Effect Of Filler Material on Mechanical Properties of Tig Welded Aluminium Alloy-A Review

Sudheesh N
Department of Mechanical Engineering College of Engineering Thalassery-670107
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***Abstract*—Aluminium 6000 series alloy is one of the most widely used aluminium alloys for the industrial application. Tungsten inert gas welding is one of the most important welding techniques for aluminium alloy. Voltage, current, and welding speed, shielding gas are the key process parameters that have significant effect on the quality, mechanical and microstructural properties of the welded joint. Filler material selection is also an important parameter in TIG welding process, because the chemical composition of the filler material significantly influences the mechanical properties of the welded joint. For attaining a sound weld, composition of the filler material should match with that of base material. In this paper the influence of different types of filler material on microstructural and mechanical properties of TIG welded aluminium alloy are reviewed.**

***Index Terms*—Aluminium Alloy, TIG Welding, Filler wire composition Mechanical properties, Microstructure**

I. INTRODUCTION

Aluminium is one of the most widely used materials in industrial application due to its excellent corrosion resistance, moderate strength, light weight, good machinability. It is extensively used in the manufacturing of automobiles, aircraft bodies, trucks, railways, cars, marine vessels, bicycles frames, spacecraft parts, transport equipment, storage tanks, and general metal sheet works etc. [1]. To improve the mechanical properties, pure aluminium is commonly alloyed with other metals like copper, manganese, silicon, magnesium and zinc. The aluminum alloys of 6000 family are extensively used aluminium alloy for industrial application due to its better mechanical properties. Silicon and magnesium are the major alloying elements in the aluminium 6000 family series of alloys. High strength, very good corrosion resistance, good weldability and formability are the key properties of aluminium 6000 series of alloys [2-4]. AA 6061 and AA 6082 are the most preferred alloys in 6000 series and these alloys are used alloys in automotive, shipbuilding, aircraft and structural application [5]. Weldability of aluminium alloy is an important property that has significant role in the selection of an aluminium alloy for a specific application.

Welding is a process used for making permanent joints of between same metals or between two different types of metals or its alloys. It is a joining process in which merging of parent materials is produced by heating them to recrystallization temperature with or without the use of pressure. Sometimes filler material is also used separately to add material in the weld zone. Tungsten inert gas (TIG) welding is an arc-welding process that produces coalescence of metals by heating them with an arc between a non-consumable electrode and the base metal. [6-7].

Tungsten inert gas (TIG) welding is also called the gas tungsten arc welding (GTAW). It is one of the broadly used welding technique in modern industries for joining either similar or dissimilar materials. TIG welding uses a non-consumable tungsten electrode to produce the arc between the electrode and work piece. The high melting point of tungsten is capable of withstanding the higher heat input used in TIG welding. Weld zone is protected by a shielding gas from atmospheric air or gases and a filler material is normally used for supply materials in weld zone. Very good weld quality, low heat affected zone, absence of slag, capability for joining of similar and dissimilar metals are some of the advantages TIG welding process. For welding of aluminum and its alloys TIG welding method is generally used [5]. Welding of aluminum is a difficult process due to the presence of aluminium oxide layer on its surface. The melting point of aluminium oxide is very high compared to the melting point of aluminium. It is essential to remove and disperse this oxide film before and during welding in order to achieve the required weld quality [8]. This is achieved by applying very high heat input in a shield of inert gas. Usually argon, helium or a mixture of argon/helium is used to protect the molten metal from the atmospheric contamination and prevent oxidation. Filler metal is added externally to the arc in the form of a consumable wire. ER 4043, ER 4047, ER 5356 are some of the most common filler wires used for the TIG welding of 6000 series of aluminium alloys. Chemical composition of filler wire is an important parameter that decides the mechanical properties of the welded joint.

