People's Democratic Republic of Algeria

Ministry of Higher Education and Scientific Research

Mohamed Boudiaf University of Msila

Faculty of Technology

الجمهورية الجزائرية الديمقراطية الشعبية

وزارة التعليم العالي والبحث العلمي

جامعة المسيلة

كلية التكنولوجيا

Department of Mechanical Engineering

THESIS

for obtaining the diploma of:

MASTER

In Mechanical Engineering

Option: Industrial Production Technique

Presented by:

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Theme

FRICTION STIR WELDED JOINTS OF DISSIMILAR AA6061 AND AA5083 ALUMINUM ALLOYS

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University Year: 2020/2021

N° Ordre: MG/…………… /2021

ACKNOWLEDGEMENTS

We would like to express our deepest appreciation to our supervisor Mr. DEBIH Ali who continually and convincingly conveyed a spirit of adventure regarding research. Without his guidance and persistent help, this research would not have been possible. Thank you so much Prof for your patience and confidence in our abilities. We also express our gratitude to the members of the jury who spared time to read this dissertation though their tight timetables. We thank them for their contribution, invaluable remarks, and support.

DEDICATIONS

To our families and our teachers, without you, this would be impossible, May Allah bless you.

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Abstract

The joining technology of similar and dissimilar materials plays a crucial role in various areas, include manufacturing. Many conventional welding techniques have been used over the years to successfully join various materials. Friction stir welding (FSW) is a solid-state welding process. This thesis discusses the investigation of mechanical characteristics of butt weld joints of aluminum alloy AA6061 along with AA5083. An experiment was conducted for different tool rotational speeds of 600 rpm, 1000 rpm and 1400 rpm. Using the vertical milling machine and welding speed of 40 mm/min. Friction stir welded (FSW) joints of higher tensile strength, lower flexural strength, and lower impact strength with maximum hardness, for the work piece fabricated at 1000 rpm using a high-speed steel tool with a cylindrical profile was observed. Better understanding of the effect of tool rotational speed and mechanical properties was illustrated through the experimental result.

Keywords: Aluminum alloy, tensile strength, impact, strength, cylindrical pin profile

GENERAL INTRODUCTION

Welding is a joining process that fabricates various parts or components to produce products of complex shapes and geometry, which are otherwise too difficult to produce through other manufacturing processes. To produce efficient, compact complex products that can fulfill their functional and esthetic requirements, it is necessary to use a suitable fabrication process to assemble several smaller components possessing exotic properties. Welding is a common option to join such components. Joining of dissimilar material often poses serious challenges
to such an extent that joining is sometimes not possible at all. This problem is mainly because of difference in mechanical, physical, chemical, and metallurgical properties of the materials being joined. Difference in melting point, thermal expansion coefficient, thermal conductivity, etc. may cause failure at the weldments even during welding. Welding constitutes an essential manufacturing process that enables the production of a wide range of products being used in automotive, shipbuilding, aerospace, and several other industrial sectors. However, welding processes are extremely complex and multidimensional in terms of materials, process, and workmen skill, which make the fabrication of desired quality joint extremely difficult.

Joining of dissimilar materials with desirable overall quality is a challenging research field and welding of dissimilar materials has always been a matter of concern for engineers and scientists worldwide. There has been an ever-increasing demand for products possessing properties such
as light weight, high strength, good corrosion resistance, etc. To fabricate a single structure, comprising several components often of different materials that exhibit various desirable properties, it is essential to join dissimilar materials together. Thus, welding of different grades of aluminum alloys having desirable mechanical and thermal properties owing to their high specific strength, thermal conductivity, and corrosion resistance are in great demand. Property–microstructure relationship in aluminum alloys. Several examples are found where aluminum alloys of different grades are joined together to provide desirable properties to the structure. For example, joining of 5xxx aluminum alloy (used for hull) with 6xxx aluminum alloy (used for secondary structural component) in a ship; similarly joining of 2xxx (a material for lower wing) and 7xxx series aluminum alloy (used to make upper wing) in aircraft, etc.

Economical and technical advantages of joining dissimilar materials have enabled its use in various industrial applications. Joining dissimilar materials by FSW has emerged as a new research topic. FSW has not only been found to produce near-defect-free joints with sound post welding
mechanical properties while joining various similar and dissimilar aluminum alloys but has also been able to effectively join a few previously difficult-to-weld aluminum alloys such as 2xxx and 7xxx series. However, to obtain acceptable quality welds important FSW process parameters need to be established for efficient joining of dissimilar aluminum alloys by preventing brittle intermetallic formation and imperfections in the joints to promote adequate flow of material and to mitigate deterioration in mechanical properties and surface morphology. Efficient and effective
joining of dissimilar materials requires adequate flow of material around the tool pin and proper mixing of material at stir zone (SZ) during welding for which the strategies pertaining to the joint design, tool design, and tool offset from the faying surface of base materials (BMs) need to be addressed as they play a critical role in the success of FSW of dissimilar alloys.

CHPTER I

1.1. INTRODUCTION

In this world we have two type of metals, ferrous and non-ferrous metals.

Ferrous metals contain iron, and are known for their strength, stainless steel, think steel, carbon steel, cast iron, ferrous metals are used in both architectural and industrial fabrication, such as skyscapes, bridges, vehicles and rail roads, thanks to their magnetic properties, ferrous metal are also used in appliances and engines, ferrous metals also have a high carbon content, which generally makes them prone to rust, the exceptions are stainless steel because of chromium, and wrought iron because of its high pure content

For non-ferrous metals it's have been used since the age copper, it doesn't contain iron, they're usually more corrosion resistant than ferrous metal, some example of non-ferrous metals are aluminum, aluminum alloys and copper, wish are often used in industrial application, such as gutters, roofing, pipes, and electrical, non-ferrous metals also include brass, gold, gold, nickel, silver, tin and zinc, other common properties of non-ferrous metals are non-magnetic, malleable, and lightweight, this makes them ideal for use in aircraft and other application.

Aluminum's unique properties, its lightweight strength, and resistance to corrosion- make it an ideal material for use in conventional and novel applications.

Aluminum has become increasingly important in the production of automobiles and trucks, packaging of food and beverages, construction of buildings, transmission of electricity, development, manufacture of machinery and tools, and production of defense and aerospace equipment, manufacture of machinery and tools, and production of durable consumer products, as demand for more technologically complex and ecologically sustainable products increases, opportunities for aluminum will continue to expand

In this chapter we will focus on aluminum, and see some of its properties, and mechanical properties and how we can get it from the earth and some advantages of this metal and how we can weld it.

1.2. Nature of aluminum alloys

Aluminum is the most abundant metal and the third most abundant chemical element in Earth’s crust, comprising over 8% of its weight. Only oxygen and silicon are more prevalent. Yet, until about 150 years ago aluminum in its metallic form was unknown to humans. The reason for this is that aluminum, unlike iron or copper, does not exist as a metal in nature. Because of its chemical activity and its affinity for oxygen, aluminum is always found combined with other elements, mainly as aluminum oxide. As such it is found in nearly all clays and many minerals. Rubies and sapphires are aluminum oxide colored by trace impurities, and corundum, also aluminum oxide, is the second hardest naturally occurring substance on Earth—only diamond is harder. It was not until 1886 that scientists learned how to economically extract aluminum from aluminum oxide via electrolytic reduction. Yet in the more than 100 years since that time, aluminum has become the second most widely used of the approximately 60 naturally occurring metals, second only to iron.

Aluminum alloys are broadly used in products and applications that touch us regularly in our daily lives, from aluminum foil for food packaging and easy-open aluminum cans for your beverages to the structural members of the ground vehicles and the aircraft in which we travel. The broad use of aluminum alloys is dictated by a very desirable combination of properties, combined with the ease with which they may be produced in a great variety of forms and shapes plus the ease with which they may be recycled and reused endlessly. In this chapter, we will review the characteristics of aluminum alloys that make them so attractive and note the variety of applications in which they are used.[1]

1.3. History of aluminum

Aluminum is a strongly electro-negative metal and possesses a strong affinity for oxygen; this is apparent from the high heat of formation of its oxide. For this reason, although it is among the six most widely distributed metals on the surface of the earth, it was not isolated until well into the nineteenth century.

Alumina (Al_2O_3) was known, however, in the eighteenth century, and the first unsuccessful attempts to isolate the metal were made by Sir Humphry Davy in 1807, when the isolation of the alkali metals had made a powerful reducing agent available. It was not, however, until 1825 that the Danish Worker, H.C. Oersted, succeeded in preparing aluminum powder by the reduction of anhydrous aluminum chloride with sodium amalgam; two years later, F. Wohler replaced the amalgam by potassium, and between 1827 and 1847 discovered and listed many of the chemical and physical properties. However, many years passed before the metal could be produced commercially.

The father of the light metal industry was probably the French scientist, Henri Sainte-Claire Deville, who in 1850 improved Wohler's method of preparation by replacing potassium by sodium, and by using the double chloride of sodium and aluminum as his source of the metal, thus making the production of aluminum a commercial proposition; the price of the metal, however, was still comparable with that of gold.

The production of aluminum received a further impetus when Robert Bunsen and, following him, Deville, showed how the metal could be produced electrolytically from its ores.

In 1885, the brothers Cowie produced the first aluminum alloys containing iron and copper, soon after which the invention of the dynamo made a cheaper supply of electricity available and resulted, in 1886, in Heroult's and Hall's independent French and American patents for the electrolytic production of aluminum from alumina and molten cryolite (AIF_3NaF). Thenceforth, the production of aluminum in Europe centered round the first factory in Neuhausen, while Hall's process was applied in the U.S.A. in Pittsburgh. Modem production of aluminum begins from the mineral bauxite, which contains approximately 25% of aluminum. This is converted to alumina by digestion with a solution of sodium hydroxide under pressure (the Bayer process), and the purified alumina produced is added to a molten mixture of cryolite and fluorspar. This mixture
is electrolysis in a cell with carbon anodes and the molten mixture is tapped from the bottom of the cell.[3]

1.4. Molten metal processing

Virgin molten aluminum produced by Hall-Heroult process contains Fe, Si, Zn, Ga, Na as major impurity elements, Ti , V, Mn, Cu, Mg, B as minor one and Al2O3, Al_4C_3, VB et al. as inclusions. Na is usually removed by Cl2 gas or N2 þ Cl2 gas fluxion into virgin molten aluminum in smelter-based cast house because a few ppm Na in Al-Mg alloy induces cracking during hot working. The primary aluminum produced by smelter is usually about 99.50^99.85% pure, and a small amount of 99.85^99.96% pure aluminum can be produced from a few electrolysis cells operated carefully. Primary aluminum can be refined to 99.990 - 99.998% purity by three-layer electrolysis process in a fused salt mixture. Three-layer electrolysis and Na removal treatment are both smelter-based molten aluminum processing. Pure aluminum of 99.99% is mostly utilized as foil material for capacitors. Recently, several segregation (fractional solidification) methods which are superior on cost performance of purification process, have been developed and 99.98^99.996% pure aluminum purified by those solidification processing has come to be utilized for capacitor instead of three-layer electrolysis aluminum. Ultra-purity aluminum over 99.9990% can be made by zone-melting. Molten primary aluminum for electronic wire is treated by B addition for the purpose of Ti and V removal because Ti and V in solid solution remarkably reduces the electroconductivity of aluminum. Aluminum is very reactive and the chemical reaction between aluminum and water vapor generates hydrogen gas at high temperature. This is the source of hydrogen dissolved into aluminum. Hydrogen solubility in aluminum is determined by an equilibrium relationship between hydrogen concentration in aluminum and hydrogen gas partial pressure in ambient atmosphere. Hydrogen solubility in solid aluminum is far smaller than in liquid aluminum. Therefore, excess dissolved hydrogen in molten aluminum over solid solubility forms hydrogen gas pores during solidification or is frozen into super saturated hydrogen solid solution. Excess hydrogen frozen into
solid solution heterogeneously precipitates to make gas pores during some heat treatment of cast product. These gas pores impair the strength, ductility, and the cutting surface quality of cast product. This is the reason why the melt treatment to remove hydrogen gas is necessary at cast house. The removal of inclusions at cast house is also necessary to assure the quality of aluminum

products because inclusions impair the mechanical property and cutting surface quality of the material. Many ways of the melt treatment to remove hydrogen gas and inclusions in aluminum have been developed. Particularly, the development of the process of inert gas dispersion into molten aluminum by a rotating nozzle (Union Carbide is the first developer in 1976) innovated the current way to remove gas and inclusion in the cast house of the aluminum industry, because of its high efficiency, low-cost performance, and environmental improvement. Filtration method of molten aluminum for inclusion removal has been available from long ago. The technological innovation in this area is due to the development of the new material for filtration such as foamed ceramics and bonded particle media, and the improvement of the reliability of filtration with the development of a quantitative analyzing method for inclusions. The above-mentioned processes of molten aluminum have the same purpose of ‘‘Refining.’’ Grain refining is another type of solidification processing by which fine grain size after solidification can be obtained. Fine grain size is necessary to avoid solidification cracking. Modification treatment by a small amount of Na or Sr addition to Al-Si foundry alloy is necessary to obtain fine eutectic microstructure as solidified. Such a micro alloying effect to cast structure is also observed in intermetallic phases (Al_x Fe_y) appearance of commercial pure aluminum for anodized panels. As mentioned before, several types of molten metal processing such as segregation, grain refining, medication and micro alloying may not be defined as molten metal processing but as solidification processing. So, the author here focuses on the melt treatment for refining such as hydrogen removal, inclusions removal and alkali elements removal from molten aluminum. Molten metal processing plays a very important role in the aluminum industry and the development of new process technology has made a great impact on the cost performance and the quality assurance of aluminum products. [1]

1.5. Properties of aluminum

Aluminum's unique properties – its light weight, high strength, and resistance to corrosion – make it an ideal material for use in conventional and novel applications. Aluminum has become increasingly important in the production of automobiles and trucks, packaging of food and beverages, construction of buildings, transmission of electricity, development of transportation infrastructures, production of defense and aerospace equipment, manufacture of machinery and tools, and production of durable consumer products. As demand for more technologically complex and ecologically sustainable products increases, opportunities for aluminum will continue to expand.

Aluminum is the chemical element of the 3rd group in the periodic table of the elements. The atomic number of aluminums is 13, values for the atomic weight are 26.9815 based on 12C, and 26.98974 based on 16O. Aluminum has a silver-white color. It does not have any natural isotopes. Its artificial isotopes are radioactive isotopes, – ^{26}Al and ^{26}Al. The isotope ^{26}Al has a half-life of 10^6 years and isotope ^{27}Al is stable and consists of 14 neutrons and 13 protons. Table 1 lists the properties and characteristics of some isotopes found in aluminum.

The nuclear properties of aluminum are of practical interest. The naturally occurring isotope Al^{27} has a cross section for thermal neutrons of 0.21 barn (1 barn = 10^{-24}cm^2). This low cross

Table 1. Isotopes of aluminum [2].

Isotope	Half-life	Particles absorbed	Type of decay	Energy of radiation, ev*	Some typical modes of formation
Al^{23}	0.13 sec	–	–	–	–
Al^{24}	2.7 sec	Neutron	$\beta+$	~8.5	Mg^{24} (p, n)
			γ	1.38–7.1	–
Al^{25}	7.5 sec	Neutron	$\beta+$	3.2	Mg^{25} (p, n)
Al^{26m}	7.0 sec	Neutron	$\beta+$	3.2	Mg^{25} (d, n)
Al^{26}	10^6 years	Neutron	ec (**)	–	Mg^{25} (d, n)
			β	1.16	Mg^{26} (p, n)
			γ	1.83, 1.14	Al^{27} (n, 2n)
Al^{27}	100% abundance, stable	–	–	–	–
Al^{28}	144 sec	2 protons	β-	2.86	Al^{27} (n, γ)
		1 proton	γ	1.78, 1.27	Al^{27} (n, γ)
Al^{29}	396 sec	Proton	β-	2.5, 1.4	Al (α, 2p)
		Proton	γ	1.28, 2.43	Mg (α, p)

* Electron-volts
** Electron capture

section combined with the short half-life of the radio- active product from the irradiation of aluminum an especially attractive material for use within nuclear reactors. In the early nuclear reactors, aluminum was used almost exclusively for protective sheaths around uranium fuel elements and as tube and fittings for conducting coolant through the pile.

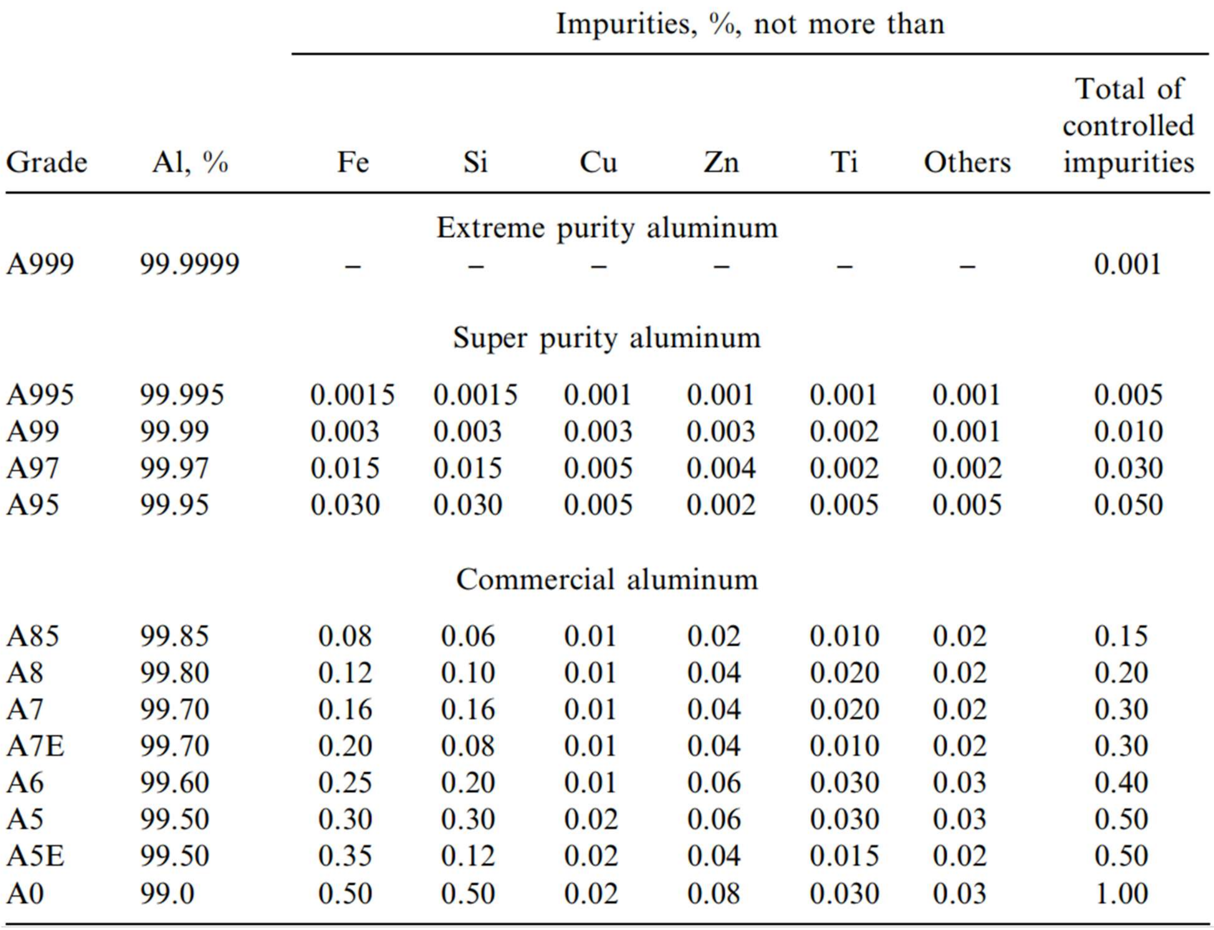
Aluminum may possess a coordination number for oxygen of either 4 or 6. The process of recrystallization of aluminum oxide is normally slow. Thus, there are a great many crystal structures for aluminum oxide. The corundum structure has only 6 coordinate Al in hexagonal crystals. It can probably be viewed as a distorted hex- agonal closest packed structure of oxide ions, with some of the octahedral holes occupied by Al3+ ions. Beta alumina has spinal structure with extra cation vacancies to bring the stoichiometry to M_2O_3 from the ideal spinal formula of MM_2O_4.[2]

1.6. Grades of aluminum

Depending on number of impurities, aluminum is classified into extreme purity aluminum and commercial purity aluminum (primary aluminum).

