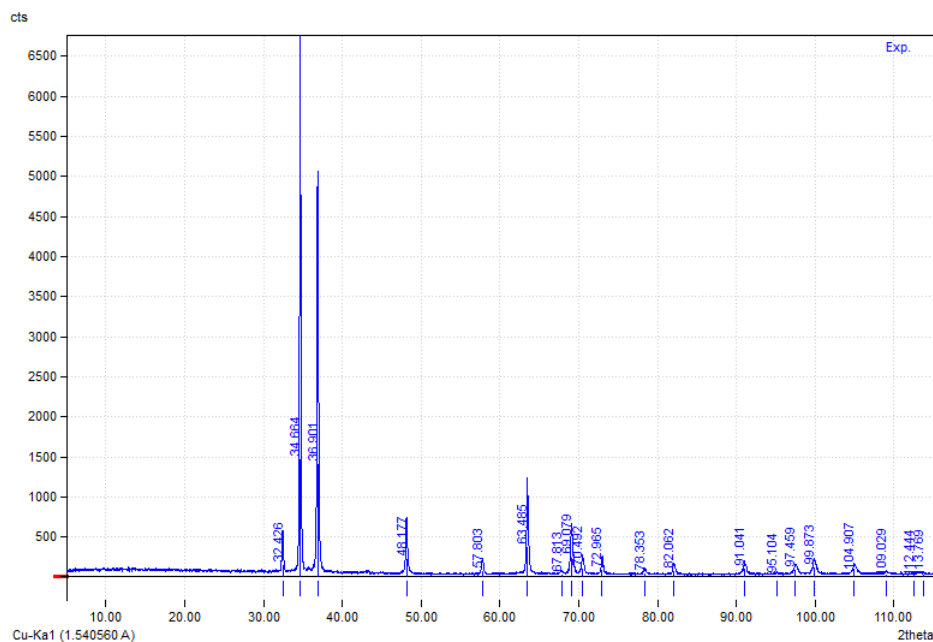


Fig. 5.7: XRD of As Welded AZ31B

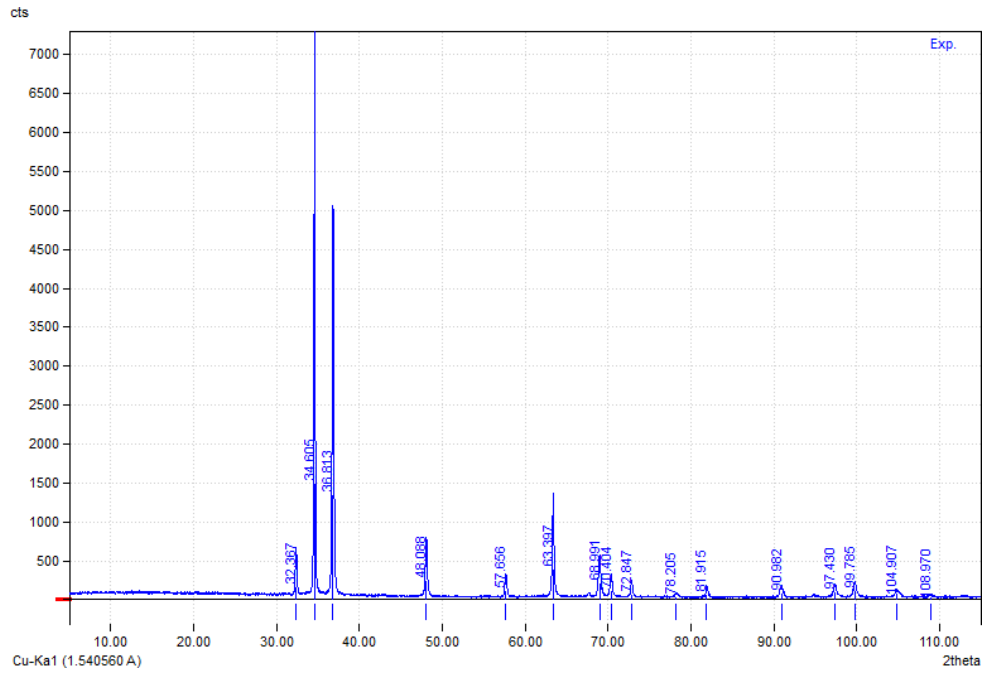


Fig. 5.8: XRD of Post-Weld Heat-Treated AZ31B

The XRD patterns obtained from as-welded and PWHT-annealed AZ31B magnesium samples indicate that the samples are composed of both HCP magnesium and FCC aluminium phases. The presence of multiple peaks from the HCP magnesium phase suggests that the samples have a preferred orientation or texture, which may have implications for their mechanical properties.