M. Ishak et al. [9] investigated the effect of filler on weld metal structure of aa6061 aluminum alloy by tungsten inert gas welding and it is found that welding using filler ER5356 produced a finer grain size at the FZ of 25.69 µm compared to fillers ER4043 and ER4047 with grain sizes of 52.75 µm and 76.78 µm, respectively. Using filler ER5356 also produced the highest hardness value of 72.9 HV compared to the ER4043 and ER4047 counterparts, with 59.3 HV and 57.6 HV, respectively. The welded joints produced by using ER5356 filler wire obtained highest strength (171.53 MPa) compared to tensile strength of the welded joints made by using ER4043 and ER4047 fillers wires with their corresponding values of 167.34 MPa and 168.03 MPa. It can be concluded that TIG welding using ER5356 filler yields better joints compared to ER4043 and ER4047.

L.H. Shah et.al [10] conducted investigation on Mechanical Properties of TIG Welded AA6061 Alloy Weldments Using Different Aluminium Fillers and it is found that aluminium alloy welded with ER4043 sample shows better hardness in the HAZ and WM compared to the ER4047 sample. Corrosion analysis shows that the ER4043 filler samples obtained a lower corrosion rate compared to the ER4047 filler samples. So, it is concluded that ER4043 filler metals are more suitable in joining AA6061 samples due to its superior mechanical and corrosion characteristics compared to samples welded with ER4047 filler.

S. Missori and A. Sili, [11] investigated mechanical behavior of 6082 aluminium alloy welds. They found that Tensile strength of welded joints of 6082-T6 Al alloy, under the experienced welding conditions, undergo a remarkable reduction of the initial value. The residual strength of the welded joint is around 60% of the parent metal; this is consistent with indications of design norms such as in [19], assessing a reduction of allowable design stress of 57% for this class of welded joints. In the HAZ both tensile strength and hardness reduce to a minimum at a distance from the weld fusion line of about 6 mm, presumably due to over-aging consequent to the transformation of the strengthening metastable precipitate.

Ahmad Wael AlShaer et.al [12] investigated the effect of filler on weld metal structure AC-170PX (AA6014) typically used in lightweight automobile vehicles. It has been found that the use of filler wires with higher Mg and Mn content such as AA5083 and AA3004 leads to a significant reduction in porosity to less than 1.5% in both types of joints compared with up to 80% porosity with the silicon-rich AA4043 wire.

S. Amal Bosco Jude [13] investigated the effect Influence of Mg2Si on the grain refinement of TIG welded AA6082 Aluminium alloy. And it is found that Microstructure of the sample welded at optimum parameter reveals that the weld zone contains predominantly eutectics of Mg2Si in primary dendritic aluminium solid solution and insoluble sludge particles.nt. The SEM analysis was carried out on the weld region of the sample welded under optimum conditions reveals that the microstructure of the weld zone is further resolved to show the dendrites of Al-Si which are in uniform distribution with random orientation showing no directional solidification. The particles of Mg2Si are fine and present inside the grains of the eutectic silicon with aluminium

Kumar and Sundarrajan [14] employed Taguchi method to optimize process parameters for the TIG welding of AA 6061 Aluminum alloy. From the investigation it was concluded that for aluminum alloy 6061-T6 welding with 4043 filler wire, joint gap at 1.6mm, welding current at 220A, welding speed at 150 mm/min and shielding gas flow rate at 16l/min are capable of producing maximum butt-joint UTS of 158.08MPa.

G. Mrówka et al [15] conducted investigation to identify various intermetallic phases in the AA 6082 aluminium alloy and it was found that seven phases are present in this aluminium alloy. These seven phases are, namely: α-Al, β-Al5FeSi, α-AlFeSi, α-$Al_{15}(FeMn)_3Si$, Al_9Mn_3Si, Mg_2Si and Si between the aluminium dendrites.

Gażyna et al. [16] investigated the effect of chemical composition variation on mechanical properties of 6xxx aluminum alloys. It was found that the mechanical properties of the 6xxx series aluminium alloys in the T6 tempers increase with increasing Si concentration in their chemistry. The degree of strengthening depends on the extent of β″ precipitation which increases with increasing Mg2Si content of the alloys. In this work the highest mechanical properties connected with good plastic properties was achieved for 6061 alloy with the highest volume fraction of β-Mg2Si.