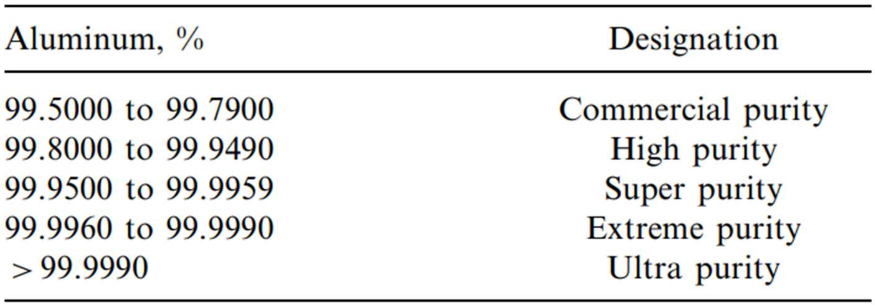
In Russia there are four grades of extreme purity metal with the content of aluminum no less than 99.996%; 99.99%; 99.97%, 99.93%, other elements present are iron, silicon, copper. The chemical composition of primary aluminum is pre- scented in Table 2 (Russian Standard GOST 11069–74). Table 3 shows nomenclature for the various degrees of purity of aluminum accepted in the USA. Aluminum exceeding 99.99% in purity, produced by the Hoopes electrolytic process, was first available early in 1920. In 1925, Edwards reported some of the physical and mechanical properties of this grade of aluminum. Taylor, Willey, Smith, and Edwards published a paper in 1938 that gave several properties for 99.996% Al that was produced in France by a modified Hoopes process.

Table 2. Russian classification of aluminum [2].



Grade	Al, %	Fe	Si	Cu	Zn	Ti	Others	Total of controlled impurities
		Impurities, %, not more than						
		Extreme purity aluminum						
A999	99.9999	–	–	–	–	–	–	0.001
		Super purity aluminum						
A995	99.995	0.0015	0.0015	0.001	0.001	0.001	0.001	0.005
A99	99.99	0.003	0.003	0.003	0.003	0.002	0.001	0.010
A97	99.97	0.015	0.015	0.005	0.004	0.002	0.002	0.030
A95	99.95	0.030	0.030	0.005	0.002	0.005	0.005	0.050
		Commercial aluminum						
A85	99.85	0.08	0.06	0.01	0.02	0.010	0.02	0.15
A8	99.80	0.12	0.10	0.01	0.04	0.020	0.02	0.20
A7	99.70	0.16	0.16	0.01	0.04	0.020	0.02	0.30
A7E	99.70	0.20	0.08	0.01	0.04	0.010	0.02	0.30
A6	99.60	0.25	0.20	0.01	0.06	0.030	0.03	0.40
A5	99.50	0.30	0.30	0.02	0.06	0.030	0.03	0.50
A5E	99.50	0.35	0.12	0.02	0.04	0.015	0.02	0.50
A0	99.0	0.50	0.50	0.02	0.08	0.030	0.03	1.00

Table 3. The various degrees of purity of pure aluminum (the USA standard) [2].



Aluminum, %	Designation
99.5000 to 99.7900	Commercial purity
99.8000 to 99.9490	High purity
99.9500 to 99.9959	Super purity
99.9960 to 99.9990	Extreme purity
> 99.9990	Ultra purity

Based on ISO standards the classification of aluminum is shown in the table 4

The chemical composition of the extreme purity and primary aluminum according to the DIN1712 is shown in Table 5. Great Britain, Germany, France, Japan, Russia, and in the recommendations of the international organization for standardization (ISO). The list includes only those alloys that are essentially in agreement composition-wise with the composition of the AA alloy. Standards are subject to change and the actual issue of the specification or standard currently in effect should be consulted for full information.[2]

Table 4. Classification of aluminum based on international standard (ISO) [2].

Purity of aluminum	Designation
Extreme purity	A199.99R; A199.95R; A199.9R; A199.8; A199.7
Commercial purity	A199.8; A199.7; A199.5
For electrical industry (wires)	A199.4; A199.0; A198 E-Al
Extreme purity	A199.99R; A199.95R; A199.9R; A199.8; A199.7; A199.5
Commercial purity	E-Al*
For electrical industry (wires)	E-Al**

* Electrical conductivity in annealing condition is more than 35.7 μOhm × mm^{-2}
** Electrical conductivity in annealing condition is more than 35.4 μOhm × mm^{-2}

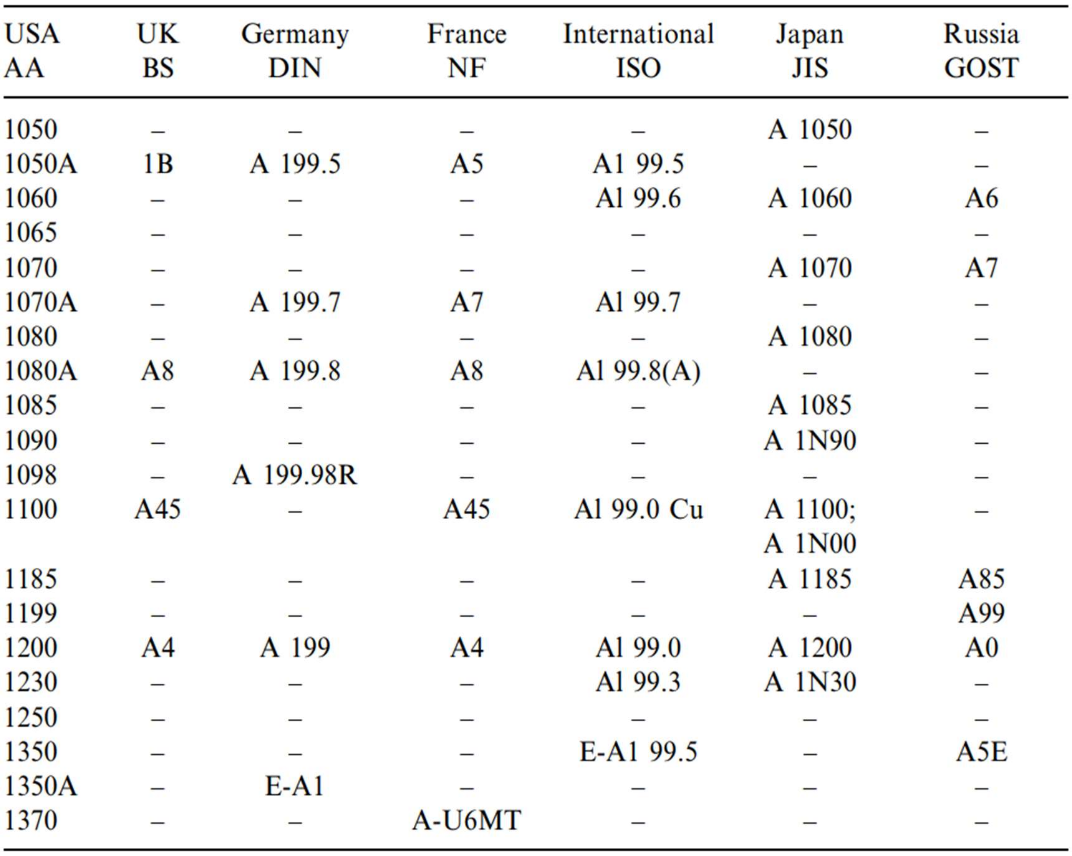
Table 5: The chemical composition of the aluminum of different grades (The German standard).

		Allowable impurities						
			Including					
Grade	Number	Total	Si	Fe	Ti	Cu	Zn	Others
A 199.99R	3.0400	0.01	0.060	0.005	0.002	0.003	0.005	0.001
A 199.99R	3.0300	0.10	0.050	0.035	0.006	0.005	0.040	0.003
A 199.8H	3.0280	0.20	0.150	0.15	0.030	0.010	0.060	0.010
A 199.7H	3.0270	0.30	0.200	0.25	0.030	0.010	0.060	0.010
A 199.5H	3.0250	0.50	0.300	0.40	0.030	0.020	0.070	0.030
A 199.0H	3.0200	1.00	0.500	0.06	0.030	0.020	0.080	0.030

1.7. PHYSICAL PROPERTIES

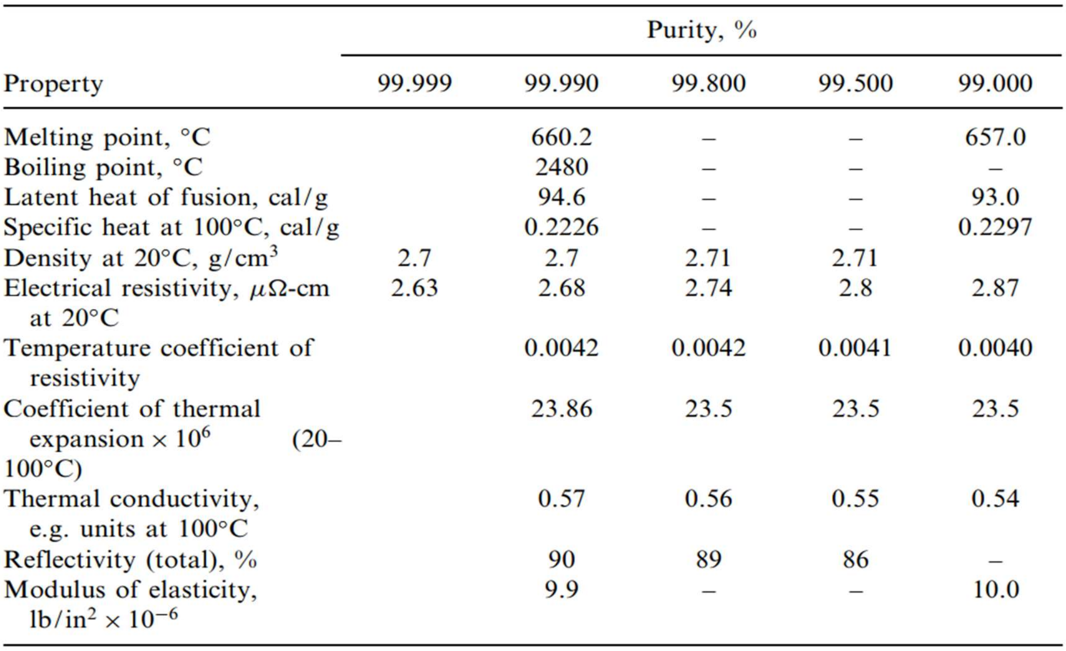
The properties of aluminum depend to some extent on purity. This may vary from the ordinary aluminum of commercial purity to super-purity aluminum. For special purposes, aluminum may be further purified by zone refining to give a purity of about 99.99995%. Aluminum is well known for its low density, 2.7 g/cm^3, high reflectivity and high electrical and thermal conductivity. It is very resistant to atmospheric corrosion, due to instantaneous formation of an adherent oxide film, which protects the metal against further attack. The more important physical properties are shown in Table 7, which also indicates how these properties are affected by purity. It will be seen that the main effects of purity are upon electrical resistivity (the electrical resistance offered by a material to the flow of current, times the cross-sectional area of current flow and per unit length of current path; the reciprocal of the conductivity) and thermal conductivity.[2]

Table 6. International Cross References on Aluminum [2].



USA AA	UK BS	Germany DIN	France NF	International ISO	Japan JIS	Russia GOST
1050	–	–	–	–	A 1050	–
1050A	1B	A 199.5	A5	A1 99.5	–	–
1060	–	–	–	Al 99.6	A 1060	A6
1065	–	–	–	–	–	–
1070	–	–	–	–	A 1070	A7
1070A	–	A 199.7	A7	Al 99.7	–	–
1080	–	–	–	–	A 1080	–
1080A	A8	A 199.8	A8	Al 99.8(A)	–	–
1085	–	–	–	–	A 1085	–
1090	–	–	–	–	A 1N90	–
1098	–	A 199.98R	–	–	–	–
1100	A45	–	A45	Al 99.0 Cu	A 1100; A 1N00	–
1185	–	–	–	–	A 1185	A85
1199	–	–	–	–	–	A99
1200	A4	A 199	A4	Al 99.0	A 1200	A0
1230	–	–	–	Al 99.3	A 1N30	–
1250	–	–	–	–	–	–
1350	–	–	–	E-A1 99.5	–	A5E
1350A	–	E-A1	–	–	–	–
1370	–	–	A-U6MT	–	–	–

Table 7. Physical properties of aluminum [2].



	Purity, %				
Property	99.999	99.990	99.800	99.500	99.000
Melting point, °C		660.2	–	–	657.0
Boiling point, °C		2480	–	–	–
Latent heat of fusion, cal/g		94.6	–	–	93.0
Specific heat at 100°C, cal/g		0.2226	–	–	0.2297
Density at 20°C, g/cm^3	2.7	2.7	2.71	2.71	
Electrical resistivity, $\mu\Omega$-cm at 20°C	2.63	2.68	2.74	2.8	2.87
Temperature coefficient of resistivity		0.0042	0.0042	0.0041	0.0040
Coefficient of thermal expansion × 10^6 (20–100°C)		23.86	23.5	23.5	23.5
Thermal conductivity, e.g. units at 100°C		0.57	0.56	0.55	0.54
Reflectivity (total), %		90	89	86	–
Modulus of elasticity, lb/in^2 × 10^{-6}		9.9	–	–	10.0

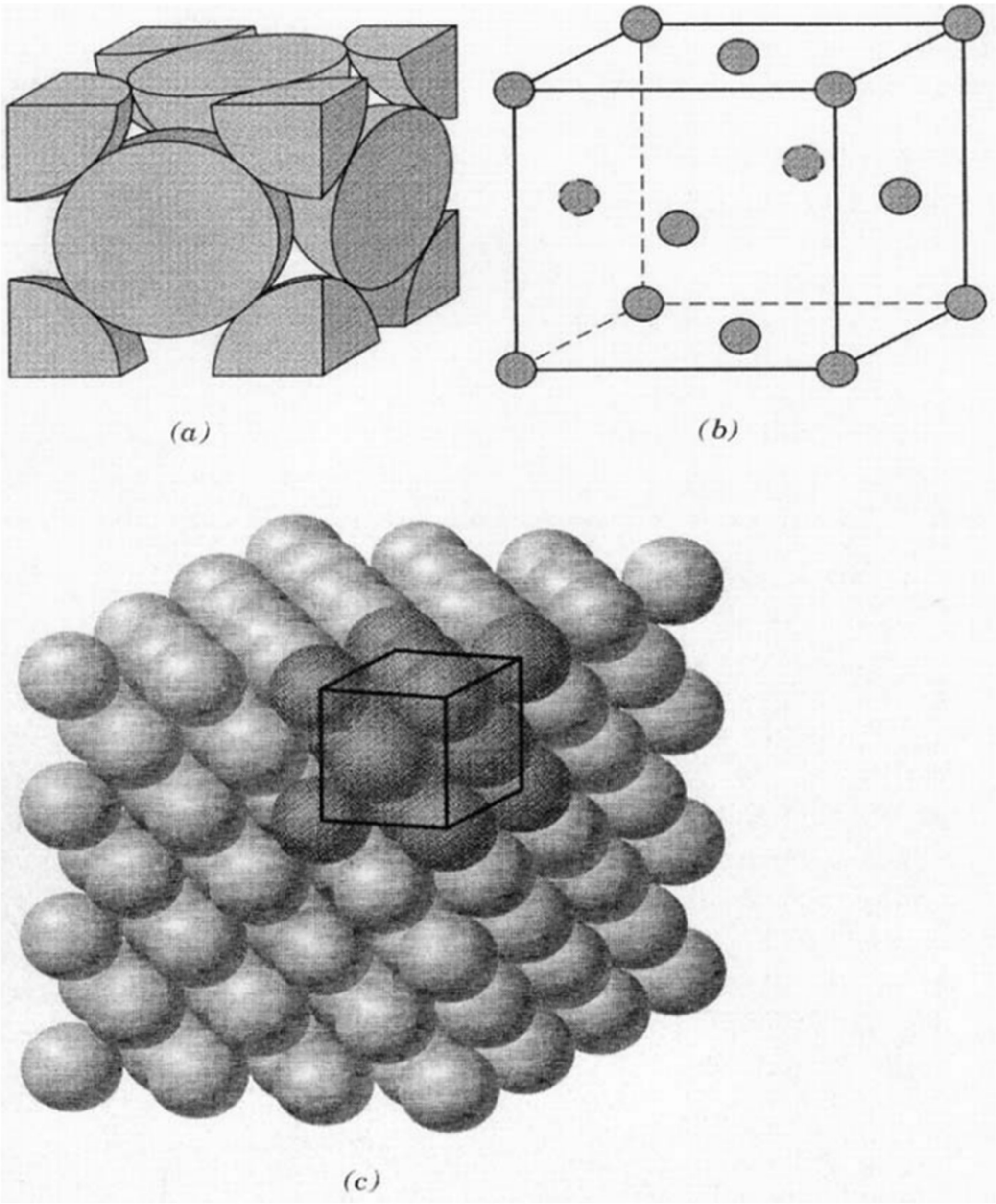


Figure 1. the crystal structure of aluminum – the face-centered cubic crystal structure: (a) a hard sphere unit cell representation, (b) a reduced-sphere unit cell, and (c) an aggregated of many atoms

1.8. Development of aluminum alloys

The chief alloying constituents added to aluminum are copper, magnesium, silicon, manganese, nickel, and zinc. All of these are used to increase the strength of pure aluminum.

Two classes of alloys may be considered. The first are the 'cast alloys' which are cast directly into their desired forms by one of three methods (i.e., sand-casting, gravity die casting or pressure die casting), while the second class, the 'wrought alloys', are cast in ingots or billets and hot and cold worked mechanically into extrusions, forgings, sheet, foil, tube and wire. The main classes of alloys are the 2000 series (Al-Cu alloys), which are high-strength materials used mainly in the aircraft industry, the 3000 series (Al-Mn alloys) used mainly in the canning industry, the 5000 series (Al-Mg alloys) which are used unprotected for structural and architectural applications, the 6000 series (Al-Mg-Si alloys) which are the most common extrusion alloys and are used particularly in the building industry, and the 7000 series (Al-Zn-Mg alloys) which are again high strength alloys for aircraft and military vehicle applications.

The alloy used in any application will depend on factors such as the mechanical and physical properties required, the material cost and the service environment involved. If a finishing treatment is to be applied, then the suitability of the alloy for producing the finish desired will be an additional factor to be considered. The great benefit of aluminum is that such a wide variety of alloys with differing mechanical and protection properties is available, and these, together with the exceptional range of finishes which can be used, make aluminum a very versatile material.

1.9. Advantages of aluminum alloys

The first step in becoming familiar with the opportunities to utilize aluminum alloys advantageously is to briefly note some of the basic characteristics of wrought and cast aluminum alloys that make them desirable candidates for such a wide range of applications as well as their limitations. Wrought alloys (those mechanically formed by rolling, forging, and extrusion into useful products) are addressed first, then cast alloys (those cast directly to the near-final finished shape).[1]

1.10. Wrought aluminum alloys

1.10.1. Low density/specific gravity. One property of aluminum that everyone is familiar with is its light weight or, technically, its low density or specific gravity. The specific gravity of aluminum is only 2.7 times that of water and roughly one-third that of steel and copper. An easy number to remember is that 1 cubic inch (in.3) of aluminum weighs 0.1 lb; 1 cubic foot (ft3) weighs 170 lb compared to 62 lb for water and 490 lb for steel.[1]

1.10.2. High strength–weight ratio. The combination of relatively high strength with low density means a high-strength efficiency for aluminum alloys and many opportunities for replacement of heavier metals with no loss (and perhaps a gain) in load-carrying capacity. This characteristic, combined with the excellent corrosion resistance and recyclability, has led to aluminum's broad use in containers, aircraft, and automotive applications.

1.10.3. Excellent corrosion resistance. As a result of a naturally occurring tenacious surface oxide film, many aluminum alloys provide exceptional resistance to corrosion in many atmospheres and chemical environments. Alloys of the 1xxx, 3xxx, 5xxx, and 6xxx systems are especially favorable in this respect and are even used in applications where they are in direct contact with seawater and antiskid salts. With some electrocoating enhancements, the oxide coating can be thickened for even greater protection. Aluminum and several its alloys possess excellent resistance to corrosive attack by many foods and chemicals as well as natural environments.