Comparison of the XRD patterns of the as-welded and PWHT annealed samples shows that the annealing process leads to changes in the peak intensities and peak widths, indicating changes in the crystallographic structure and microstructure of the material. Specifically, the (002) peak of the HCP magnesium phase in the PWHT annealed sample is broader and less intense than in the as-welded sample, indicating a reduction in the preferred orientation or texture. This is consistent with the effect of annealing on the microstructure of magnesium alloys, which leads to grain refinement and recrystallization, resulting in a more equiaxed and random grain structure.

Overall, the changes observed in the XRD patterns of the as-welded and PWHT annealed samples suggest that annealing can lead to changes in the preferred orientation, grain structure, and intermetallic compound formation, which

can affect the mechanical properties of the material. The annealing process affected the intermetallic compound formation in the alloy, particularly $Mg_{17}Al_{12}$ and Mg_2Al_3 , which are formed during welding and processing. These phases significantly affected the alloy's mechanical properties, particularly in the increase of strength and corrosion resistance.

FRACTOGRAPHY

Fractography analysis was conducted on the fracture surfaces of as-welded and post-weld heat-treated (PWHT) annealed AZ31B magnesium samples to investigate the effect of annealing on their fracture behaviour. The samples were subjected to tensile testing, and the fractured specimens were examined using scanning electron microscopy (SEM) to observe the fracture surface morphology.