S. R. Koteswara Rao.et al. [17] al investigated the effect of scandium addition in the 2319 and 5356 filler wire on mechanical properties of AA2219 aluminium alloy. The following conclusions were made based on their study. Small addition of scandium resulted in fine equiaxed grain structure in 2219 aluminum alloy weld metals. Hardness values of weld metals increased by the addition of scandium, particularly in the presence of Mg. Addition of 0.25% Sc to Al-Cu filler did not result in improvement of strength of the weld metal. However, addition of 0.4% Mg to AlCu-Sc filler improved the strength significantly. Scandium addition in general resulted in significant increase in percent elongation

J. H. Lia, A. Wimmer, G. Dehm and P. Schumacher.[18] studied the intermetallic phase selection during homogenization of AA6082 aluminium alloy and it was found that A short homogenization treatment at 580°C for 4h and a subsequent slow cooling with a rate of about 8°C/min, rather than a conventional quick quenching into water, results in the formation of the rounded discrete Al15(FeMnCr)3Si2 phase, which greatly suppressed the formation of the plate-shaped β-Al5FeSi phase. Fine Mg2Si particles were also observed to be located in the vicinity of Al15(FeMnCr)3Si2 particles. This investigation demonstrates that the size and distribution of the desired intermetallic phases can be influenced by suitable homogenization treatments.

R. S. Rana et al. [19] studied the effect of Influences of Alloying elements on the Microstructure and Mechanical Properties of Aluminum Alloys and Aluminum Alloy Composites. From this study it was concluded that, Silicon lowers the melting point and increase the fluidity (improve casting characteristics) of Aluminum. A moderate increase in strength is also provided by Silicon addition. Magnesium provides substantial strengthening and improvement of work Harding characteristic of aluminium alloy. It can impart good corrosion resistance and weldability or extremely high strength. Copper has a greatest impact on the strength and hardness of aluminum casting alloys; both heats treated and not heat treated and at both ambient and elevated service temperature. It improves the machinability of alloys by increasing matrix hardness. Nickel (Ni) enhances the elevated temperature strength and hardness.

[20] K. Prasad Rao et al studied partially melted zone cracking susceptibility in AA6061 alloy welds. From their study it was inferred that partially melted zone cracking susceptibility of AA6061 alloy is less when ER 4043 filler wire was used rather than ER 5356 filler wire in TIG welding.

Sankaralingam T et al. [21] used scandium-reinforced filler wire to join dissimilar welding of Al5083-H111 and AA6061-T6 alloys with a tungsten inert gas welding process at different combinations of input process parameters, such as current, voltage and gas flow rate. These alloys are popular in automobile and structural applications. In their investigation they compared the mechanical and metallurgical properties of welded joints produced by commercially available ER5356 filler material and the scandium alloyed filler material. From the study it was found that the scandium-reinforced filler produced better mechanical strength (264 MPa.) and a maximum weld metal hardness of 97 HV. The percentage of elongation was also increased due to the influence of scandium in the filler. From the design of experiments, it was inferred that the influence of current is a significant factor for commercial fillers wire and for the modified filler wire gas flow rate is a predominant factor. The optimum welding parameters are obtained by modified genetic algorithm (187 A and 27.3 V) for maximum weldment strength (241 MPa). The study recommended scandium-reinforced filler material for improved material properties in structural applications.

II. TUNGSTEN INERT GAS WELDING

TIG welding (Tungsten inert gas welding), also called as gas Tungsten Arc Welding (GTAW) is an arc welding process that uses a non-consumable electrode and an inert gas shield to protect the electrode, arc column and the weld pool as shown in the fig.1. In TIG welding the arc acts as a source of heat only and therefore a separate filler material is used which melts in the arc heat and deposits material in the joint as weld pool. TIG process welding set utilizes suitable power sources, a cylinder of shielding gas, welding torch having connections of cable for current supply, tubing for shielding gas supply and tubing water for cooling the torch. Helium, Argon or mixture of Helium-Argon is normally used as shielding gas to eliminate the possibility of atmospheric contamination.