1.10.4. High thermal conductivity. Aluminum and its alloys are good conductors of heat, and, while they melt at lower temperatures than steels, about 1000◦F (about 535◦C), they are slower to reach very high temperatures than steel in fire exposure.

1.10.5. High Electrical Conductivity. Pure aluminum and some of its alloys have exceptionally high electrical conductivity (i.e., very low electrical resistivity), second only to copper among common metals as conductors.

1.10.6. Excellent Reflectivity. Aluminum with appropriate surface treatment becomes an excellent reflector and does not dull from normal atmospheric oxidation.

1.10.7. High Fracture Toughness and Energy Absorption Capacity. Many aluminum alloys are exceptionally tough and excellent choices for critical applications where resistance to unstable crack growth and brittle fracture are imperatives. Alloys of the 5xxx series, for example, are prime choices for liquefied natural gas (LNG) tankage. Special high-toughness versions of aerospace alloys, such as 2124, 7050, and 7475, replace the standard versions of these alloys for critical bulkhead applications.

1.10.8. Superior Cryogenic Toughness. Aluminum alloys, especially of the 3xxx, 5xxx, and 6xxx series, are ideal for very low temperature applications because the ductility and toughness as well as strength of many alloys at subzero temperatures are as high as or higher than at room temperature, even down to near absolute zero. As noted above, the 5xxx series alloys are regularly used for liquefied gas tankage operating at temperatures from -150 to -452◦F (-65 to -269◦C).

1.10.9. Fatigue Strength. On an efficiency basis (strength to density) the fatigue strengths of many aluminum alloys are comparable to those of steels.

1.10.10. Low Modulus of Elasticity. Aluminum alloys have elastic moduli about one-third those of steels (about 10 × 106 psi vs. about 30 × 106 psi), so they absorb about three times as much elastic energy upon deformation to the same stress. They also deflect three times more under load.

1.10.11. Superior Workability. Aluminum alloys are readily workable by virtually all metalworking technologies and especially amenable to extrusion (the process of forcing heated metal through shaped dies to produce specific shaped sections). This enables aluminum to be produced in a remarkable variety of shapes and forms in which the metal can be placed in locations where it can most efficiently carry the applied loads.

1.10.12. Ease of Joining. Aluminum alloys may be joined by a very broad variety of commercial methods, including welding, brazing, soldering, riveting, bolting, and even nailing in addition to an unlimited variety of mechanical procedures. Welding, while considered difficult by those familiar only with joining steel and who try to apply the same techniques to aluminum, is particularly easy when performed by proven techniques such as gas–metal arc welding (GMAW or MIG) or gas–tungsten arc welding (GTAW or TIG).

1.10.13. Versatile Array of Finishes. Aluminum can be finished in more ways than any other metal used today, including a variety of techniques that build upon its strong oxide coating and employ coloring, plus more conventional means such as painting and enameling.

1.10.14. Ease of Recycling. Aluminum and its alloys are among the easiest to recycle of any structural materials. In addition, they are recyclable in the truest sense, unlike materials which are reused but in lower quality products: Aluminum alloys may be recycled directly back into the same high-quality products as rigid container sheet (cans) and automotive components. Through such recycling, the life-cycle assessment advantages for aluminum are optimized.

1.11. Cast aluminum alloys

The desirable characteristics of wrought alloys, including recyclability, are also generally applicable to cast alloys, but in fact the choice of one casting alloy or another tends to be more often made based on their relative abilities to meet one or more of the four following characteristics[1]:

- Ease of casting
- Quality of finish
- High strength, especially at high temperatures
- High toughness.

1.11.1. Ease of Casting. Many aluminum casting alloys have relatively high silicon contents that provide excellent flow characteristics during casting, enabling them to be utilized for large and complex castings (e.g., even complete engines). Relatively minute details in the shape of the casting can be accurately and reliably replicated.

1.11.2. Quality of Finish. By proper selection of aluminum casting alloy, extremely fine surface quality can be achieved. While such alloys typically require more attention to casting practice, they are widely used in applications where the finished casting surface mirrors the finish needed in surface.

1.11.3. High Strength. Many aluminum casting alloys respond to heat treatment following casting and achieve relatively high levels of strength and excellent strength–weight ratios. With careful design of molds, high chill rates can be assured and both high strength and high toughness can be achieved.

1.11.4. High Toughness. With careful selection of alloy and heart treatment combined with process technology often referred to as premium engineered casting, optimizing metal flow and chill rated, the toughness of castings may be comparable to that of wrought alloys at comparable strength levels. Techniques such as hot isostatic pressing (HIP) are available to further reduce porosity and improve performance.

Unfortunately, few casting alloys possess all four characteristics, but some generalizations useful in alloy selection for specific applications may be made:

1.11.5. Ease of Casting. The high-silicon 3xx.x series are outstanding in this respect as the relatively high silicon contents lend a characteristic of good flow and mold-filling capability. As a result, the 3xxx.x series are the most widely used and are especially chosen for large and very complex casting.

1.11.6. Finish. The 5xx.x and 7xx.x series are noteworthy for the fine finish they provide, but they are more difficult to cast than the 3xx.x series and so are usually limited to those applications where that finish is paramount. A good example is the use of 7xx.x alloys for bearings.

1.11.7. Strength and Toughness. The 2xx.x alloys typically provide the very highest strengths, especially at high temperatures, but are among the more difficult to cast and lack good surface characteristics. Therefore, their use is usually limited to situations where sophisticated casting techniques can be applied and where strength and toughness are at a premium, as in the aerospace industry. Relatively high strengths and superior toughness can also be achieved with some of the higher purity 3xx.x alloys (e.g., A356.0, A357.0) in heat-treated conditions.

1.12. Limitations of wrought and cast aluminum alloys

There are several characteristics of aluminum alloys that require special attention in alloy selection or design [1]:

1.12.1. Moduli of Elasticity. As noted earlier, the elastic moduli of aluminum alloys are about one-third those of steel. In applications such as bridges, where some designs may be deflection critical, this is a disadvantage and consideration should be given to the fact that aluminum alloys will deflect about three times more than comparably sized steel members. To compensate for this, aluminum members subject to bending loads are usually made deeper or thicker in their upper and lower extremities to reduce stresses and/or deflections.

1.12.2. Melting Temperature. Aluminum alloys melt at about 1000∘F (535∘C), well below where steels melt, and so they should not be selected for applications such as flue pipes and fire doors where the low melting point may result in unsatisfactory performance. The useful limit of high-temperature structural application of aluminum alloys is about 500∘F (about 260∘C) for conventional alloys or about 600∘F (315∘C) for alumina-enhanced alloys. It is useful to note, however, that even in the most intense fires, aluminum alloys do not burn; they are rated noncombustible in all types of fire tests and achieve the highest ratings in flame-spread tests. Further, as noted earlier, they are slower to reach high temperatures in fires than other metals such as steels because of their higher thermal conductivity and emissivity. Nevertheless, they should not be used where service requirements include structural strength above 500∘F (260∘C) or exposure above 700∘F (370∘C).

1.12.3. Stress Corrosion Susceptibility of Some Alloys. Some aluminum alloys, notably the 2xxx and 7xxx alloys, when stressed perpendicular to the major plane of grain flow (i.e., in the short-transverse direction), may be subject to intergranular stress corrosion cracking (SCC) unless they have been given a special thermal treatment to reduce or eliminate this type of behavior. If short-transverse stresses are anticipated in relatively thick components, 2xxx alloys should only be utilized in the T6- or T8-type tempers (not T3- or T4-type tempers), and 7xxx alloys should only be used in the T7-type tempers (not T6- or T8-type tempers). Similarly, 5xxx alloys with more than 3% Mg should not be used in applications where a combination of high stress and high temperature will be experienced over a long period of time (more than several hundred hours at or above 150∘F, or 65∘C) because some susceptibility to SCC may be encountered (i.e., the alloys may become "sensitized"); for applications where temperatures above about 150∘F (65∘C) are likely to be encountered for long periods, the use of 5xxx wrought alloys or 5xxx casting alloys with 3% or less Mg, e.g.

1.12.4. Mercury Embrittlement. Aluminum alloys should never be used when they may be in direct contact with liquid or vaporized mercury; severe grain boundary embrittlement may result. This is an unlikely exposure for most applications, but in any instance where there is the possibility of mercury being present, the use of aluminum alloys should be avoided.

1.13. Non-heat treatable alloys

Non-heat treatable and heat treatable alloys are two main groups of aluminum alloys. Non-heat treatable alloy categories (1xxx, 3xxx and 5xxx) are not strengthened by second- phase particles and usually are called non- precipitation hardening alloys. The strengthening methods for these alloys include cold working (strain hardening) or refining the microstructure (reduction of grain size or formation of substructure). For non-heat treatable alloys, the only appropriate heat treatment is annealing. The annealing process of cold worked metals includes recovery, recrystallization, and grain growth, and it is applied to increase the capacity for further deformation. In the case of Al alloys, a completely annealed alloy is assigned usually as ‘O temper’, while alloys with some levels of cold deformation are called ‘Hxxx’, in which the xxx indicates the amount of cold working.

In FSW joints of non- heat treatable alloys, the only heat treatment possible in different distinct zones is an annealing cycle. The final microstructural features depend on the type of alloys (O or H condition). For example, if the BM is in the O condition, it will be possible that the temperature transient results in grain growth in HAZ. However, if the BM is in the H condition, recrystallization can occur in the HAZ area.

1.14. Heat treatable alloys

The heat treatable Al alloys (2xxx, 6xxx and 7xxx) are strengthened by second-phase particles and are popular to precipitation hardening of alloys. The primary alloying elements for the three alloy classes are copper (2xxx), magnesium and silicon (6xxx) and magnesium and zinc (7xxx), respectively. Usually, the strengthening effect is mainly due to the existence of a single precipitate phase. However, it can be due to several precipitate phases in the microstructure. Therefore, because of the heat input associated with FSW in these alloys, metallurgical phenomena other than annealing can take place in different regions of the joints, such as ageing, over- ageing, precipitation growth or dissolution. In NZ of heat treatable alloys, depending on the alloy type and welding condition, different phenomena may happen. For example, NZ may experience an over- aged condition, a partially solution heat treated condition or a single- phase solid solution. The microstructural features of different zones can be investigated directly by TEM and inferred by its response to a post- weld ageing treatment.

1.15. Designation systems

One advantage in using aluminum alloys and tempers is the universally accepted and easily understood alloy and temper systems by which they are known. It is extremely useful for both secondary fabricators and users of aluminum products and components to have a working knowledge of those designation systems. The alloy system provides a standard form of alloy identification that enables the user to understand a great deal about the chemical composition and characteristics of the alloy, and similarly, the temper designation system permits one to understand a great deal about the way in which the product has been fabricated.

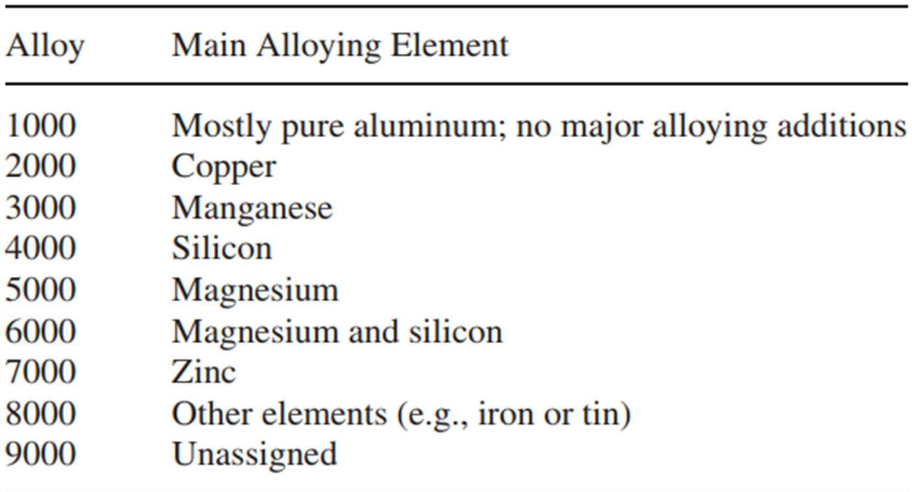
The alloy and temper designation systems in use today for wrought aluminum were adopted by the aluminum industry in about 1955, and the current cast system was developed somewhat later. The aluminum industry created and continues to maintain the designation of the systems through its industry organization, the Aluminum Association. The alloy registration process is carefully controlled and its integrity maintained by the Technical Committee on Product Standards of the Aluminum Association, made up of industry standards experts.5 Further, as noted earlier, the Aluminum Association designation system is the basis of the American National Standards Institute (ANSI) standards, incorporated in ANSI H35.16 and, for the wrought alloy system at least, is the basis of the near-worldwide *International Accord on Aluminum Alloy Designations*.7 It is useful to note that the international accord does not encompass casting alloy designations, so more variation will be encountered in international designations for casting alloys than for wrought aluminum alloys.

1.16. Wrought aluminum alloy Designation system

The Aluminum Association wrought alloy designation system consists of four numerical digits, sometimes with alphabetic prefixes or suffices, but normally just the *four* numbers:

- The first digit defines the major alloying class of the series starting with that number.
- The second defines variations in the original basic alloy; that digit is always a 0 for the original composition, a 1 for the first variation, a 2 for the second variation, and so forth; variations are typically defined by differences in one or more alloying elements of 0.15–0.50% or more, depending upon the level of the added element.
- The third and fourth digits designate the specific alloy within the series; there is no special significance to the values of those digits, and they are not necessarily used in sequence. Table 8 shows the meaning of the first of the four digits in the wrought alloy designation system. The alloy family is identified by that number and the associated main alloying ingredient(s), with three exceptions:
- Members of the 1000 series family are commercially pure aluminum or special-purity versions and as such do not typically have any alloying elements intentionally added; however, they do contain minor impurities that are not removed unless the intended application requires it.

Table 8. Main alloying element in wrought alloy designation system [1].



Alloy	Main Alloying Element
1000	Mostly pure aluminum; no major alloying additions
2000	Copper
3000	Manganese
4000	Silicon
5000	Magnesium
6000	Magnesium and silicon
7000	Zinc
8000	Other elements (e.g., iron or tin)
9000	Unassigned

- The 8000 series family is an “other elements” series, comprised of alloys with rather unusual major alloying elements such as iron and nickel.
- The 9000 series is unassigned. The major benefit of understanding this designation system is that one can tell a great deal about the alloy just from knowledge of which it is a member. For example:
- As indicated earlier, the 1xxx series are pure aluminum and its variations; compositions of 99.0%

or more aluminum are in this series. Within the 1xxx series, the last two of the four digits in the designation indicate the minimum aluminum percentage. These digits are the same as the two digits to the right of the decimal point in the minimum aluminum percentage specified for the designation when expressed to the nearest 0.01%. As with the rest of the alloy series, the second digit indicates modifications in impurity limits or intentionally added elements. Compositions of the 1xxx series do not respond to any solution heat treatment but may be strengthened modestly by strain hardening.

- The 2xxx series alloys have copper as their main alloying element and, because it will go in significant amounts into solid solution in aluminum, they will respond to solution heat treatment; they are referred to as heat treatable.
- The 3xxx series alloys are based on manganese and are strain hard enable; they do not respond to solution heat treatment.
- The 4xxx series alloys are based on silicon; some alloys are heat treatable, others are not, depending upon the amount of silicon and the other alloying constituents.
- The 5xxx series alloys are based on magnesium and are strain hard enable, not heat treatable.
- The 6xxx series alloys have both magnesium and silicon as their main alloying elements; these combine as magnesium silicide (Mg2Si) following solid solution, and so the alloys are heat treatable.
- The 7xxx series alloys have zinc as their main alloying element, often with significant amounts of copper and magnesium, and they are heat treatable.
- The 8xxx series contain one or more of several less frequently used major alloying elements like iron or tin; their characteristics depend on the major alloying element(s).

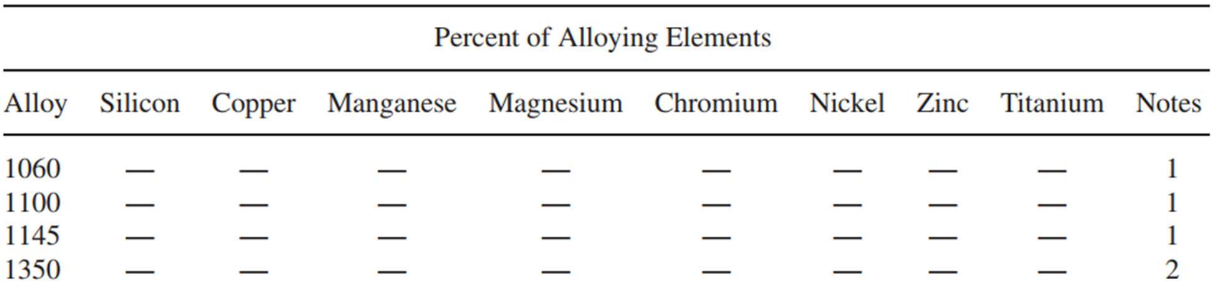
The compositions of a representative group of widely used commercial wrought aluminum alloys are given in Table 8, from Aluminum Standards and Data2 and other Aluminum Association publications[1].

1.17. Cast Aluminum alloy designation system

The designation system for cast aluminum alloys is similar in some respects to that for wrought alloys but has a few very important differences as noted by the following description.

Like the wrought alloy system, the cast alloy designation system also has four digits but differs from the wrought alloy system in that a decimal point is used between the third and fourth digits to make clear that these are designations to identify alloys in the form of castings or foundry ingot.

Table 9. Nominal Compositions of Wrought Aluminum Alloy [1].



	Percent of Alloying Elements								
Alloy	Silicon	Copper	Manganese	Magnesium	Chromium	Nickel	Zinc	Titanium	Notes
1060	—	—	—	—	—	—	—	—	1
1100	—	—	—	—	—	—	—	—	1
1145	—	—	—	—	—	—	—	—	1
1350	—	—	—	—	—	—	—	—	2

Table 9 (continued)

2010	—	1.0	0.25	0.7	—	—	—	—	
2011	—	5.5	—	—	—	—	—	—	4
2014	0.8	4.4	0.8	0.50	—	—	—	—	
2017	0.50	4.0	0.7	0.6	—	—	—	—	
2024	—	4.4	0.6	1.5	—		—	—	
2025	0.8	4.4	0.8	—	—		—	—	
2036	—	2.6	0.25	0.45	—	—	—	—	
2117	—	2.6	—	0.35	—	—	—	—	
2124	—	4.4	0.6	1.5	—	—	—	—	5
2195	—	4.0	—	0.50	—	—	—	—	5
2219	—	6.3	0.30	—	—	—	—	0.06	7
2319	—	6.3	0.30	—	—	—	—	0.15	7
2618	0.18	2.3	—	1.6	—	1	—	0.07	8
3003	—	0.12	1.2	—	—	—	—	—	
3004	—	—	1.2	1	—	—	—	—	
3005	—	—	1.2	0.40	—	—	—	—	
3105	—	—	0.6	0.50	—	—	—	—	
4032	12.2	0.9	—	—	—	—	0.9	—	
4043	5.2	—	—	—	—	—	—	—	
4643	4.1	—	—	0.20	—	—	—	—	
5005	—	—	—	0.8	—	—	—	—	
5050	—	—	—	1.4	—	—	—	—	
5052	—	—	—	2.5	0.25	—	—	—	
5056	—	—	0.12	5.0	0.12	—	—	—	
5083	—	—	0.7	4.4	0.15	—	—	—	
5086	—	—	0.45	4.0	0.15	—	—	—	
5154	—	—	—	3.5	0.25	—	—	—	
5183	—	—	0.8	4.8	0.15	—	—	—	
5356	—	—	0.12	5.0	0.12	—	—	0.13	
5454	—	—	0.8	2.7	0.12	—	—	—	
5456	—	—	0.8	5.1	0.12	—	—	—	
5457	—	—	0.30	1.0	—	—	—	—	
5554	—	—	0.8	2.7	0.12	—	—	0.12	
5556	—	—	0.8	5.1	0.12	—	—	0.12	
5657	—	—	—	0.8	—	—	—	—	
5754	—	—	0.5	3.1	0.3	—	—	—	
6005	0.8	—	—	0.50	—	—	—	—	
6009	—	—	—	—	—	—	—	—	
6013	0.8	0.8	0.50	1.0	—	—	—	—	
6053	0.7	—	—	1.2	0.25	—	—	—	
6061	0.6	0.28	—	1.0	0.20	—	—	—	
6063	0.40	—	—	0.7	—	—	—	—	

Table 9 (continued)

	Percent of Alloying Elements								
Alloy	Silicon	Copper	Manganese	Magnesium	Chromium	Nickel	Zinc	Titanium	Notes
6066	1.4	1.0	0.8	1.1	—	—	—	—	
6070	1.4	0.28	0.7	0.8	—	—	—	—	
6101	0.50	—	—	0.6	—	—	—	—	
6111	0.85	0.7	0.28	0.75	—	—	—	—	
6151	0.9	—	—	0.6	0.25	—	—	—	
6201	0.7	—	—	0.8	—	—	—	—	
6262	0.6	0.28		1.0	0.09				9
6351	1.0	—	0.6	0.6	—	—	—	—	
6951	0.35	0.28	—	0.6	—	—	—	—	
7005	—	—	0.45	1.4	0.13	—	4.5	0.04	10
7049	—	1.6	—	2.4	0.16	—	7.7	—	
7050	—	2.3	—	2.2	—	—	6.2	—	11
7072	—	—	—	—	—	—	1.0	—	
7075	—	1.6	—	2.5	0.23	—	5.6	—	
7116	—	0.8	—	1.1	—	—	4.7	—	12
7129	—	0.7	—	1.6	—	—	4.7	—	12
7175	—	1.6	—	2.5	0.23	—	5.6	—	5
7178	—	2.0	—	2.8	0.23	—	6.8	—	
7475	—	1.6	—	2.2	0.22	—	5.7	—	5
8017	—	0.15	—	0.03	—	—	—	—	13
8090	—	1.3	—	0.95	—	—	—	—	14
8176	0.09	—	—	—	—	—	—	—	13

[a] Based-on industry handbooks. Consult those references for specified limits. Values are nominal, i.e., middle range of limits for elements for which a composition range is specified.