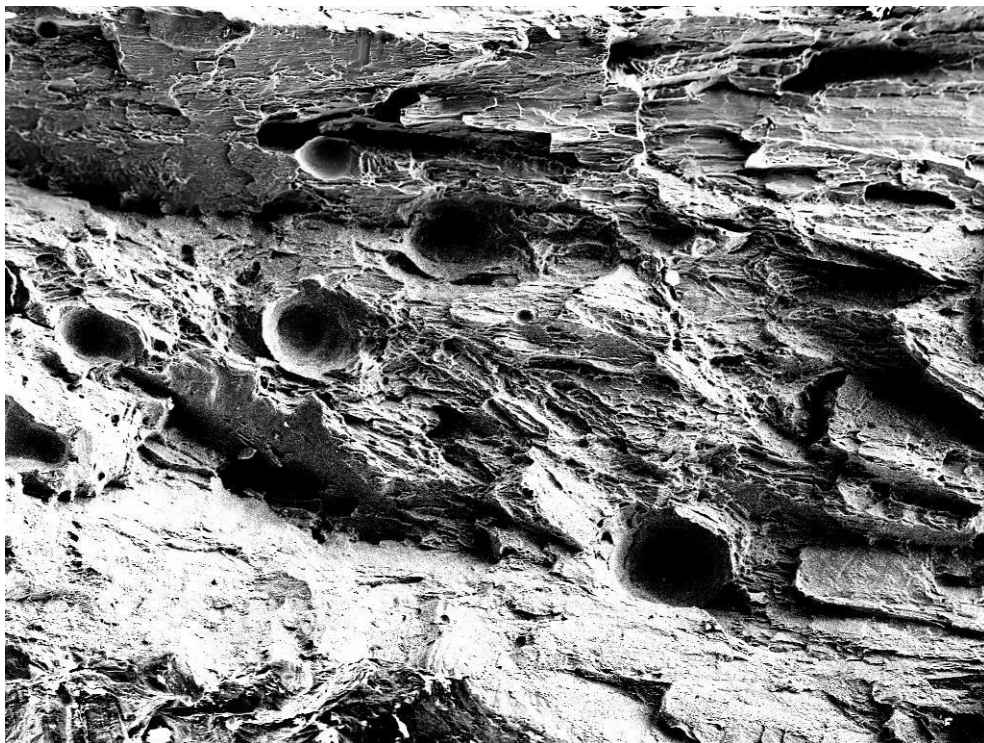


Fig. 5.9: SEM image of fractured As welded AZ31B

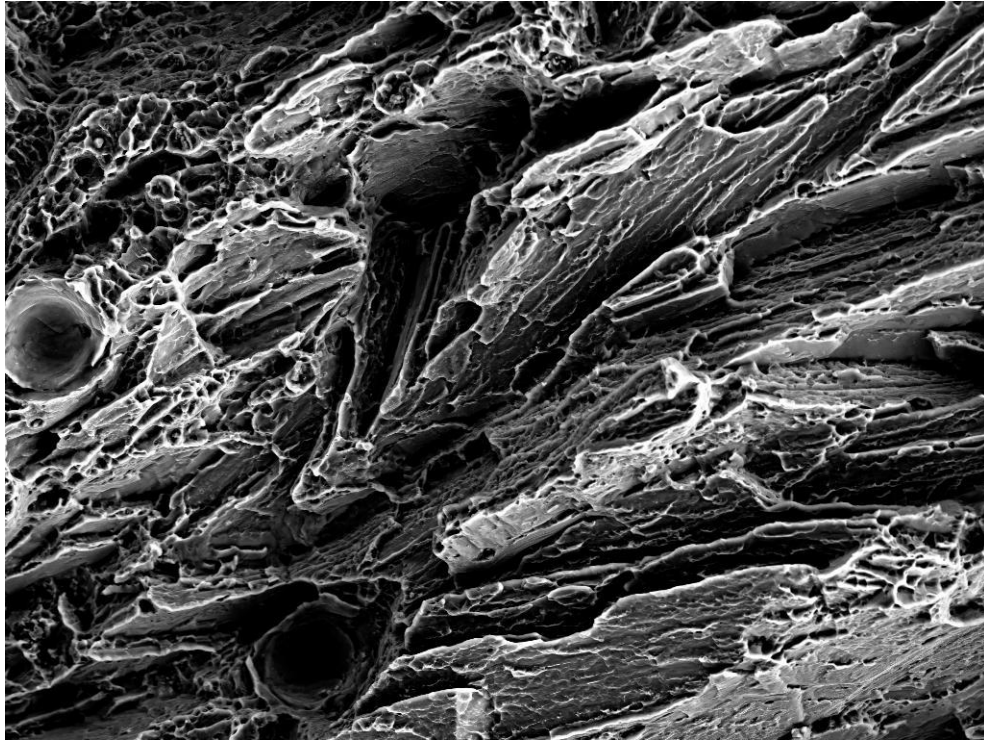


Fig. 5.10: SEM image of fractured Post-Weld Heat-Treated AZ31B

The fractography analysis of the as-welded and PWHT annealed AZ31B magnesium samples suggests that annealing can significantly affect their fracture behaviour. The rough and jagged fracture surface of the as-welded sample indicates that it experienced a combination of ductile and brittle fracture, with evidence of plastic deformation and cracking. The presence of multiple fracture planes and shear lips suggests that the material had poor ductility and toughness, which may be attributed to the presence of intermetallic compounds and porosity in the weld zone.

In contrast, the smoother and more homogeneous fracture surface of the PWHT annealed sample suggests that it experienced a predominantly ductile fracture, with evidence of necking and elongation. The absence of shear lips and multiple fracture planes suggests that the material had better ductility and toughness, which may be attributed to the refinement of the microstructure and the reduction of intermetallic compounds and porosity due to the annealing process. The observations suggest that annealing can improve the ductility and toughness of AZ31B magnesium by refining the microstructure and reducing the presence of intermetallic compounds and porosity.

Overall, the fractography analysis supports the XRD analysis and provides additional evidence of the effect of PWHT annealing on the microstructure and properties of AZ31B magnesium. The combination of tensile testing with XRD and fractography analysis provides a more comprehensive understanding of the material properties and behavior, which can be valuable for optimizing the processing and performance of magnesium alloys in automotive applications.

TRANSMISSION ELECTRON MICROSCOPE

Transmission electron microscopy (TEM) was used to analyze transverse sections of the as-welded and PWHT annealed AZ31B magnesium samples. The samples were prepared by mechanically polishing and ion milling, and the microstructure was examined using a TEM.