III. TUNGSTEN INERT GAS WELDING PARAMETERS

Even though TIG welding process is capable of producing high quality welds, proper execution of the process and control of a number of parameters is required for achieving successful results. The mechanical properties of the joint are determined by the welding process parameters selected such as root gap, welding current, welding speed and shielding gas flow rate. Hence it is important to select the welding process parameters to obtain the required weld-joint strength [9]. The key parameters that have significant role in the weld quality are discussed below.

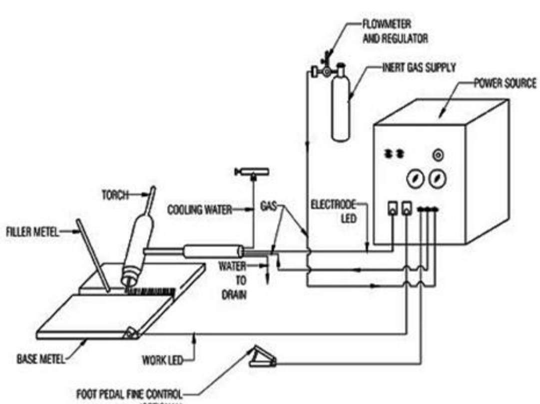

Fig.1-TIG Welding set-up

A. Arc voltage and stand of distance:

arc voltage and stand of distance are efficient parameters which help to control and generate continuous electric arc between non-consumable tungsten electrode and base material in welding process. Increased arc voltage increases the arc length which results in wider bead width [17].

B. welding speed:

Welding speed/travel speed is another parameter which controls the depth of penetration with its variation. Depth of penetration is more in slow welding speed as compare to fast welding speed shown in graph 2. So as increased welding speed results in decreasing weld bead width

C. Shielding gas:

The inert gases are used as a shielding gas in the form of blankets in gas tungsten arc welding. The main purpose of the use of inert gas in welding: i) To shield the welding area from air, preventing oxidation, ii) to transfer the heat from electrode to base material and iii) to helps to start and maintain a stable arc between electrode to base material (due to low ionization potential). There are various types of inert gas available as helium, neon, argon and mixture of gases. Shielding gas used for stainless steel as a backing. But argon and helium are used for aluminium, magnesium and other metals that oxidize readily [8]. Argon-helium mixtures are also frequently utilized in GTAW. But normally, the mixtures are made with primarily helium (often about 75% or higher) and a balance of argon. These mixtures increase the speed and quality of the AC welding of aluminium, and also make it easier to strike an arc. Another shielding gas as a mixture of argon-hydrogen, is used in the welding of stainless steel, but its use is limited because hydrogen can cause porosity

D. Welding current:

Proper selection of welding current is an important parameter to ensure the required heat input and fusion base metal. Insufficient welding current will lead to lack of fusion and improper melting of parent material. Very high welding current leads to burning of parent material, vaporization of molten metal and large heat effected zone. Optimum value of welding current is to be selected for better results.

E. Filler road:

Proper selection of filler road is an important parameter in TIG welding of aluminium alloy. The composition of the filler alloy should match with the composition of the base material. Filler rods are generally available in various grades such as 1100, 4043, 5154, 5183 and 5356 of aluminium alloys with standard diameters.

When choosing the optimum filler alloy, the application (end use) of the welded part and its desired performance must be prime considerations. Many alloys and alloy combinations can be joined using any one of several filler alloys, but only one filler may be optimal for a specific application. The primary factors commonly considered when selecting a welding filler alloy are Ease of welding Tensile or shear strength of the weld, Weld ductility, Service temperature, Corrosion resistance, Color match between the weld and the base alloy after anodizing Sensitivity to Weld Cracking.

IV. EFFECTS OF MAJOR ALLOYING ELEMENTS IN ALUMINIUM ALLOY

The alloying elements in aluminium are classified in to major alloying elements and minor alloying elements. The major alloying elements in aluminium alloys are commonly silicon (Si), copper (Cu) and magnesium (Mg).

A. Effect of Silicon addition:

It is one of the most widely used alloying elements to produce aluminium casting alloys. It is responsible for imparting high fluidity, low shrinkage and low density for aluminium alloys. Since the solubility of silicon in aluminium is poor, it is precipitating as virtually pure silicon during solidification. This hard precipitates of pure silicon improves the abrasion resistance of the alloy.