[b] Aluminum and normal impurities constitute remainder.

[c]
1. Percent minimum aluminum— for 1060: 99.60%; for 1100: 99.00%; for 1145: 99.45%; for 1350: 99.50%. Also, for 1100, 0.12% iron.
2. Formerly designated EC.
3. Also contains 0.05% vanadium (max.).
4. Also contains 0.40% lead and 0.4% bismuth.
5. This alloy has tighter limits on impurities than does its companion alloy (2024 or 7075).
6. Also contains 1.0% lithium, 0.42% silver, and 0.12% zirconium.
7. Also contains 0.10% vanadium plus 0.18% zirconium.
8. Also contains 1.1% iron.
9. Also contains 0.55% lead and 0.55% bismuth.
10. Also contains 0.14% zirconium.

11. Also contains 0.12% zirconium.
12. Also contains 0.05% max. vanadium plus 0.03% max. gallium.
13. Also contains 0.7% iron.
14. Also contains 2.4% lithium plus 0.10% zirconium.

As for the wrought alloy designation system, the various digits of the cast alloy system convey information about the alloy:

- The first digit indicates the alloy group, as can be seen in Table 9. For 2xx.x through 8xx.x alloys, the alloy group is determined by the alloying element present in the greatest mean percentage, except in cases in which the composition being registered qualifies as a modification of a previously registered alloy. Note that in Table 9 the 6xx.x series is shown last and for cast alloys is designated as the unused series.

- The second and third digits identify the specific aluminum alloy or, for the aluminum 1xx.x series, indicate purity. If the greatest mean percentage is common to more than one alloying element, the alloy group is determined by the element that comes first in sequence. For the 1xx.x group, the second two of the four digits in the designation indicate the minimum aluminum percentage. These digits are the same as the two digits to the right of the decimal point in the minimum aluminum percentage when expressed to the nearest 0.01%.

- The fourth digit indicates the product form: xxx.0 indicates castings and xxx.1 for the most part indicates ingot having limits for alloying elements the same as those for the alloy in the form of castings. A fourth digit of xxx.2 may be used to indicate that the ingot has composition limits that differ from but fall within the xxx.1 limit; this typically represents the use of tighter limits on certain impurities to achieve specific properties in the cast product produced from that ingot.

- A letter before the numerical designation indicates a modification of the original alloy or an impurity limit. These serial letters are assigned in alphabetical sequence starting with A, but omitting I, O, Q, and X, with X being reserved for experimental alloys. Note that explicit rules have been established for determining whether a proposed composition is a modification of an existing alloy or if it is a new alloy.

Experimental alloys of either the wrought or cast series are indicated by the addition of the prefix X. The prefix is dropped when the alloy is no longer experimental. However, during development and before an alloy is designated as experimental, a new composition may be identified by a serial number assigned by the originator. Use of the serial number is discontinued when the composition is registered with the Aluminum Association and the ANSI H35.1 designation is assigned.

The compositions of a representative group of widely used commercial cast aluminum alloys are given in Table 10, from Standards for Aluminum Sand and Permanent Mold Castings3 and other aluminum casting industry publications. [1]

Table 10. Cast alloys designation system [1].

Alloy	Main Alloying Element
1xx.x	Pure aluminum, 99.00% maximum
2xx.x	Copper
3xx.x	Silicon, with added copper and/or magnesium
4xx.x	Silicon
5xx.x	Magnesium
7xx.x	Zinc
8xx.x	Tin
9xx.x	Other elements
6xx.x	Unused series

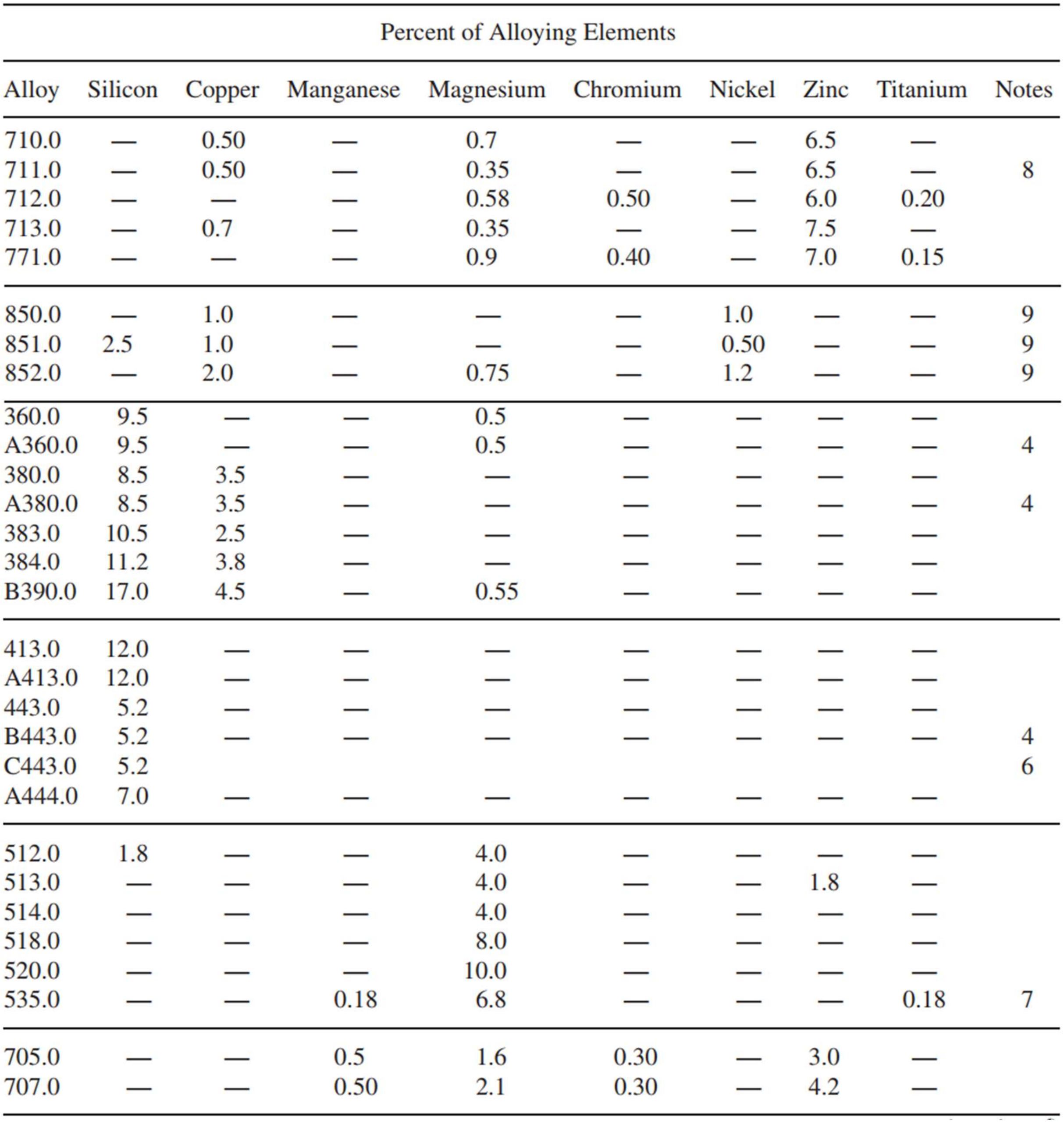
1.18. Aluminum alloy temper designation system

The temper designation is always presented immediately following the alloy designation (Section 3.2), with a dash between the two, e.g., 2014-T6 or A356.0-T6.

Table 11. Nominal compositions of aluminum alloy castings [1].

Percent of Alloying Elements									
Alloy	Silicon	Copper	Manganese	Magnesium	Chromium	Nickel	Zinc	Titanium	Notes
201.0	—	4.6	0.35	0.35	—	—	—	0.25	1
204.0	—	4.6	—	0.25	—	—	—	—	
A206.0	—	4.6	0.35	0.25	—	—	—	0.22	
208.0	3.0	4.0	—	—	—	—	—	—	
213.0	2.0	7.0	—	—	—	—	2.5	—	2
222.0	—	10.0	—	0.25	—	—	—	—	
224.0	—	5.0	0.35	—	—	—	—	—	3
240.0	—	8.0	0.5	6.0	—	0.5	—	—	
242.0	—	4.0	—	1.5	—	2.0	—	—	
A242.0	—	4.1	—	1.4	0.20	2.0	—	0.14	
295.0	1.1	4.5	—	—	—	—	—	—	
308.0	5.5	4.5	—	—	—	—	—	—	
319.0	6.0	3.5	—	—	—	—	—	—	
328.0	8.0	1.5	0.40	0.40	—	—	—	—	
332.0	9.5	3.0	—	1.0	—	—	—	—	
333.0	9.0	3.5	—	0.28	—	—	—	—	
336.0	12.0	1.0	—	1.0	—	2.5	—	—	
354.0	9.0	1.8	—	0.5	—	—	—	—	
355.0	5.0	1.25	—	0.5	—	—	—	—	
C355.0	5.0	1.25	—	0.5	—	—	—	—	4
356.0	7.0	—	—	0.32	—	—	—	—	
A356.0	7.0	—	—	0.35	—	—	—	—	4
357.0	7.0	—	—	0.52	—	—	—	—	
A357.0	7.0	—	—	0.55	—	—	—	0.12	4, 5
359.0	9.0	—	—	0.6	—	—	—	—	

Table 11 (continued).



Alloy	Silicon	Copper	Manganese	Magnesium	Chromium	Nickel	Zinc	Titanium	Notes
				Percent of Alloying Elements					
710.0	—	0.50	—	0.7	—	—	6.5	—	
711.0	—	0.50	—	0.35	—	—	6.5	—	8
712.0	—	—	—	0.58	0.50	—	6.0	0.20	
713.0	—	0.7	—	0.35	—	—	7.5	—	
771.0	—	—	—	0.9	0.40	—	7.0	0.15	
850.0	—	1.0	—	—	—	1.0	—	—	9
851.0	2.5	1.0	—	—	—	0.50	—	—	9
852.0	—	2.0	—	0.75	—	1.2	—	—	9
360.0	9.5	—	—	0.5	—	—	—	—	
A360.0	9.5	—	—	0.5	—	—	—	—	4
380.0	8.5	3.5	—	—	—	—	—	—	
A380.0	8.5	3.5	—	—	—	—	—	—	4
383.0	10.5	2.5	—	—	—	—	—	—	
384.0	11.2	3.8	—	—	—	—	—	—	
B390.0	17.0	4.5	—	0.55	—	—	—	—	
413.0	12.0	—	—	—	—	—	—	—	
A413.0	12.0	—	—	—	—	—	—	—	
443.0	5.2	—	—	—	—	—	—	—	
B443.0	5.2	—	—	—	—	—	—	—	4
C443.0	5.2								6
A444.0	7.0	—	—	—	—	—	—	—	
512.0	1.8	—	—	4.0	—	—	—	—	
513.0	—	—	—	4.0	—	—	1.8	—	
514.0	—	—	—	4.0	—	—	—	—	
518.0	—	—	—	8.0	—	—	—	—	
520.0	—	—	—	10.0	—	—	—	—	
535.0	—	—	0.18	6.8	—	—	—	0.18	7
705.0	—	—	0.5	1.6	0.30	—	3.0	—	
707.0	—	—	0.50	2.1	0.30	—	4.2	—	

A: on industry handbooks,[3,5,8–10] consult those references for specified limits. Values are nominal, i.e., average of range of limits for elements for which a range is shown; values are representative of separately cast test bars, not of specimens taken from commercial castings.

B: Aluminum and normal impurities constitute remainder.

C:1. Also contains 0.7% silver.

2. Also contains 1.2% iron.

3.Also contains 0.10% vanadium and 0.18% zirconium.

3. Impurity limits are much lower for this alloy than for alloy listed above it.
4. Also contains 0.055% beryllium.
5. Also contains up to 2.0% total iron.
6. Also contains 0.005% beryllium and 0.005% boron.
7. Also contains 1.0 iron.
8. Also contains 6.2% tin.

The first character in the temper designation is a capital letter indicating the general class of treatment as follows:
F = as fabricated
O = annealed
H = strain hardened
W = solution heat treated
T = thermally treated
Further information on each of these designations is provided by the descriptions that follow:
F = as fabricated. Applies to wrought or cast products made by shaping processes in which there is no special control over thermal conditions or strain-hardening processes employed to achieve specific properties. For wrought alloys there are no mechanical property limits associated with this temper, though for cast alloys there may be.
O = annealed. Applies to wrought products that are annealed to obtain the lower strength temper, usually to increase subsequent workability, and to cast products that are annealed to improve ductility and dimensional stability. The O may be followed by a digit other than zero.
H = strain hardened. Applies to products that have their strength increased by strain hardening. They may or may not have supplementary thermal treatments to produce some reduction in strength. The H is always followed by two or more digits.

W = solution heat treated. Applies only to alloys that age spontaneously after solution heat treating. This designation is specific only when digits are used in combination with W to indicate the period of natural aging, i.e., W ½ h.
T = thermally treated to produce stable tempers other than F. Applies to products that are thermally treated with or without supplementary strain hardening to produce stable tempers.
The T is always followed by one or more digits.
The most widely used temper designations above are the H and T categories, and these are always followed by from one to four numeric digits that provide more detail about how the alloy has been fabricated.[1]

1.19. Corrosion behavior of aluminum alloys

Although aluminum is a chemically active metal, its resistance to corrosion is attributable to an invisible oxide film that forms naturally and is always present unless it is deliberately prevented from forming. Scratch the oxide from the surface and, in air, the oxide immediately re-forms. Once formed, the oxide effectively protects the metal from chemical attack and from further oxidation. Some properties of this natural oxide are as follows:

- It is very thin—200–400 billionths of an inch thick.

- It is tenacious. Unlike iron oxide or rust that spall from the surface leaving a fresh surface to oxidize, aluminum oxide adheres tightly to aluminum.
- It is hard. Aluminum oxide is one of the hardest substances known.
- It is relatively stable and chemically inert.
- It is transparent and does not detract from the metal's appearance.

1.19.1. General Corrosion

The general corrosion behavior of aluminum alloys depends basically on three factors: (1) the stability of the oxide film, (2) the environment, and (3) the alloying elements; these factors are not independent of one another. The oxide film is considered stable between pH 4.5 and 9.0. however, aluminum can be attacked by certain anions and cations in neutral solutions, and it is resistant to some acids and alkalis.

In general, aluminum alloys have good corrosion resistance in the following environments: atmosphere, most fresh waters, seawater, most soils, most foods, and many chemicals. Since "good corrosion resistance" is intended to mean that the material will give long service life without surface protection, in support of this rating is the following list of established applications of aluminum in various environments:

In Atmosphere. Roofing and siding, truck, and aircraft skin, architectural.
With Most Fresh Waters. Storage tanks, pipelines, heat exchangers, pleasure boats.
In Seawater. Ship hulls and superstructures, buoys, pipelines.
In Soils. Pipelines and drainage pipes.
With Foods. Cooking utensils, tanks and equipment, cans and packaging.
With Chemicals. Storage tanks, processing and transporting equipment.

It is generally true that the higher the aluminum purity, the greater is its corrosion resistance. However, certain elements can be alloyed with aluminum without reducing its corrosion resistance and in some cases an improvement result. Those elements having little, or no effect include Mn, Mg, Zn, Si, Sb, Bi, Pb, and Ti; those having a detrimental effect include Cu, Fe, and Ni. Some guidelines for the different alloy groupings include the following: Al–Mn Alloys. Al–Mn alloys (3xxx series) have good corrosion resistance and may possibly be better than 1100 alloy in marine environments and for cooking utensils because of a reduced effect by Fe in these alloys.

Al–Mg Alloys. Al–Mg alloys (5xxx series) are as corrosion resistant as 1xxx alloys and even more resistant to salt water and some alkaline solutions. In general, they offer the best combination of strength and corrosion resistance of all aluminum alloys. As a result, they are a popular choice for marine vessels such as fishing boats and ferries.

Al–Mg–Si Alloys. Al–Mg–Si alloys (6xxx series) have good resistance to atmosphere corrosion but generally slightly lower resistance than Al–Mg alloys. Like the Al–Mg (5xxx) alloys, they can be used unprotected in most atmospheres and waters.

Alclad Alloys. Alclad alloys are composite wrought products comprised of an aluminum alloy core with a thin layer of corrosion-protective pure aluminum or aluminum alloy metallurgically bonded to one or both surfaces of the core. As a class, alclad alloys have a very high resistance to corrosion. The cladding is anodic to the core and thus protects the core.[1]

1.20. Demand of aluminum alloys in industries

Aluminum alloys possess various desirable properties such as good corrosion resistance, high strength-to-weight ratio, better fatigue strength that enable them to be used in different structural parts and other components. for aerospace, marine, shipbuilding, and rail transport industries. The use of aluminum is expected to continue to increase worldwide, particularly in the transportation and manufacturing sectors. Aluminum alloys, being light in weight, have been the primary structural material for military and commercial aircraft for almost 80 years owing to their well-known mechanical behavior, strength-to-weight ratio, and mature manufacturing processes; and will remain so with the development of new-generation high-strength aluminum alloys. Use of lightweight material (aluminum alloys) in transportation sector reduces vehicle mass, which in turn minimizes fuel consumption and harmful emissions. Reduction in weight of the various modes of transportation reduce fuel consumption, which lessens frequent filling of fuel tanks. Use of lightweight material with high strength-to-weight ratio in making structures has a great impact on r duction in the cost that occur due to fuel consumption, frequent repair, and maintenance, etc. Airframe manufacturers and material producers focus on the development of new aluminum alloys having good mechanical, metallurgical properties to meet customer requirements. Good mechanical properties and corrosion resistance of the materials may increase the life of the component and reduce repair costs.

Aluminum alloys are widely used by various industries in the fabrication of parts and components. More specifically 5xxx and 6xxx aluminum alloys have applications in shipbuilding, automobile, and aerospace, whereas 2xxx and 7xxx aluminum alloys have wide applications in aircraft components such as wings, tanks, fuselage, stringers, etc. as shown in. Application of different aluminum alloys is listed in Reducing the weight of vehicles without compromising on the safety passengers are the two major challenges faced by automobile industries. Vehicle weight affects its performance, which is generally measured in terms of acceleration, top speed, and fuel consumption. Aluminum alloy is a light material with a high specific strength owing to which its use in the manufacturing of cars has tremendously increased. The use of aluminum alloy in space frame reduces the body weight of Audi A8 by 40%).