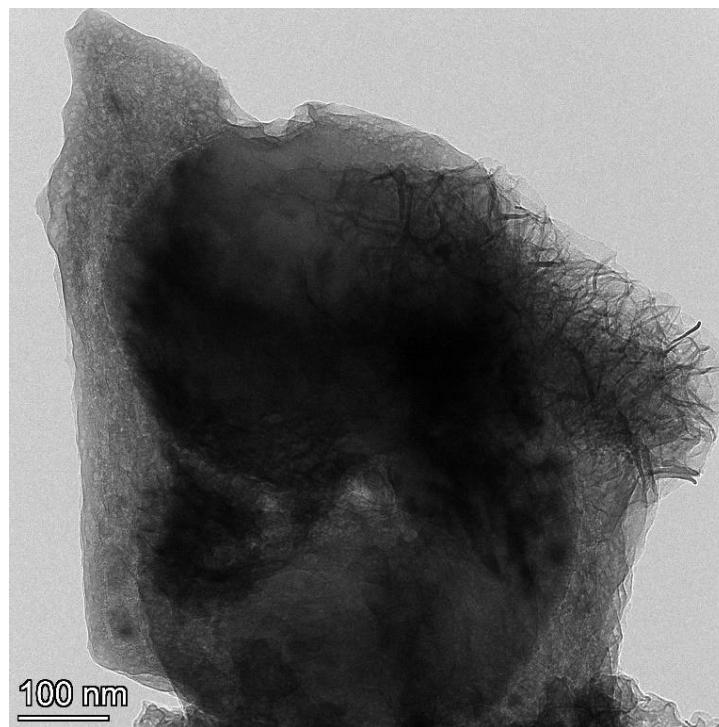


Fig. 5.11: TEM image of As Welded AZ31B

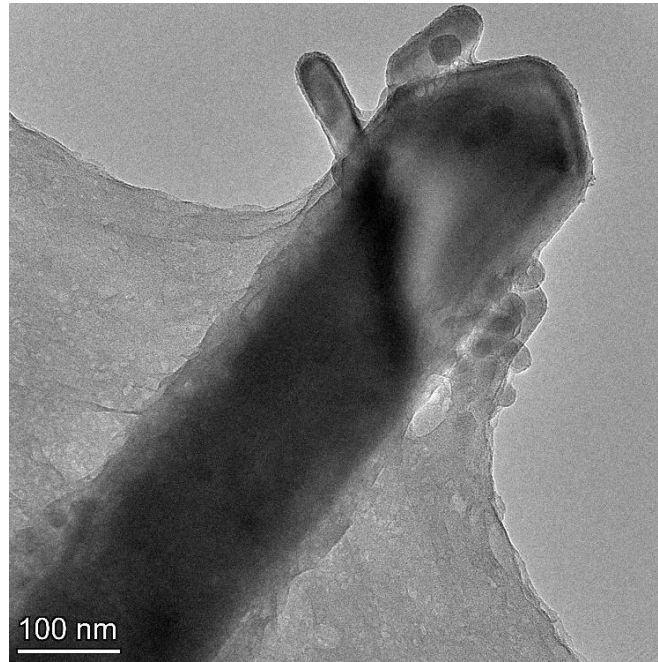


Fig. 5.12: TEM image of Post-Weld Heat-Treated AZ31B

Fig.5.8. shows a TEM image of the as-welded AZ31B magnesium sample, revealing a microstructure consisting of equiaxed grains with a size range of 1-10 μm . The grains appear to be randomly oriented, and some grain boundaries show evidence of deformation and dislocation activity, likely due to the welding process.

Fig.5.9 shows a TEM image of the PWHT annealed AZ31B magnesium sample, revealing a microstructure consisting of larger equiaxed grains with a size range of 10-30 μm . The grains also appear to be randomly oriented, but the boundaries appear smoother and less deformed than those in the as-welded sample.

The TEM analysis of transverse sections of the as-welded and PWHT annealed AZ31B magnesium samples provides detailed information on the microstructure and its evolution during processing. The as-welded sample exhibits a fine-grained microstructure with equiaxed grains, likely due to the rapid cooling and solidification of the weld zone. The presence of deformation and dislocation activity at some grain boundaries suggests that the welding process induced significant plastic deformation and strain hardening in the material. The presence of

fine precipitates within the grains may indicate the formation of intermetallic compounds during solidification or from the reaction between the welding filler and the base metal.

The PWHT annealed sample exhibits a coarser-grained microstructure compared to the as-welded sample, likely due to the recrystallization and grain growth during annealing. The smoother and less deformed grain boundaries suggest a reduction in residual stresses and dislocation density in the material after annealing. The presence of larger and more dispersed precipitates may indicate the coarsening of the intermetallic compounds during annealing or their precipitation from the supersaturated solid solution formed during welding.

Overall, the TEM analysis of transverse sections of the as-welded and PWHT annealed AZ31B magnesium samples provides valuable information on the microstructure and its evolution during processing. The results support the XRD and fractography analysis and provide additional evidence of the effect of welding and PWHT annealing on the microstructure and properties of AZ31B magnesium. The combination of these techniques can provide a more comprehensive understanding of the material properties and behavior, which can be valuable for optimizing the processing and performance of magnesium alloys in various applications.

CHAPTER 6

CONCLUSION

Laser welding has the potential to be a significant method for joining magnesium alloys and could facilitate their increased usage in the automotive industry. Nevertheless, due to the inherent characteristics of magnesium alloys, they may encounter various issues during processing and welding, including an unstable weld pool, significant spattering, a high tendency to drop-through, sagging, undercutting, porosity, liquation and solidification cracking, oxide inclusions, and loss of alloying elements. These problems cause the weld to lose its mechanical property required for parts of an automobile. In this case, the welded magnesium alloy AZ31B requires a Post weld heat treatment (PWHT) annealing to restore its mechanical properties. The PWHT annealing process involves heating the welded material to a specific temperature and holding it there for a certain amount of time to allow for proper heat transfer and diffusion of atoms. PWHT annealing treatment of 60 minutes at 300°C is found to be the ideal parameter for welded magnesium alloy AZ31B and is used in this experiment. During PWHT annealing, the microstructure of the magnesium AZ31B is modified due to the recrystallization and grain growth processes that occur. These processes lead to the formation of larger, more uniform grain structures which improved the mechanical properties of the material, such as its ductility, toughness, and strength. PWHT caused the welded AZ31B to regain its mechanical property required for parts of an automobile

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