B. Effect of Copper addition:

The addition of copper to aluminium enhances both strength and hardness of the alloy and it also improves the machinability of the alloy. The addition of copper reduces the corrosion resistance of the alloy.

C. Effect of Magnesium addition:

The addition of Magnesium is capable of imparting high strength, good corrosion resistance and weldability. The addition of magnesium can improve the work hardening characteristics of aluminium.

V. EFFECT OF MINOR ELEMENTS IN ALUMINIUM ALLOY

A. Effect of Ni addition:

The addition of small amount of Nickel can improve hot hardness of aluminium-silicon casting and forging alloys. This is due to the formation of Al_3Ni intermetallic compound in the aluminium matrix [22].

B. Effect of titanium addition:

Small amount of titanium addition up to 0.015% is helpful for grain refinement of aluminium alloy. The precipitation of Al3Ti intermetallic phase will improve the micro hardness of Al-Si alloy [23].

C. Effect of Manganese addition:

up to 0.5 wt. % of manganese addition to aluminium alloy will improve the tensile strength of alloy significantly without compromising ductility of the alloy [24].

D. Effect of Zinc addition:

It was found that the addition of zinc is capable of forming high density precipitates. The alloy with 1.5% Zn addition has the highest ultimate tensile strength.

E. Effect of Iron addition:

iron leads to the formation of complex inter-metallic phases during solidification, and how these phases can adversely affect mechanical properties, especially ductility, and also lead to the formation of excessive shrinkage porosity defects in castings [25].

VI. FILLER WIRES FOR WELDING OF ALUMINIUM ALLOY

A separate filler wire is required in TIG welding. The filler wires are used for depositing material in the joint. Filler metal selection is crucial to producing crack free, optimum strength welded joints but there are other considerations that may need to be considered when making the choice. During the welding process of steel, filler wires are selected in such way that it generally matches that of the parent metal with respect to composition, mechanical properties, corrosion resistance, colour, response to anodizing and creep strength. Whereas aluminium alloys are often welded with filler metals that do not match the parent metal in some or all of these properties. There are different types of filler wires have been developed for the welding of aluminium alloys. The chemical combination of commercially available filler wires is given in table 1

Table II

Filler wire	Mn	Si	Fe	Mg	Cr	Cu	Ti	Zn	Al
ER1100	0.05	b	b	--	--	0.1	--	0.10	Rest
ER2319	0.20-0.40	0.20	0.30	0.02	--	5-7	0.10-20	0.10	Rest
ER4043	0.05	4.5-6	0.80	0.05	--	0.3	0.20	0.10	Rest
ER4047	0.15	11-13	0.80	0.10	--	0.3	--	0.20	Rest
ER4643	0.05	3.6-4.6	0.80	0.10-0.30	--	0.1	0.15	0.10	Rest
ER5052	0.10	0.25	0.40	2.2-2.8	0.15-0.35	0.1	--	0.10	Rest
ER5056	0.05-0.20	0.30	0.40	4.5-5.6	0.05-0.20	0.1	--	0.10	rest
ER5087	0.60-1.00	0.25	0.40	4.3-5.2	0.05-0.25	0.05	0.15	0.25	rest
ER5154	0.10	0.25	0.40	3.1-3.9	0.05-0.35	0.1	0.20	0.20	rest
ER5183	0.50-1.00	0.40	0.40	4.3-5.2	0.05-0.25	0.1	0.15	0.25	rest
ER5356	0.05-0.20	0.25	0.40	4.5-5.5	0.05-0.20	0.1	0.06-0.20	0.10	rest
ER5554	0.50-1.00	0.25	0.40	2.4-3.0	0.05-0.20	0.1	0.05-0.20	0.25	rest
ER5556	0.50-1.00	0.25	0.40	4.7-5.5	0.05-0.20	0.05	0.05-0.20	0.25	rest
ER5654	0.01	c	c	3.1-3.9	0.15-0.35		0.05-0.15	0.20	rest

The selection of the filler wire is based on the type of alloy to be joined. Standard charts are available for this purpose. Generally, filler rod is used similar in composition as the welded base material. Filler rods are generally available in various grades such as 1100, 4043, 5154, 5183 and 5356 of aluminum alloys with standard diameters. The filler materials selection chart for welding different aluminum alloys is shown in the table II.