Currently, all aluminum vehicles are also being produced on a commercial scale. Aluminum alloy sheets are widely used in inner and outer body panels of cars, which significantly reduce weight of vehicle. The sustained growth of industrial use of aluminum alloys depends to a great extent on the availability of a suitable joining process. Increasing use of aluminum in automobiles often requires dissimilar joining of steel with aluminum.

Table 12. Specific Uses of Various Aluminum Alloys [5]

ALUMINUM ALLOYS	Major Alloying Element	Typical Composition (wt.%)	Typical Properties and Application
1000 SERIES	Unalloyed aluminum	>99 Al	Good electrical conductor, low strength: cooking foil, power transmission, utensils
2000 SERIES	Copper	Al + 4–6 Cu + Mg	Strong heat-treatable alloy: aircraft external tanks, lower wings, fuselage
3000 SERIES	Manganese	Al + Mn	Medium strength, excellent corrosion resistance, ductile: beverage cans, roofing, cooking pans, automotive radiators
5000 SERIES	Magnesium	Al + 3 Mg	Strong work hardening alloy: pressure vessel, ship hulls, inner automotive body panel, boilers, storage tanks
6000 SERIES	Magnesium + silicon	Al + Mg + Si	Moderate strength heat-treatable alloy: pipelines, bridges, external automotive body panel, structural members
7000 SERIES	Zinc	Al + 6 Zn + 2 Mg + 1.5 Cu	Strong heat-treatable alloy: aircraft upper wings, fuselage
AL–LI ALLOYS	Lithium	Al + 3 Li	Good strength to weight and low density: aircraft spar and skins

alloys, and employment of efficient joining techniques becomes highly crucial as these BMs have large differences in their physical, thermal, and chemical properties. A typical combination of strain hard enables Al–Mg (5xxx) alloys and the medium strength age hard enable Al–Mg–Si (6xxx) alloys is extensively used in automotive industry by car manufacturers. The 6xxx series alloys (e.g., AA6061) are exclusively used in external body panels and the 5xxx series alloys (AA5052) are used in inner body panels. But the biggest challenge with aluminum alloys is the problems associated with solidification during welding by conventional methods.

Efficient welding process is required to weld the aluminum alloys to meet their heavy demand raised by user industries.[5]

1.21. Welding aluminum

Welding aluminum requires different welding techniques, different shielding gases, different specifications, and different pre-weld and post-weld processing than welding steel. The welding processes that are fit to weld both may require alterations so that they can be used to weld aluminum. Aluminum can be welded with relative ease, but first and foremost, the correct welding process must be selected.

Before highlighting different welding processes that are used for joining aluminum, it is important to understand some of the difficulties that are inherent to welding aluminum. One area of difficulty is filler metal. First, some aluminum alloys cannot be welded without filler materials. Alloys such as 6061 will undergo solidification cracking if welded without filler metal. Furthermore, the correct filler material must be selected. For instance, welding a 6061 alloy with a 6061-filler metal will result in weld failure. Instead, a 5356 or 4043 aluminum filler metal should be used when welding a 6061-base material. Another challenge with aluminum filler metal is feeding. If a mechanical wire feeding process is being used, special drive systems will most likely be needed. This is because aluminum has less column strength than steel and will more than likely buckle and tangle if special wire drive systems, such as a push-pull gun, are not used. This is especially true for thinner aluminum filler metals (i.e., 0.8 mm or 1 mm diameter).

Aluminum also has a greater thermal conductivity than steel. The heat created when the welding process is initiated on aluminum is dispersed more rapidly than when welding an iron-based alloy. Therefore, full penetration may not occur until the weld has progressed quite far from the start. This is known as a cold start. Care must be taken so that cold starts do not occur when welding aluminum. Another result of the increased thermal conductivity is larger craters. By the time the end of the weld is reached, more heat is present than at the start. This heat disperses well in aluminum and can create a large crater. Aluminum is very susceptible to crater cracking, therefore, craters should be filled in so that failure does not occur at the end of a weld.

Aluminum also requires different pre-weld and post-weld processing. Aluminum forms an oxide layer that has a higher melting temperature than the actual aluminum itself. To avoid un-melted aluminum oxide particles in the weld, an oxide removal process, such as wire brushing or chemical cleaning, should be used prior to welding. Several aluminum alloys, such as 6061-T6, are artificially aged to increase their strength. The heat from welding ruins the benefits gained by artificial aging, and large reductions in strength will be found in the heat-affected zone. Therefore, post-weld artificial aging may be required for alloys such as these. The following are welding processes that can be used for aluminum:

- GTAW/TIG
- GMAW/MIG
- Laser Beam Welding and Electron Beam Welding
- Friction stir welding

1.21.1. GTAW/TIG

One of the most popular welding processes for aluminum is gas tungsten arc welding (GTAW), otherwise known as tungsten inert gas (TIG) welding. GTAW is a great process for aluminum because it does not require mechanical wire feeding, which can create feed ability issues. Instead, the filler material is fed into the puddle by the welder with his hand. Also, the GTAW process is extremely clean, which prevents aluminum from being contaminated by the atmosphere.

1.21.2. GMAW/MIG

Gas metal arc welding (GMAW), or metal inert gas (MIG) welding is another great choice for welding aluminum. Gas metal arc welding generally has higher deposition rates and faster travel speeds than GTAW. However, GMAW uses a mechanical wire feeding system. Because of this, a push-pull gun or spool gun may be needed so that aluminum wire feeding is possible. Also, it is important to not use 100% CO2 or 75% Argon/25% C02 shielding gas. Such gas is a viable choice for steel, but aluminum cannot handle the reactive C02 gas. Follow the filler metal manufacturer recommendations for shielding gas type.

1.21.3. Laser Beam Welding and Electron Beam Welding

Beam welding processes are often quite capable of welding aluminum. Also, since the power density of beam welding processes are so high, cold starts are less of a concern. With laser welding, material light reflectivity can be a concern. Also, shielding gas optimization is key to avoid porosity. Electron beam welding generally does not have these problems because it does not use light as an energy medium, and it is performed in a vacuum.

1.21.4. Friction stir welding

Solid state welding can be performed at room temperature and at elevated temperature without melting the materials being joined. In solid state welding, metallurgical bond is created below the melting point of material through plastic deformation without adding filler material. The energy supplied during solid state welding is through pressure and/or friction. The faying surfaces of materials are brought in intimate contact, required for direct atomic bonding, by expelling the surface contaminants through application of heat and/or pressure. Heat input in solid state welding is considerably lower than in fusion welding processes, which in turn causes less disruption of microstructure of parent materials being joined. Moreover, dissimilar materials can also be easily joined as no mixing of materials takes place in liquid form and therefore, sound-welded joints can be obtained. Various welding processes such as ultrasonic welding, cold welding, friction welding (FW), explosive welding, diffusion welding, and FSW fall under the category of solid-state welding.

CHAPTER II

2.1. Introduction

Aluminum is well known for being difficult to weld, but with experience, it’s no more demanding than any other metal. That’s why it’s essential that manufacturers not only spend the time necessary researching and testing materials and methods, but also make sure welders are properly trained.

Perhaps the most common form of aluminum welding is known as gas tungsten arc welding. Another name for this is tungsten inert gas (TIG) welding. It is characterized using a non-consumable tungsten electrode. The inert gas, such as argon or helium, protects against oxidation or other atmospheric contamination. There needs to be a constant welding power supply to produce the required electrical energy, which gets conducted across the arc via a column of plasma and consists of highly ionized gas and metal vapors.

Another possible option is called gas metal arc welding or metal inert gas (MIG) welding. This method relies on an electric arc between the consumable MIG wire electrode and the work piece. There is also a shielding gas that is fed through the welding gun to block any possible contaminants. The method was originally developed in the 1940s specifically for welding aluminum and other non-ferrous metals, and it is prized for its faster welding time. Additionally, it has increased in popularity because of the ease of adapting the process to robotic automation.

And we have laser beam welding can also be used. This method joins the separate pieces of metal using a laser. The laser beam offers a concentrated heat source, which allows for narrow, deep welds and high welding rates. One advantage of laser beam welding is it offers a high-power density, which allows for a smaller heat-affected zone, with higher heating and cooling rates. It’s important to remember that the depth of penetration is proportional to the amount of power supplied.

But all this method mentioned needs a welder trained because need skills. Today we have a new method doesn’t need skills or welders trained, it called Friction stir welding. This new method today highly recommended in the industry.

In this chapter we will know a lot about this method and how its work and see some advantages of this method and where there use it.

2.2. Introduction to solid state welding

Solid state welding can be performed at room temperature and at elevated temperature without melting the materials being joined. In solid state welding, metallurgical bond is created below the melting point of material through plastic deformation without adding filler material. The energy supplied during solid state welding is through pressure and/or friction. The faying surfaces of materials are brought in intimate contact, required for direct atomic bonding, by expelling the surface contaminants through application of heat and/or pressure. Heat input in solid state welding is considerably lower than in fusion welding processes, which in turn causes less disruption of microstructure of parent materials being joined. Moreover, dissimilar materials can also be easily joined as no mixing of materials takes place in liquid form and therefore, sound welded joints can be obtained Various welding processes such as ultrasonic welding, cold welding, friction welding (FW), explosive welding, diffusion welding, and FSW fall under the category of solid-state welding.[5]

2.3. Historical background of FSW

Over a century ago, a patent on the very first use of frictional heat for forming and solid-state welding was obtained by the United States (Bevington, 1891). Another development in the technology related to friction took place in the form of friction surfacing in a British patent in 1941 (Klopstock and Neelands, 1941). After another 50 years, a novel solid-state welding was introduced that used frictional heat for welding operation. This invention is known as FSW, which was pioneered by “TWI” at Cambridge in 1991 (Thomas et al., 1991). This recent innovation has enhanced the use of technology related to friction for producing welded joints in materials that are difficult to be welded such as high-strength heat-treatable aluminum alloys by conventional processes.

FSW is a revolutionary version of FW process, which can weld materials in different configurations such as lap, butt, T-joint, scarf, etc. with good post weld properties and little weld distortion. Moreover, FSW is a clean, economical, and simple welding process. Initially, FSW mainly remained as a joining process for aerospace and shipbuilding applications. Now FSW has revolutionized the manufacturing sector and thereby commercialized in railways, automotive, and electronics industries too. With optimum process parameters, FSW produces defect-free joints with good mechanical properties and little distortion in various similar and dissimilar materials that were previously not weldable. As a solid-state joining process, FSW has been a prominent process for welding dissimilar aluminum alloys. Various industries throughout the world (Japan, USA, Scandinavia, etc.) are using FSW as an important joining process, especially for welding of high-strength aluminum alloys.[5]

2.4. Principle of solid-state welding

Solid state welding works on the principle of interatomic bonding obtained in solid state. Bonding force (interatomic force) between metallic atoms depends on their interatomic distance. By increasing interatomic distance to a few atomic spacing, the attractive interatomic force reduces to almost zero. Similarly, the force increases sharply and attains a very large value when the distance is reduced. If the faying surfaces of parent material to be welded are close enough to a value such that only grain boundary separates them, then parent material adheres with a very large force, resulting in a permanent joint. Solid state welding processes are characterized by the involvement of plastic deformation, which removes impure layer from the material's surface to bring pure atoms close enough to generate large attractive force to obtain permanent joint.[5]

2.5. Introduction to FSW technique

FSW process is a welding process in which the term friction refers to the utilization of frictional heat required for softening the BM (Base materials) and term stir signifies the movement of the material in the form of plastic deformation. Overall, FSW is a welding process that utilizes heat caused by friction between the tool and BM, and plastic deformation of BM caused by stirring of the tool. Generated heat softens the BM while plastic deformation mixes the BM that leads to the sound welded joint. Frictional heat was initially used in FW for joining materials. In conventional rotary FW process, one of the parts being joined is rotated while the other remains stationary. FW is limited to join cylindrical- (rotary friction) and rectangular-shaped components (for linear friction) of specific length; for example, small- and medium-sized round bars, tubes, and rectangular blocks. It is restricted to specific joint design and component geometry. Unlike FW, the FSW utilizes frictional heat for joining materials in different joint configurations.

FSW is a solid-state welding process invented and patented by W. M. Thomas (Thomas et al., 1991) at "TWI" in Cambridge, UK. FSW technique was initially invented for welding of high-strength aluminum alloys (2xxx and 7xxx), but its success made way for its phenomenal growth, and it emerged as a major process for joining magnesium, copper and their alloys, ferrous, and other nonferrous alloys. It has been extended to dissimilar welding of the above-mentioned alloys and to the welding of high melting point materials such as steel and titanium. Being a solid-state welding process, FSW produces joints without melting of BM and therefore, problems associated with solidification are not encountered and joints made are free from porosity or blowholes leading to improved mechanical properties of the joints as compared to conventional welds. Various attempts have been made to implement FSW for joining dissimilar aluminum alloys and those materials having large difference in properties (physical, thermal, and mechanical) such as aluminum with steel, aluminum with copper, and aluminum with titanium. FSW joints have largely replaced the use of riveted joints in aerospace because of their lower production costs and as a remedy for various problems associated with riveting. Therefore,
FSW process has been identified as key technology for joining materials in fuselage and wing manufacturing by leading aircraft manufactures. Despite being a new process, products with welded joints made by FSW have already been launched into space in the form of seams in fuel tanks of a Boeing.

FSW has now established itself to be a remarkable solid state welding technique to effectively join similar and dissimilar aluminum alloys. The process does not require any consumables (filler material, fluxes and shielding gas, etc.) for joining, produces no harmful emissions, safe to humans and is, therefore, considered to be an energy-efficient, environment-friendly, and clean material joining process, as detailed in Figure 2.1.

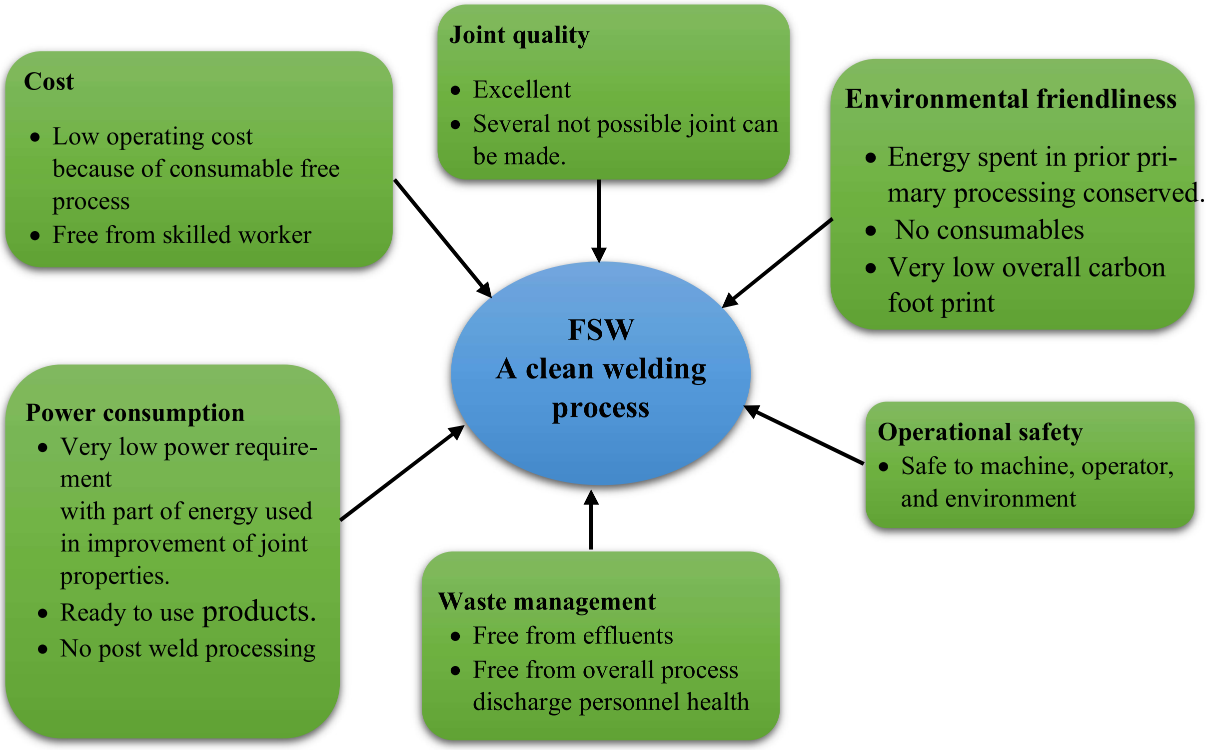


Figure 2.1. FSW, a clean welding process

FSW can be used to obtain various types of joint configurations such as butt, lap, T-joint, fillet shapes, etc. Butt and lap joints are the most convenient joint configurations for FSW. A typical butt joint configuration is shown in Figure 2.2. Two rectangular plates or sheets are placed on the anvil of fixture in such a way that the faying surfaces of BMs touch each other. BMs are clamped by a robust clamping arrangement on work fixture to restrict their movement during plunging of the FSW tool and subsequent welding. Backing plate is used between BM and anvil to prevent sticking of the welded plates with the anvil of fixture. Large axial forces are applied by the tool during its plunging into BM and proper clamping of the BM is ensured so that the faying surfaces do not move apart. To complete weld, the rotating tool is plunged into joint line and traversed along welding direction keeping the tool shoulder in contact with the surface of material being welded. FSW involves step-by-step operations from initiation to completion of welded joints as shown in Figure 2.3. During welding, the material ahead of the traversing tool first starts preheating before the tool reaches the location and once the tool reaches there the material deforms plastically. Material in contact with the pin is extruded around it and forged by the tool shoulder behind it. Material already forged cools down after the tool moves ahead resulting in a welded joint.

FSW is a continuous autogenous process that involves a non-consumable rotating tool, which is harder than the BM. Despite several merits of FSW, fabricating a successful joint is a challenging task, mainly because the quality of joint is very sensitive to FSW parameters.

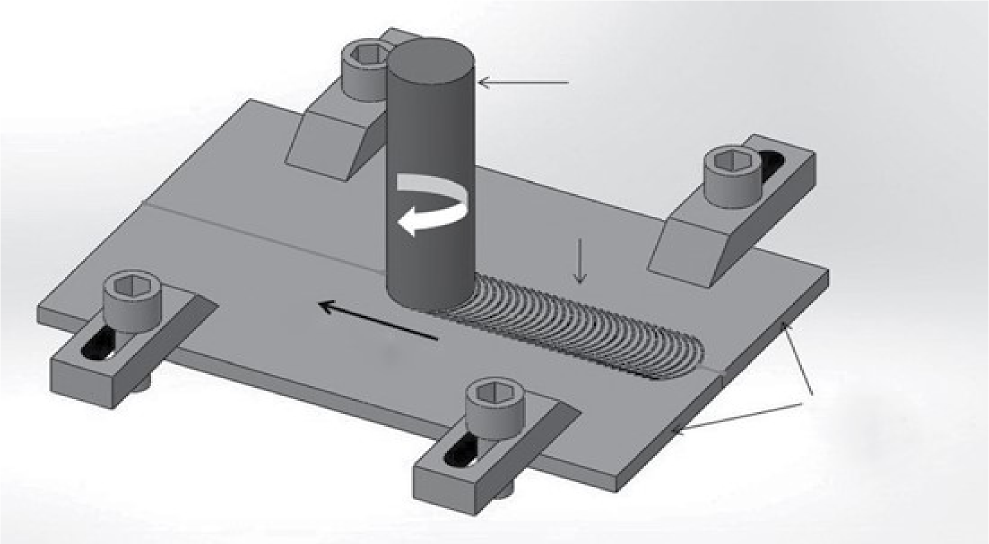


Figure 2.2. FSW of butt joint configuration.

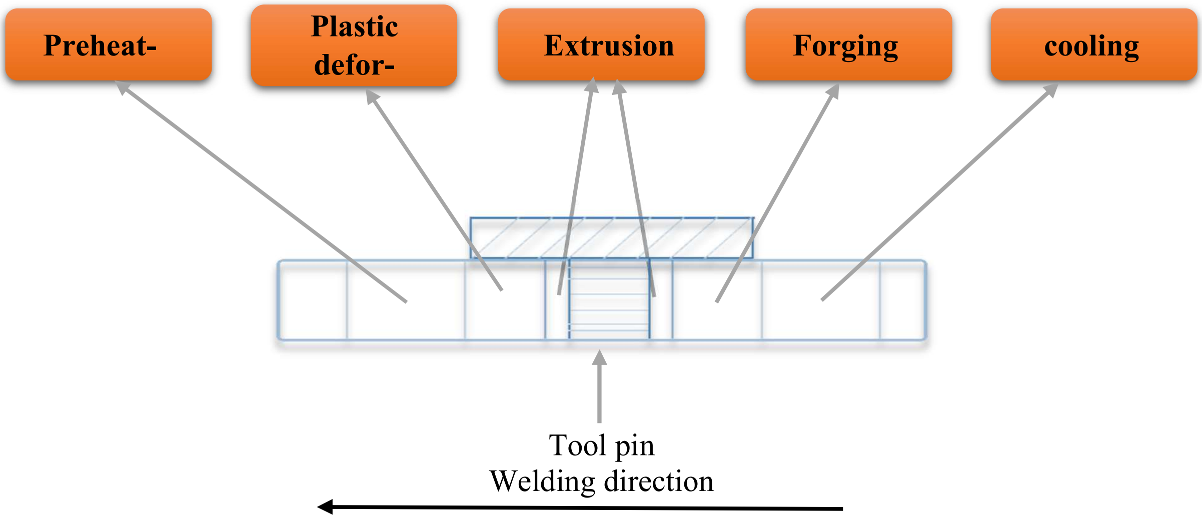


Figure 2.3. Processes involved in FSW.

The process requires careful selection of welding parameters, mainly tool rotational speed and traverse speed, tool plunge depth, tool tilt angle, tool offset, and tool geometry so that a defect-free joint is obtained (Leal and Loureiro, 2004; Khan et al., 2015b). FSW has undergone massive commercialization by many industrial sectors and has evolved as widely used solid state welding process due to superior joint properties relative to a conventional fusion weld. It is important to understand the effects of FSW parameters on material properties, while determining the quality of welded joint. During FSW, the material undergoes SPD. The stresses and strains involved during SPD are complex to analyze and estimate due to the heterogeneous movement of material around the tool pin. FSW process affects the material not only thermally but also mechanically, leading to the creation of three microstructurally distinct regions of a friction stir weld: the SZ (stir zone), the thermomechanical affected zone (TMAZ), and the HAZ. Each of these regions has unique microstructure and mechanical properties. Evolution of microstructure and mechanical properties in each of these regions of the joint produced by FSW are essential to understand and analyze.

Despite enormous merits, FSW is no exclusion to limitations. Capital investment in FSW infrastructure is one of its major disadvantages, but fortunately it can be significantly reduced by adapting heavy duty vertical milling machines to enable it to perform FSW. Based on the unique properties of the joints produced, commercialization of FSW began long before establishing a basic understanding of the process. Research on FSW is progressing at a very high pace in many industries especially in transportation industry. It is of great importance to develop deep insight into the effect of process and other parameters on the quality and cost effectiveness of the joint so that its potential can be exploited to the fullest.[5]

2.6. Heat transfer and material flow in FSW

Friction stir welding (FSW) has gained significant attention in recent years, as the solid-state joining process of primarily aluminum and/or aluminum alloys is now extended to join relatively harder materials and plastics. Understanding the synergistic interaction of the physical phenomena during welding of various similar or dissimilar materials is of practical significance. Models of increasing complexity and sophistication have been used beneficially in exploring and understanding the underlying physics of the process. The most general configuration of an FSW tool is a solid cylindrical object with a terminating pin. The rotating tool moves along the contact surfaces of two rigidly clamped substrates on a backing plate support. The tool shoulder makes firm contact with the top surface of the workpiece with an applied load. Therefore, heat generated by friction occurs on the surface in contact with the tool. The tool shoulder experiences a larger amount of heat than the pin surface. The process also experiences severe plastic deformation surrounding the tool and flow of the plasticized metal, from around the front of the tool to the trailing edge where it is forged into a joint. The heat transfer aspect during FSW can be described as three phases. The first phase is called the dwelling period, where the material is preheated by a stationary rotating tool to achieve a sufficient temperature ahead of the tool to allow for the traverse movement. The second phase is the transient heating when the welding tool begins traversal movement until the pseudo steady-state is reached. Finally, the pseudo steady state is where the system reaches an effective constant thermal field around the tool. The relative velocity on a symmetrical point of the advancing side (AS) and retreating side (RS) is not the same, due to a combination of similar directional rotational and transverse motions of the tool. This leads to asymmetry in heat transfer and material flow on the two sides of the weld joint. FSW involves complex physical interactions between heat generation, plastic deformation, and metallurgical aspects. The heat is generated by friction as well as by plastic deformation, altering the microstructure and properties. The kinetics depend mainly on the temperature and strain rate, and microstructure evolution influences the energy transfer within the system. The phenomenological understanding of heat transfer and material flow demands a strong coupling between thermal, mechanical, and metallurgical aspects. The center of the stir zone (SZ) experiences dynamic recrystallization and is followed by recovered microstructure around the SZs at low levels of deformation and temperature. This increases the amount of grain surface energy and number of grain edges. A part of the plastic deformation energy is also stored within the thermo-mechanically affected zone (TMAZ) in the form of increased dislocation densities within the deformed grains. The heat affected zone (HAZ) is affected only by temperature through diffusion heat transfer and with a microstructure almost like the base material. In FSW, the heat and mass transfer are mainly influenced by material properties as well as welding variables including the rotational and transverse tool speed. However, the joining takes place by extrusion and forging of the metal at high strain rates. Therefore, the mechanical behavior of material is assumed either as fully plastic or visco-plastic or only viscous fluid. The material flow field and the temperature field are significant since they influence the recrystallization kinetics during the FSW process. There exist two modelling approaches for material flow. The plasticized material can be treated as a high viscous fluid and the flow field is obtained by solving fluid dynamics. On the other hand, the plastic deformation is modelled on the principals of solid mechanics and the displacement field is used to find the velocity or acceleration field. The understanding of the heat transfer process in the workpiece can be helpful in predicting the thermal history during welding, which subsequently influences the mechanical properties to evaluate weld joint quality.

The heat transfer process for both workpiece and tool can be formulated as a standard boundary value problem and then solved by using an inverse approach combining experimental and numerical studies that consider frictional heat at the interface of the tool shoulder and the workpiece. It is observed that the maximum temperature ranges from 80 to 90% of the melting temperature of the welding material at the interface between the tool and the workpiece. However, 20% of the total heat is attributed to the pin and the addition of heat due to the pin has little effect on the thermal profile. There are two sources of heat generation for FSW. One is due to friction and the other to plastic deformation at the tool–workpiece interface and at the TMAZ. The tool–workpiece interface can be further subdivided into shoulder–workpiece and tool pin–workpiece interfaces. The heat generation between tool–workpiece interfaces is greatly influenced by frictional heat, but the effect of heat generated due to plastic deformation is very much less. Moreover, the difference in temperature distribution between the AS and RS due to non-symmetrical heat flux distribution brings complexity to the heat transfer analysis. [8]

2.7. FSW process

FSW process works on the heat produced by friction and plastic deformation affected by rotating tool. In FSW, BMs being welded are clamped together rigidly and a cylindrical no consumable tool with shoulder and pin is rotated and plunges into faying surfaces of the materials to be welded until the tool shoulder contacts the surface. Rubbing action of tool generates sufficient heat to soften BM and traversing tool mixes the material; thereby, completing the joint as shown in Figure 2.4. Tool rotation softens material under the shoulder and traversing tool deforms the material plastically, pushing it simultaneously from AS to RS and forges it behind the tool to complete joint. The tool shoulder prevents plasticized material from being expelled out of the weld. Thus, the BMs are mechanically mixed while simultaneously undergoing SPD without melting. SPD due to stirring action of the tool probe/pin leads to dynamic recrystallization of the BM, which results in grain refinement and improvement of its properties.

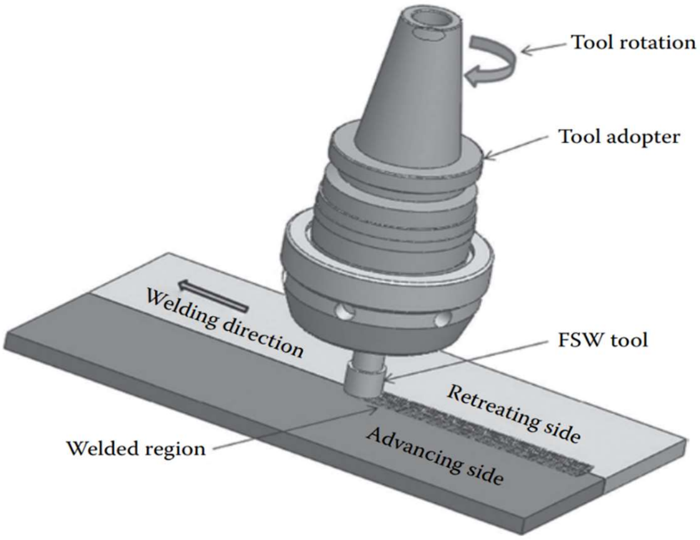


Figure 2. 4. Schematic representation of FSW process.

During FSW, when the softened BM moves around the pin without reaching its melting point it avoids difficulties that arise from change in state (like melting, recasting, and volumetric changes), which are common in conventional fusion welding processes. Also, lower distortion and residual stresses generated due to lower welding temperature during FSW result in improvement in fatigue and fracture toughness that make thin material welding possible. FSW is a mechanized process with high equipment cost compared to conventional arc welding processes and less skilled operator is required.

Before performing FSW, the material is first rigidly clamped on a welding fixture, as shown in Figure 2.5. Base plates are fixed in such a way that faying surfaces are close enough at the joint line so that the plates do not spread or lift during welding.

Fixture design considerations play a vital role in the success of welding.

The process of FSW can be performed in a definite sequence of operations to complete the weld. These operations are described in the following four steps and the schematic representation is shown in Figure 2.6.

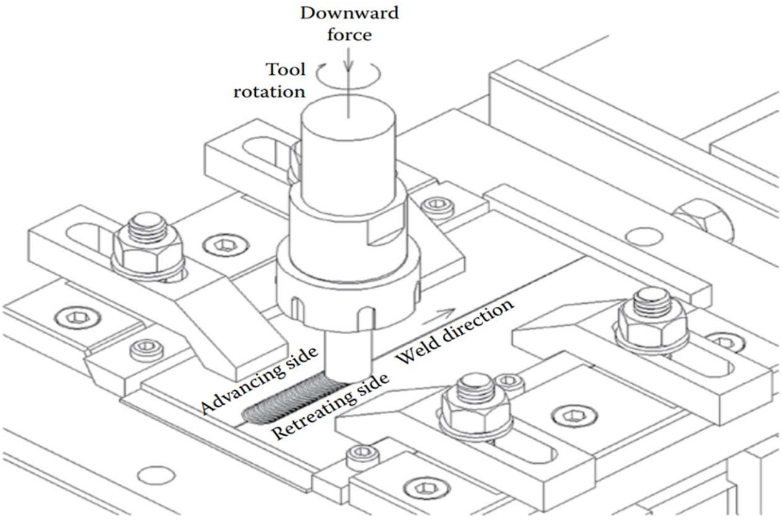


Figure 2.5. Robust clamping setup for FSW.

Step 1: Tool and workpiece clamping. The plates/sheets of required thickness are clamped together with supporting backing plate on the anvil of fixture supported by rigid clamps on the machine table/bed. The tool is clamped firmly on to the tool adopter, aligned along the joint line and rotated as shown in Figure 2.6a.

Step 2: Create friction/starting at edge. In this step, the weld is initiated, and the tool pin is plunged vertically into the abutting surfaces of the BM along the joint with a specific force until the shoulder contacts the surface of the BM, as shown in Figure 2.6b. Stirring action of the tool softens the BM due to the frictional heat. Sufficient heat should be generated since a part of the generated heat is conducted to the anvil and the surrounding material.

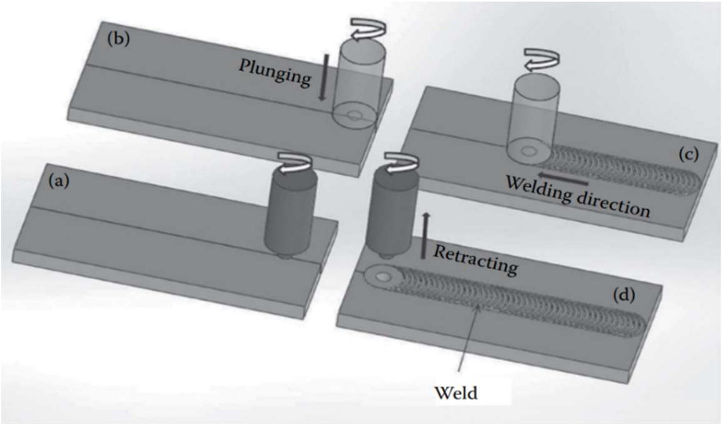


Figure 2.6. Four steps of FSW process.

Step 3: Joining/move tool when metal softens. After the welding tool is plunged into the BM, the tool traverses along the joint line in the welding direction with some dwell to allow the BM to reach sufficient temperature, as shown in Figure 2.6c. During traversing of the welding tool, heat produced by friction and plastic deformation maintains proper softening to allow sufficient material flow around the tool pin. Tool pin moves the plasticized material from AS to the RS and the tool shoulder consolidates the flowing material behind the pin to complete the joint.[5]

Step 4: Plunging out of the tool. The process is completed when the rotating tool after joining the BM is retracted from the abutted surfaces leaving a keyhole in the BM, as shown in Figure 2.6d.

2.8. Advantages and disadvantages of the FSW process

2.8.1. Advantages

In FSW, shielding environment and filler material is usually not essential for joining. Thus, it does not produce any harmful emissions and is also safe for operators, as shown in Figure 2.1. It is, therefore, considered to be an energy-efficient, environment-friendly, and a clean material joining process. The process is completely mechanical and, therefore, the welding operation and weld energy input are accurately controlled. The various advantages of FSW process over conventional fusion welding processes are shown in Figure 2.7.[5]

Friction stir welding	Aspects	Fusion welding
Friendly	Environment	Invasive
No skill intensive	skill	Highly skill intensive
Not required	Consumables (shielding gas, filler, Fluxes, etc.)	Required
Significantly less energy required and part of which is fruitfully utilized for material property enhancement.	Energy consumption	More energy required and energy fruitful effects of prior processing are lost in the joint material and neighborhood.
Not present	Harmful fumes, gases, and radiations	Present

Figure 2.7. Advantages of FSW over fusion welding.

2.8.1.1. Some of the advantages of FSW are listed below:

- Better mechanical properties in the as-welded condition
- Obtaining weld with maintained original properties
- Material that could not be welded earlier can be successfully welded
- Improved safety due to the absence of toxic fumes
- No filler or gas shield is required for reactive material
- Less-skilled operator is required
- No limitation for joint configuration and welding position, that is, it can operate in all positions (horizontal, vertical, overhead, etc.) due to the absence of weld pool
- Uniform weld bead with good appearance, thus reducing the machining after welding
- Low environmental impact
- Welding preparation not usually required
- Smaller HAZ that improves the joint quality for heat-treatable alloys
- Low energy consumption

2.8.2. Disadvantages of the FSW Process

- Low welding speed compared to some automatic fusion welding processes
- High forces are required for rigid clamping of BM
- Key hole is left at the end of the weld
- For avoiding key hole in the welded plate, run-on/run-off plates are required
- Robust fixture is required for counteracting the large plunging forces
- High investment is needed

Figure 2.8. Retractable pin tool.

- Less flexible compared to manual and arc welding processes
- Slower production rate than some fusion welding techniques
- Different size of the tool pin is required when welding materials of varying thickness

To overcome some of the drawbacks of FSW, an engineer at Marshall Space Flight Center (MSFC), NASA, helped to design a computer controlled automatic retractable pin tool, as shown in Figure 2.8. This tool automatically retracts the pin inside the tool shoulder after the completion of weld before withdrawal from the welded plates, which leads to a smooth hole closure at the end of the weld. This design also allows adjustable pin length for varying thickness and prevents the use of different pins of varying length for different plate thickness.

2.9. Application of FSW

Application of FSW in several industrial sectors resulted in remarkable benefits in terms of performance and cost reduction. FSW possesses numerous applications in different industries including aerospace, shipbuilding, railways, automobile, etc. Dissimilar material joining is becoming increasingly important to fulfill the requirements of engineering structures and components with reduced weight, improved strength, and functionality. FSW has been adopted extensively for welding aluminum alloys in various industries owing to economic and environmental benefits. Dissimilar material joining such as aluminum to aluminum, aluminum to steel, and aluminum to copper significantly utilizes the benefits of the properties of both the materials. For instance, joining aluminum alloy and steel is important, and recently, Honda has successfully performed such dissimilar welding in a vehicle suspension system for large-scale production (Honda, 2012).

Formation of brittle intermetallic compound (IMC), difference in softening temperatures, and thermal expansion act as barriers in dissimilar materials joining, which adversely affects the performance of components and structures. FSW results in reduction in formation of IMCs during dissimilar material welding, which in turn improves the performance of components and dissimilar structures for industry-oriented applications. Sound joining of dissimilar aluminum alloys by FSW enhances the use of high strength-to-weight ratio aluminum alloys in aerospace, automobile, and railways. It makes mass production of light-weight transportation system that results in remarkable reduction in fuel consumption. For more than a decade, FSW has been adopted by the aerospace and automotive industry to join different aluminum alloys. The list of companies that adopted FSW as a joining process in several applications is presented in Table 2.1.[5]

Table 2.1.Sample List of Companies Adopting FSW in Applications in the Last Two Decades [5].

Year	Application	Company
1995	Heat exchangers	Marine Aluminum, Norway
1996	Shipbuilding	Marine Aluminum, Norway
1998	Delta II rockets	Boeing, United States
1999	Shipbuilding	SAPA, Sweden
2000	Automotive components	SAPA, Sweden
2000	Laser system housings	General Tool, United States
2001	Motor housings	Hydro Aluminum (formerly Marine Aluminum), Norway

2001	Suburban trains	Alstom, Germany, and Hydro Marine
2001	Automotive components	Showa, Japan
2001	Train bodies	Hitachi, Japan
2002	Automotive components	Tower Automotive, United States
2003	Aircraft structure	Eclipse, United States
2003	Commercial shipbuilding	Advanced Joining Technologies, United States
2004	Space shuttle external tank	Lockheed Martin, United States
2006	Shipbuilding	Friction Stir Link, United States
2012	Automotive components	Honda Motor Company, Japan

2.9.1. Shipbuilding and Marine Industries

The shipbuilding and marine industries adopted the FSW process for joining 5xxx and 6xxx series aluminum alloys. The process is suitable for the following applications:

- Panels for decks, sides, bulkheads, and floors
- Aluminum hulls
- Boat internal surface
- Superstructures
- Helicopter landing platforms
- Ship body structures.

2.9.2. Aerospace Industry

The US aerospace industry uses FSW for fabricating the satellite launch vehicle’s tanks made of high-strength heat-treatable aluminum alloys.

The first rocket fabricated by FSW was successfully launched in 1999. Components and structures made of different materials are used in aerospace industry as they undergo different loading conditions and require different properties in a single component. FSW is successfully employed in military aircraft for welding of stringers and ribs with skins. This results in weight saving and reduction in costs associated with manufacturing compared with riveting and other mechanical fastening. Aircraft fuel tanks made of AA2219 are commercially joined by using FSW. The process has been applied by various companies such as Boeing, Lockheed Martin, Air Bus, etc. This method has also been used in many of the world’s space launch vehicles, including the Space Shuttle, Delta II and IV, SpaceX Falcon 9, and Ariane.

FSW is used in the fabrication of various parts and components of aircraft and space vehicles such as wings, fuel tanks, stringers, etc. Further, it is also used in the repair of faulty welds.