Table II [26]

Al alloys	7005 7021 7039 7046 7146	6009 6010 6070	6005 6061 6063 6082 6201 6351 6951	5456	5052 5454 5154 5254 5652	3004	2219 2014 2036
1060 1070 1080 1100 1350	4043 5183 5356 5556	4043 4145 4047	4043 4145	5356 5183	4043 4047 5183 5356	4043 4047 5183	4145 4043 4047
2002 2036 2037 2117	----	4145	4145	----	---	4145	4145 2319 4043
3004	5356 5183 5554	4043 4047	4043 4047 5183	5356 5183 5554 5556	5356 5183 5554 5556	5356 4043 5183	
5043 5052	5356 5183	4043 4047	4043 5183	5356	5356		
5454	5554		5356	5183 5554 5556	5183 5554 5556		
5030 5182 5754	5356 5183 5554	4043 4047	5356 5183 5554	5356 5183 5554	5356 5183 5554		
6005 6061 6063 6082 6201 6351 6951	5356 4043 5183	4043 4145	4043 4047 5183				
6009 6010 6070	4043	4043 4145 4047					
7005 7021 7039 7046 7146	5356 5183 5556						

VII. CONCLUSION

From the review it is clear that the chemical composition of filler wire has a significant role in the mechanical properties of the welded joint. The chemical composition of the filler material should be matching to the base metal to provide superior quality for the joint. From the various investigations conducted earlier, it is clear that by suitably adding major and minor alloying elements at optimum level, novel filler wires can be produced which will impart superior mechanical and microstructural properties to the welded joint. The intermetallic phases formed during the solidification of weld metal have a considerable effect on the mechanical properties of the welded joint. The following conclusions are made based on the various investigations made earlier.

ER4043 filler metals are more suitable in joining AA6061 alloy due to its superior mechanical and corrosion characteristics

ER5356 filler material is suitable for joining AA6061 alloy for highest tensile strength.

For welding AA6014 aluminium alloy with minimum porosity level, ER5083 or ER3004 filler material is much suitable compared to ER4043 filler wire.

Scandium addition to ER5356 filler material can significantly improve the percent elongation of the welded joint However the selection of filler wires for welding aluminium alloys depends on the specific requirement like strength, ductility, corrosion resistance and crack formation tendency etc.

REFERENCES

[1] ASM International Handbook Committee, ASM Handbook: Welding, Brazing, and Soldering, vol. 6. Materials Park, OH, USA: ASM International, 1993, p. xvi.

[2] C. Barbosa, J. Dille, J. L. Delplancke, J. M. Rebello, and O. Acselrad, "A microstructural study of flash welded and aged 6061 and 6013 aluminum alloys," Mater. Charact., vol. 57, pp. 187–192, 2006.

[3] G. Lucas, "Aluminum structural applications," Adv. Mater. Process., vol. 149, pp. 29–30, 1996.

[4] H. Demir and S. Gunduz, "The effect of aging on machinability of 6061 aluminum alloy," Mater. Des., vol. 30, pp. 1480–1483, 2009.

[5] A. B. M. M. Rahman, S. Kumar, and A. R. Gerson, "The role of silicon in the corrosion of AA6061 aluminum alloy laser weldments," Corros. Sci., vol. 52, pp. 1969–1975, 2010.

[6] J. R. Davis, ASM Specialty Handbook: Aluminum and Aluminum Alloys. Materials Park, OH, USA: ASM International, 1994, pp. 376–686.

[7] H. B. Cary, Modern Welding Technology. Englewood Cliffs, NJ, USA: Prentice-Hall, 1989, pp. 95–106.

[8] G. Mathers, The Welding of Aluminium and Its Alloys. Cambridge, UK: Woodhead Publishing, 2002, pp. 23–24.

[9] M. Ishak et al., "Effect of filler on weld metal structure of AA6061 aluminum alloy by tungsten inert gas welding," Int. J. Automot. Mech. Eng. (IJAME), vol. 11, pp. 2438–2446, Jun. 2015.