2.9.3. Railway Industry

FSW is widely used in production of rail car bodies made of aluminum alloys such as Hitachi superfast trains (Shinkansen), which can reach speeds up to 320 km/h. Applications include the following:

- Bodies of high-speed trains made of high-strength aluminum alloys
- Underground carriages and trams
- Railway tankers and goods wagons.

2.9.4. Automobile

The use of aluminum tackled two largest challenges faced by the automobile industry. First is vehicle's weight reduction and second is passengers' safety. Aluminum alloys provide enough strength and is also light in weight. The problem associated with aluminum is its welding. Conventional fusion welding processes rarely achieve sound welding of aluminum alloys. Following the invention of FSW, aluminum alloys are increasingly being used in vehicle bodies. Currently, FSW is widely used by various car manufacturers worldwide such as Honda, Mazda, Ford, Audi, and Tower Automotive. Tower Automotive substituted the gas metal arc welding (GMAW) by FSW because of reduction in weight by 40% and improvement in mechanical properties by two times compared to GMAW for 6000 aluminum alloy series.

In recent years, automobile manufacturers have shown interest in joining various automotive parts by FSW and investigation is going on for its commercial application.

Some of the potential applications of FSW in automobile industry includes joining of

- Front portion of engine
- Alloyed wheel rims
- Fuel tankers
- Bodies of heavy-duty vehicles
- Tailored blanks.

2.9.5. Construction Industry

The use of FSW in construction industry needs its portability and portable FSW machines have been introduced for making parts and components including the following:

- Facade panels made from aluminum, copper, or titanium
- Window frames
- Aluminum bridges
- Reactors for power plants
- Pipe fabrication.

2.9.6. Electrical Industry

FSW is widely employed by electrical industry in

- Electric motor housings
- Encapsulation of electronics
- Electrical connectors.

2.10. FSW tool material

Tool material plays a vital role in determining suitability of a tool for welding a particular material. Generally, during FSW temperature reaches to around 85% of the workpiece material's melting point; such a high operating temperature requires tool of high hardness, high hot strength, hot hardness and good wear resistance, and high-temperature chemical stability. Such properties of tool material prevent its deformations, twisting, breakage, and erosion during FSW (Rowe and Thomas, (2005). Tool material also affects the temperature attained at the SZ of welded joint. Adequate generation and distribution of heat at the interface of tool and workpiece during FSW depends on coefficient of friction between tool and workpiece and thermal conductivity of tool and workpiece. Erosion of tool by sticking and slipping of the workpiece on the tool depends on hot hardness of the tool material. A general consideration is that the hardness of tool material should be two or three times higher than that of the workpiece material. Properties such as friction coefficient, thermal conductivity, hot hardness, and toughness of the tool depend on the tool material. Friction coefficient governs the sticking and slipping of the material around the tool pin, which affects material movement and heat generation. Inappropriate coefficient of friction results in improper material movement and insufficient heat generation leading to degradation of joint quality. The rate of heat dissipation during welding is significantly affected by thermal conductivity of the tool and workpiece materials, which in turn governs the thermal field and flow stress around the weld. High thermal conductivity of tool dissipates excessive heat from interface of workpiece and tool that requires high rotational speed and low welding speed, which in turn minimize productivity. This at the same time keeps the tool cold and minimizes tool degradation as well. Low thermal conductivity minimizes heat loss that results in fruitful utilization of generated heat. Erosion of the tool due to rubbing with the material being welded is controlled by the hardness of tool material at elevated temperature. Also, reaction of ambient oxygen with hot tool material enhances the degree of erosion of tool. Tool's reaction with oxygen is an important consideration for selection of the tool material. Adequate values of friction coefficient, thermal conductivity, and hardness of the tool depend on the material of workpiece, process variables, and tool geometry.

Tool steel is generally used for welding low melting point material such as aluminum alloys, copper alloys, and magnesium alloys for up to 700°C of working temperature. Various tool steel materials such as H13, high carbon high chromium (HCHCr), SKD61, high carbon (HC), high-speed steel (HSS), etc. are successfully used for welding of dissimilar aluminum alloys. Tool material used for FSW of dissimilar aluminum alloys along with their geometry is presented in Table 2.2.

Tools used for welding high-strength materials such as titanium alloy, nickel alloys, steel, etc. are polycrystalline cubic boron nitride (pcBN), nickel, and cobalt-based super alloys. In addition, a few specific grades of tungsten carbide are also being used. The characteristics of the tool material are crucial for FSW, and the desired characteristics depend on workpiece material to be welded. High hardness of tool is desirable for welding wide range of materials (Zhang et al., 2012). PCBN, being a super hard material, is most suitable for FSW of high-strength material, such as titanium and steel, due to its good thermal and mechanical performance, but the problem is associated with its machinability, which makes forming of FSW tool geometry very difficult.

Machining of such tools and those made from tungsten carbide is very difficult especially in case of complex pin geometry. Development of tools having desirable properties, ease of manufacture, and low cost has made the welding of dissimilar aluminum alloys easy and cost effective. Various tool materials that are available for FSW are presented in Table 2.3.[5]

Table 2.2. Tool Materials and Geometries Used for FSW of Several Dissimilar Aluminum Alloys [5].

Workpiece Material	Tool Material	Tool Geometry	References
2024-T3 and 7075-T6 3 mm	SKD61	SD: 12, PD: 4, PL: 0.6, PS: cylindrical threaded	Khodir and Shibayanagi (2007)
2024-T3 and 6082-T6 sheets 0.8 mm	56NiCrMoV7-KU (Italy grade)	SD: 6, PD: 1.7, PL: 0.6, PS: cylindrical	Scialpi et al. (2008)
AA6082 and AA2024 4 mm	Threaded C40 steel tool	SD: 9.5, PD: 3.8, PL: ----, PS: threaded conical	Cavaliere et al. (2009)
AA5052 and AA6061 5 mm	HSS tool	PL: 4.8 mm, PD: 6 mm, SD: 25 mm, PS: cylindrical	Kumbhar and Bhanumurthy (2012)
AA6351-T6 and AA5083-H111 6 mm	HCHCr steel	SD: 18, PD: 6, PL: 5.7, PS: straight square	Palanivel et al. (2014)
AA7075-T6 and AA6082-T6 8 mm	H13 steel	SD: 23, PD: 5, PL: 7.9, PS: triangular frustum	Aval (2015)
AA2219 and AA 7039 6 mm	SS 310	SD: 19, SS: flat, concave, PD: 7, PL: 5.8, PS: threaded cylindrical	Venkateswarlu et al. (2015)
AA5083 and AA6063 4.75 mm	Tungsten carbide	SD: 20, SS: flat, PD: -----, PL: 4.4,	Khan et al. (2015b)

		PS: tapered cylindrical	
AA7475-T761 and AA2219-O 2.5 mm	HCHCr steel	SD: 20, SS: flat, PD: 6, PL: -----, PS: threaded cylindrical	Khan et al. (2017)

SD, shoulder diameter (mm); SS, shoulder shape; PD, pin diameter (mm); SD, shoulder diameter (mm); PL, pin length (mm); and PS, pin shape.

Table 2.3. Characteristics of FSW Tool Materials for Butt Welding [5].

Tool Material	Advantages	Disadvantages
H13	Easy machinability, good elevated temp strength	Severe tool wear for high strength materials or metal matrix composites (MMC)
SKD61	Good thermal fatigue resistance	Tool wear with complex pin profiles
HCHCr	High hot hardness compared to another tool steel	Difficult to machine in hardened condition
Tungsten	High hot hardness and strength. Suitable for high strength materials.	Poor machinability, expensive, low coefficient of friction with aluminum

Various properties that should be possessed by a suitable tool material for performing FSW are listed below:

- Good strength and wear resistance at elevated temperature for bearing high plunging forces
- Good dimensional stability for repeated use
- Good coefficient of friction with the workpiece for adequate generation of frictional heat
- Nonreactive with oxygen and workpiece material
- Good machinability for making complex geometry
- Hot hardness should be high enough to complete long weld
- Cost effectiveness

2.11. FSW TOOL DESIGN

The two important characteristics of FSW tool geometry are as follows: (1) its shape should be as simple as possible to reduce the cost and time and (2) it should be able to produce adequate stirring effect to produce sufficient material movement. Tool design is a critical factor during FSW and plays a vital role in plasticized material flow and localized heating at the SZ that significantly

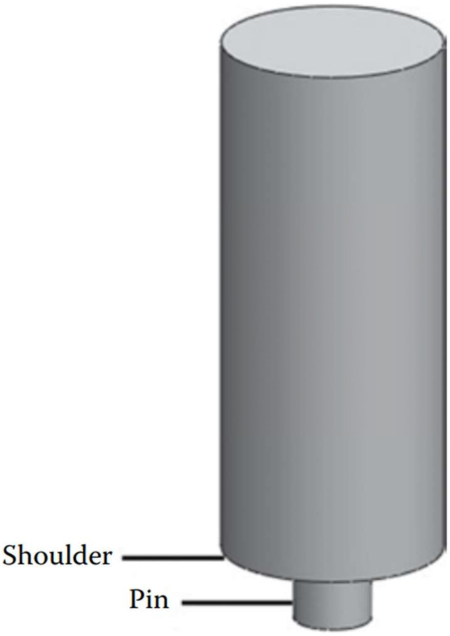


Figure 2.9. FSW tool.

affects defect formation and post weld mechanical properties. FSW tools are designed to generate sufficient heat due to friction between tool and BM and plastic deformation of BM and to obtain effective material flow. Tool comprises two main portions: (i) tool shoulder and (ii) tool pin, as shown in Figure 2.9. Tool shoulder generates heat due to friction, which is necessary for softening the BM being welded and forges the material being stirred behind the tool pin to properly consolidate the stirred material. It also restricts the material from extruding outside the shoulder. Tool pin generates heat by plastic deformation of the BM and promotes its movement around the pin (Kim et al., 2010). Different designs of tool shoulder surface that are being used in FSW include flat, concave, scrolled, concentric circle, etc. Scrolled and concentric shoulder design is shown in Figure 2.10. Tool shoulder surface plays an important role in stirring of the material as well. Different action is served by various shoulder surfaces features depending on the requirement. Flat shoulders are easy to make and simple in design and can be used for welding aluminum alloys except in special cases where enhanced stirring action and material consolidation are required. Concave shoulders are designed to restrict the stirred material within shoulder to minimize flash formation. Concave tool shoulder traps the flowing material under tool shoulder, which results in better consolidation of flowing material. Scrolled and concentric-type shoulders are designed to enhance degree of material stirring for proper mixing of the BMs to improve joint properties. Flat end surface having spiral channel toward the center constitutes a scroll shoulder. Spiral channel directs the flowing material from end toward the pin to prevent expelling of material outside the shoulder. Scroll shoulder eliminates the use of high tool tilt for consolidating the material behind pin as it works normal to the workpiece, which reduces thinning of weld region. Spiral groove in scrolled shoulder promotes plastic deformation and frictional heat. Scroll shoulder faces problems during welding of materials with different thickness. Along with the design of tool shoulder features, its diameter also significantly affects the process in terms of heat generation and material movement.

2.11.1. Shoulder Diameter

In FSW, heat is generated by friction and plastic deformation of the material and shoulder produces heat by frictional sticking and sliding of the material under it. Large shoulder diameter generates more friction and consequently increases heat input. Sticking of material is responsible for material flow in the stirred region. Tool shoulder diameter governs heat generation by friction between tool shoulder and work piece as it increases the contact area. Also, large shoulder diameter affects large portion of workpiece, which results in increased HAZ leading to deterioration of the post weld mechanical properties. Excessive heat generation is not desirable as it degrades the quality of the welded joint by grain coarsening and dissolution of strengthening precipitate (in case of precipitation hardening materials) and loss of cold work. It is also observed that the smaller tool shoulder diameter leads to less frictional heat and hence the weld metal consolidation may not be appropriate in the SZ. It consequently affects the joint strength due to insufficient softening of material causing improper material mixing in SZ. Evidently, optimum shoulder diameter is required that could generate sufficient heat and promote proper material movement, minimize torque, and traverse force and produce small HAZ.

The diameter of the tool is important because the shoulder generates most of the heat and it also contains the material being extruded from AS. Further, tool shoulder forges the flowing material behind the pin preventing plasticized material from escaping out of weld region and consequently ensuring proper consolidation of joint. It has been established through several findings that the shoulder diameter should neither be too small nor too large. For example, Padmanaban and Balasubramanian (2009) in their investigation considered three shoulder diameters (15,18, and 21 mm) and demonstrated that the joint fabricated using 18 mm diameter yielded defect-free and fine-

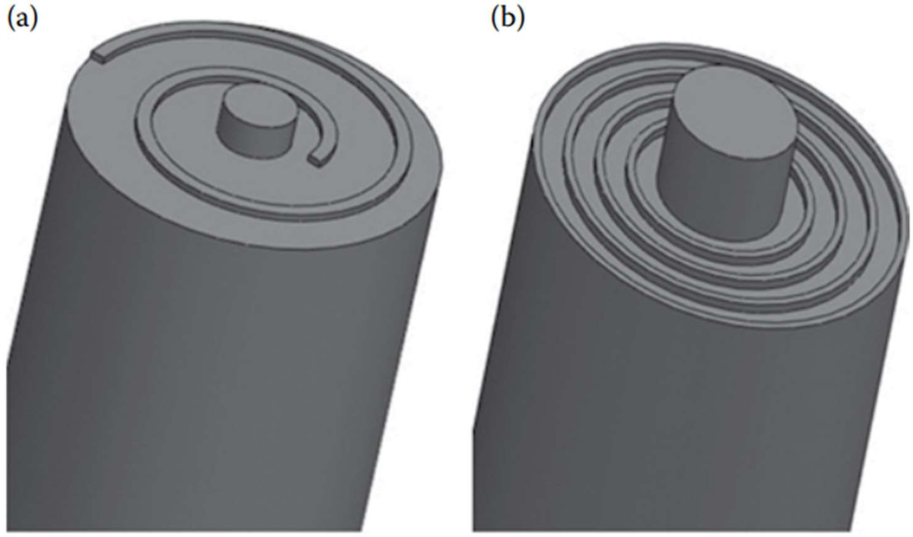


Figure 2.10. FSW tool shoulder designs:(a) scroll and (b) concentric.

grained nugget region, which subsequently showed higher hardness and superior tensile properties. Similar observations were made by Elangovan and Balasubramanian (2008) during FSW of AA6061 aluminum alloy. Thus, shoulder diameter should be carefully chosen based on the required heat input.

2.11.2. Pin Geometry

Tool pin geometry includes shape and size of pin. Size of the pin is related to shoulder diameter as their relative size affects the heat generation and plastic deformation. Pin profile mainly governs the material movement. Flow of plasticized material is significantly influenced by type of tool pin profile. During plunging of tool into faying surface, the heat is primarily generated by friction and plastic deformation of material at pin–workpiece interface, which softens the material in the vicinity of pin and moves the same around it by sticking action. FSW process uses combination of extrusion and forging processes for joining the materials. Pin extrudes the softened material around it from leading to the trailing side and shoulder forges the flowing material behind the pin for its consolidation.

Various pin profiles are used in FSW tool such as, cylindrical and tapered cylindrical (i.e., frustum of a cone, square, hexagon, threaded cylindrical, threaded cam, and threaded tri flute as shown in Figure 2.11). Each profile performs different functions in terms of material movement and material mixing. Cylindrical and tapered cylindrical pin moves material around the pin, whereas threaded pin moves it around the pin as well as in vertical direction. Square, hexagonal, and cam pin profiles produce pulsating action due to flat faces during stirring of flowing material. Good mixing is obtained by the pulsating action of the pin, which results in improved joint strength. At the same time, pin profiles other than cylindrical tends to wear out in due course of time leading to a conical form. On prolonged usage, profiled pins wear out and acquire tapered cylindrical or cylindrical shape. Hence, for long run and large number of runs with the same pin, optimum pin profile is used that can sustain its shape as well as provide better stirring action.

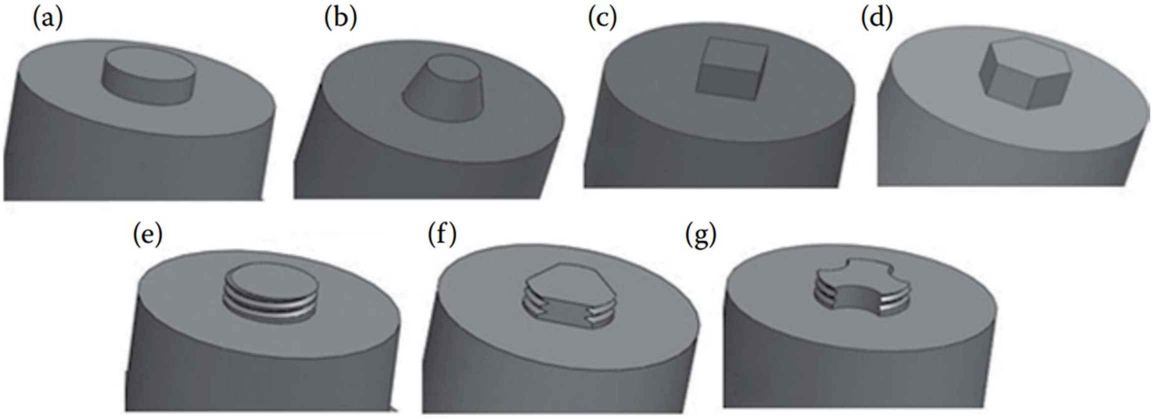


Figure 2. 11. Different FSW tool pin profiles: (a) cylindrical, (b) tapered cylindrical (i.e., frustum of a cone), (c) square, (d) hexagon, (e) threaded cylindrical, (f) threaded cam, and (g) threaded tri flute.

2.12. FSW PROCESS PARAMETERS

Precise criterion for selection of FSW process parameters is still evolving and as of now it is based on experience and outcomes of experimental trials. Often the parameters produce contradicting effect on responses; consequently, selection of process parameters should be based on combined effect in such a way that defect-free joints with good joint efficiency and high production rate are obtained. Important FSW parameters include tool travel speed, tool rotational speed, tool tilt angle, pin offset, and plunge depth. These parameters also influence heat generated during FSW process. There are some other factors related to tool that also influence resulting weld such as pin features, tool material, diameter of tool, and type of tool shoulder. Evolution of some responses such as peak temperature, longitudinal force, torque, and power requirements are determined by FSW process parameters and type of BM [5].

2.12.1. Rotational and Traverse Speeds

Tool rotation, that is, rpm helps in material movement around pin and mixes the material to complete the joint. Increase in the rotational speed increases friction heat, which in turn increases temperature in SZ. There is nonlinear relation between frictional heat and rotational speed as the interface frictional coefficient changes with increase in tool rotation and temperature. Typically, a study has revealed that an increase of rotational speed from 300 to 650 rpm increased peak temperature of SZ by 40°C and a further increase from 650 to 1000 rpm increased the peak temperature by 20°C (Tang et al., 1998). This result, like several others, suggests that the temperature increases with slower rate at higher rotational speed. Increase in tool rotational speed significantly increases the peak temperature and decreases the torque. Lower rotational speed generates insufficient heat, which results in inadequate plasticization of material leading to lower joint strength. Higher rotational speed generates more heat, which may often cause undesirable metallurgical transformation such as, dissolution and coarsening of strengthening precipitates, grain growth, and minimizing dislocation density, which will degrade the joint strength. Therefore, optimum rotational speed must be selected for defect-free joints with good post welding mechanical properties.

Tool traverse speed affects distribution of generated heat along length of weld during welding. Increase in tool traverse speed, also known as welding speed, decreases the peak temperature in SZ. However, higher welding speed reduces heat input at weld region, which makes the material flow difficult and thereby may result in slight increase in torque. Tool traversing in welding direction moves the plasticized material from AS to the back of tool pin to complete joining. Higher welding speed may lead to large longitudinal forces, which may also result in tool wear and in extreme cases cause tool breakage. Also, high welding speed is one of the causes of formation of tunneling defect at the bottom of SZ and TMAZ interface in AS due to improper consolidation of flowing material behind pin. At higher welding speed, tool moves ahead before depositing sufficient material necessary to fill space behind it vacated by tool creating a continuous void, which may be termed as tunnel. The size of defects increases with increase in the welding speed.