[10] L. H. Shah, N. A. A. Razak, A. Juliawati, and M. Ishak, "Investigation on the mechanical properties of TIG welded AA6061 alloy weldments using different aluminium fillers," GSTF Int. J. Eng. Technol. (JET), vol. 2, no. 2, pp. 116–120, Aug. 2013.

[11] S. Missori and A. Sili, "Mechanical behaviour of 6082 aluminium alloy welds," Metall. Sci. Technol., pp. 12–18, 1990.

[12] A. W. AlShaer, L. Li, and A. Mistry, "Effect of filler wire properties on porosity formation in laser welding of AC-170PX aluminium alloy for lightweight automotive component manufacture," Proc. Inst. Mech. Eng. B, J. Eng. Manuf., Feb. 2015.

[13] S. A. B. Jude et al., "Influence of Mg2Si on the grain refinement of TIG welded AA6082 Aluminium alloy using Taguchi method," Int. J. ChemTech Res., vol. 8, no. 7, pp. 42–49, 2015.

[14] A. Kumar and S. Sundarrajan, "Selection of welding process parameters for the optimum butt-joint strength of an aluminum alloy," Mater. Manuf. Process., vol. 21, no. 8, pp. 779–782, 2006.

[15] G. Mrówka-Nowotnik, J. Sieniawski, and M. Wierzbińska, "Intermetallic phase particles in 6082 aluminium alloy," Arch. Mater. Sci. Eng., vol. 28, no. 2, pp. 69–76, Feb. 2007.

[16] G. Mrówka-Nowotnik and J. Sieniawski, "Effect of chemical composition variation on mechanical properties of 6xxx aluminum alloys," Inż. Mater., vol. 31, pp. 542–545, 2010.

[17] S. R. K. Rao, G. M. Reddy, K. S. Rao, P. S. Rao, M. Kamaraj, and K. P. Rao, "Gas tungsten arc welded AA 2219 alloy using scandium containing fillers: mechanical and corrosion behavior," Trans. Indian Inst. Met., vol. 57, no. 5, pp. 451–459, Oct. 2004.

[18] J. H. Li, A. Wimmer, G. Dehm, and P. Schumacher, "Intermetallic phase selection during homogenization for AA6082 alloy," Philos. Mag., vol. 94, no. 8, pp. 830–846, 2014.
[19] R. S. Rana, R. Purohit, and S. Das, "Reviews on the influences of alloying elements on the microstructure and mechanical properties of aluminum alloys and aluminum alloy composites," Int. J. Sci. Res. Publ., vol. 2, no. 6, Jun. 2012.
[20] K. P. Rao, N. Ramanaiah, and N. Viswanathan, "Partially melted zone cracking in AA6061 welds," Mater. Des., vol. 29, pp. 179–186, 2008.
[21] T. Sankaralingam, K. S. Jayakumar, E. M. Pillai, and S. P. Jani, "Modified gas tungsten arc weld filler material and varying population genetic algorithm for studying dissimilar material welding parameters," J. Mater. Eng. Perform., vol. 33, no. 6, pp. 2991–3005, 2024.
[22] J. E. Hanafee, "Effect of nickel on hot hardness of aluminum-silicon alloys," Mater. Sci. Eng., vol. 71, pp. 514–520, 1985.
[23] M. Jaradeh and T. Carlberg, "Effect of titanium additions on the microstructure of DC-cast aluminium alloys," Mater. Sci. Eng. A, vol. 413–414, pp. 277–282, 2005.
[24] S. W. Nam and D. H. Lee, "The effect of Mn on the mechanical behavior of Al alloys," Met. Mater., vol. 6, no. 1, pp. 13–16, 2000.
[25] J. A. Taylor, "The effect of iron in Al-Si casting alloys," Coop. Res. Centre Cast Met. Manuf. (CAST), Univ. Queensland, Brisbane, Australia, pp. 1–10, 2004.
[26] R. S. Parmar, Welding Engineering and Technology, 2nd ed. New Delhi, India: Khanna Publishers, 2010.