During FSW, a material to be welded undergoes SPD due to stirring and simultaneous action of heat and SPD causes dynamic recrystallization, which results in grain refinement. Grain refinement is affected by degree of plastic deformation and amount of heat generated at SZ. Indirect effect is that the size of recrystallized grains increases with increasing rotational speed and decreasing tool traverse speed. Tool rotation and traversing speed must be selected to ensure efficient welding. Lower rotational speed combined with higher traversing speed results in colder weld whereas, higher rotational speed along with lower traversing speed results in hotter weld.

In FSW, it is essential to decide (i) how fast the tool should be rotated and (ii) how quickly it should be allowed to traverse along the interface rotates. Tool rotational and traversing speed must be carefully selected to make the flowing material hot enough for undergoing the required plastic deformation and reduce the forces experienced by the tool. At the same time, the flowing material must not be overheated to cause degradation of mechanical properties of the joint. Therefore, a process window of the parameters is required to produce defect-free welds by avoiding too cold and too hot weld.

2.12.2. Tool Tilt Angle

Inclination of the tool axis from the normal of the workpiece surface is referred to as tool tilt angle. It is defined as the angle between the tool axis and normal line to the workpiece surface, as shown in Figure 2.12. It significantly affects the rate of heat generation, material movement, and consolidation of flowing material behind the tool pin. Axial force applied by the tool and peak temperature increases with tool tilt angle. Tool tilt angle helps in preventing the flowing material from being expelled. Also, tool tilt angle affects the shape of SZ, which indicates its effect on

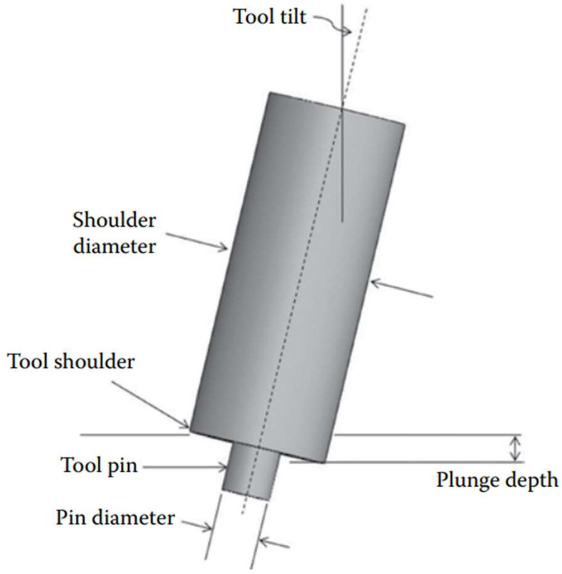


Figure 2. 12. FSW tool with plunge depth and tilt angle

vertical and horizontal flow of material in SZ. Tilting the tool by some degree in such a way that the front of tool is higher than its rear, helps in adequate forging of the plasticized material behind the tool to complete the joint.

2.12.3. Plunge Depth

Plunge depth is defined as the depth of lowest point of shoulder below the surface of welded plate, as shown in Figure 2.12. It is found to be a critical parameter for ensuring weld quality. Plunge depth is an important process parameter of FSW that plays a vital role in heat generation during welding and, it also controls the forging of flowing material. Increase in plunge depth increases axial force, which in turn increases frictional heat at tool–workpiece interface. Further, increase in plunge depth results in higher heat input, which leads to grain growth and formation of IMCs that directly affect strength and ductility of the joint. On the other hand, low plunge depth results in lower heat generation, which causes insufficient plasticization of material leading to inadequate material mixing that may lead to the formation of defects. Also, lower plunge depth decreases peak temperature that causes increase in flow stress leading to slugging material movement. Therefore, appropriate plunge depth is important for producing good-quality joints by ensuring adequate forging pressure required to consolidate flowing material properly as well as full penetration of the tool inside BM.

2.12.4. Tool Pin Offset

A shift of tool axis on either side of the joint line is regarded as tool pin offset or simply tool offset. It has a significant effect on the distribution of generated heat on either AS or RS, and on the mixing of two materials during FSW of dissimilar materials. In addition, pin offset influences post weld mechanical properties due to differences in physical, chemical, and mechanical properties in case of welding dissimilar materials. Previous studies showed that for FSW of dissimilar materials, poor joints were obtained at weld line of butted plates and the pin offset toward softer materials was usually adopted to achieve the defect-free joints (Khan et al.,2015b). Cole et al. (2014) reported that higher joint strength is obtained with tool offset toward stronger material. Joint properties can be improved by offsetting the tool toward either side of the joint line based on the materials to be welded.

CHAPTER III

3.1. Introduction

Aluminum alloys are widely used in several industrial sectors owing to their desirable properties such as strength, weight, corrosion resistance, etc. Its high strength-to weight ratio makes it very suitable in the aircraft and automotive industries. The AAs, AA6XXX and AA5XXX are extensively used in the fabrication of aircraft structures and other structural applications. Dissimilar joining of these two alloys is encountered in industrial structures. The choice of FSW, being a solid-state joining process, is preferably suitable for the welding of Al and its alloys; this eliminates the problem of weld solidification cracking. In addition, the FSW process has overcome the problems associated with fusion welding of Al and its alloys, such as porosity, segregation and heat affected zone (HAZ) liquidation cracking. Hence, FSW is suitably employed for dissimilar welding of Al and its alloys. The uniqueness of FSW of dissimilar materials has attracted extensive research interest because of the potential engineering importance and problems associated with the conventional welding process. In view of this, different dissimilar AA combinations have been successfully FSW with excellent joint efficiencies.[4]

An experiment was conducted for different tool rotational speeds of 600 rpm, 1000 rpm and 1400 rpm and welding speed of 40 mm/min. Friction stir welded (FSW) joints of higher tensile strength, lower flexural strength, and lower impact strength with maximum hardness, for the work piece fabricated at 1400 rpm using a high-speed steel tool with a cylindrical profile. Better understanding of the effect of tool rotational speed and mechanical properties was illustrated this chapter.

3.2. Experimental work

The base material used in this study were AA6061 and AA5083 aluminum alloy plates, with the chemical compositions and mechanical properties are presented in Table 3.1 and Table 3.2 respectively ,The plates were all cuts and machined into the same thickness 7 mm and wide 56 mm, also expelling the surface contaminants to achieve a superior surface finish, After that contact the faying surface for the BM and clamped rigidly and using the vertical milling machine (HURON) which is shown in figure 3.1 for welding, The welding tool used in this study was a non-consumable rotating tool made of high speed steel (HSS) is shown in Figure 3.2 . The tool pin is a cylindrical with shoulder diameter of 16 mm, 5 mm pin tip length and D/d ratio of 4. There are two inverting positions in FSW for the base metal AA6061 is placed in the retreating side (RS) due to its lower tensile strength, while AA5083 is placed in the advancing side (AS). The tool pen was positioned at center of joint line and start welding longitudinal direction after plunged the pin tool and the shoulder contact the surface. Moreover, we worked on three different tool rotational speed of 600, 1000 and 1400 rpm, keeping the constant welding speed of 40 mm/min.

Figure 3.2. Cylindrical tool

Figure 3.1. Vertical milling machine (HURON)

Quality welds ca be produced with tool rotational speeds ranging from 600 to 1600 rpm. The single pass welding procedure was adopted for fabrication of dissimilar joints, which is shown in the Figure 3.3.

Table 3.1. Chemical composition of the material AA6061 and AA 5083

ALLOYING ELEMENTS	6061 (%)	5083 (%)
AL	97.752	92.529
SN	0.008	-
ZR	0.002	-
PB	0.027	-
ZN	0.221	0.080
CU	0.209	0.063
FE	0.736	0.370
MN	0.120	0.979
SI	0.741	2.021
MG	0.891	3.789
CR	-	0.139

Table 3.3. Mechanical properties of base materials.

BASE METAL	ULTIMATE TENSILE STRENGTH (MPA)	HARDNESS BRINELL	TENSILE ELONGATION
AA 6061	310	42	17
AA5083	350	75	12

3.3. Mechanical properties

The mechanical properties of joints like tensile, impact and hardness are determined. To determine

Figure 3.3. Friction stir welded specimens of different tool rotational speeds.

Figure 3.4. GUNT WP 310.

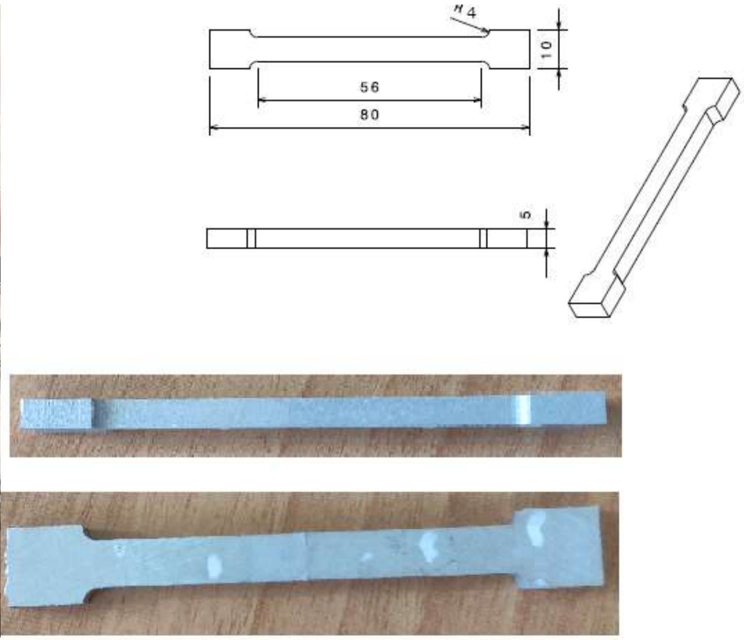


Figure 3.5. Tensile test spacemen dimensions.

the mechanical properties of dissimilar FSW welded joints, test was performed as per the American Society for Testing of Materials standards (ASTM). Tensile test was conducted at room temperature using an electromechanical controlled universal testing machine Figure 3.4 (GUNT WP 310) with an ultimate load of 50 KN and at a strain rate (dε/dt) = 10^{-3} s^{-1}. Tensile specimens were prepared as per the ASTM B557-84 standard for evaluating the yield strength, ultimate strength, and the percentage of elongation of the weld joints, Figure 3.5 shows the dimensions of the tensile specimen's test in conjunction with the American Society for Testing and Materials (ASTM)

Figure 3.6. WILSON HARDNESS type TUKON

standards. For the hardness teste we used WILSON HARDNESS type TUKON 2500/Vickers automated hardness testers which is shown in Figure 3.6. Impact testing was conducted at room temperature using a pendulum type impact testing machine, Figure 3.7 with a maximum capacity of 300 J. Charpy impact specimens were prepared as per the ASTM E23-04 standards. The Charpy test was carried out with an impact testing machine for determining the amount of energy absorbed in fracture, which was recorded. The absorbed energy is defined as the impact toughness of the material.

Figure 3.7. Charpy impact teste machine.

3.4. Results and discussion

3.4.1. Tensile test

We used GUNT WP 310 to find yield strength, tensile strength, percentage of elongation of the dissimilar FSW joints. Three specimens are tested for each rotational speed and the average of the results is presented in Figure 3.8. As we can see all the joints have lower yield strength, tensile strength and percentage of elongation compared to the base material of both aluminum alloys.

All the joints are fractured along the retreating side, which is shown in Figure 3.7. This happened due to the smaller yield strength and minimum hardness value of the base material AA60601 compared to the advancing side base material AA5083.

The influence of the welding speed on the tensile properties of FSW joints is inferred through test tensile and we saw the results in the Figure 3.8 and the specimen in Figure 3.7, and therefore, depending on the three rotational speeds we found 1400 rpm specimen has a superior tensile property. This result of the effect of higher heat input during welding as it results in good ductility.

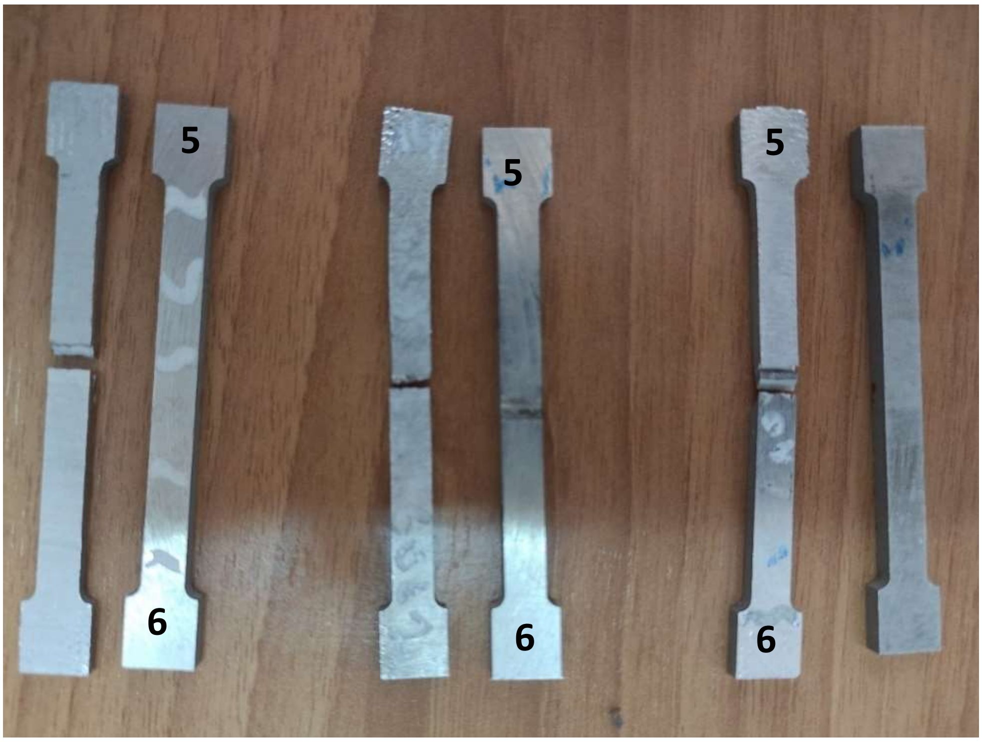


Figure 3.7. Tensile tested AA6061 and AA5083 samples welded with cylindrical pin.

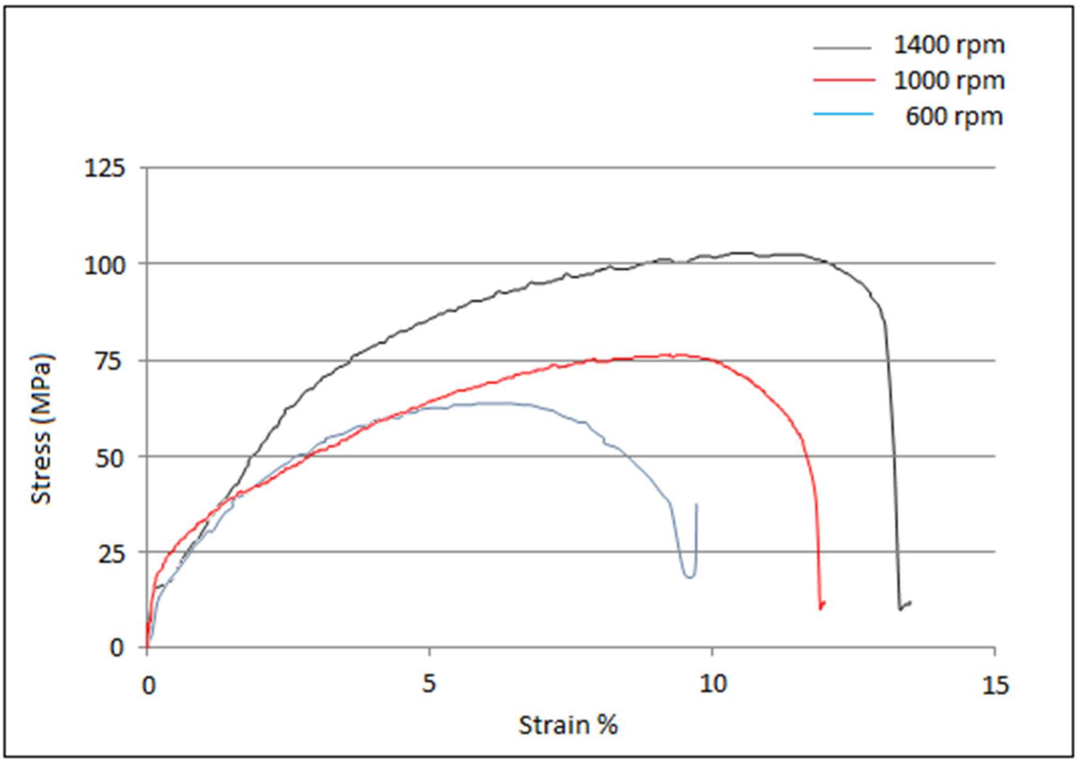


Figure 3.8. Stress versus strain curves for welded dissimilar aluminum (AA6061-AA5083).

This shows that an increase in tool rotational speed increase the tensile properties of a joint. The overall observation was that the essential nature of use of higher rotational speed for providing good heat input, welds thus obtained displayed good tensile strength. These reveal that the ductility of stir zone is lower than base materials.

3.4.2. Impact test

The Charpy impact strength of dissimilar FSW weld joint was evaluated and presented for three different tool rotational speeds. Impact strength of FSW joint with the notch was places at the weld center line. Table 3.3 illustrates that an increase in the tool rotational speed causes reduction in the impact strength of weld joint due to the evolution of high heat, resulting in coarse grain structure. The impact strength for the tool rotational speed of 600 rpm is 0.56 J/mm^2, which is 17.85% higher than the 1400 rpm welded specimen. All the impact tested specimen does not break into two pieces, as shown in the Figure 3.9, reveals that the FSW joint does not lose its ductility.

Table 3.3. Impact strength results.

TOOL ROTATIONAL SPEED (RPM)	IMPACT STRENGTH (J/MM^2)
600	0.56
1000	0.51
1400	0.46

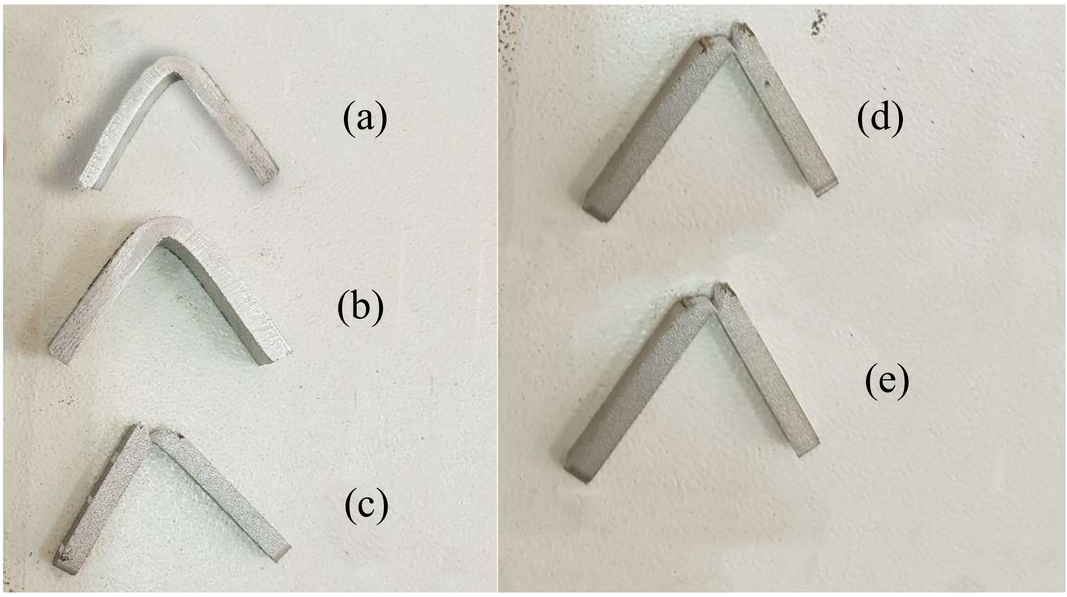


Figure 3.9. Impact test specimen, (a: 6000, b: 5000, c: 5/6 600, d: 5/6 1000, e: 5/6 1400).

3.4.3. Hardness test

AA6061-AA5083 for three different tool rotational speeds is illustrated in Figure 3.10. The fusion zone has a lower hardness compared to the base material AA5083 and 68% higher than the base material value of AA6061. Retreating side was identified with hardness value of 56 HB and advancing side hardness value of 103 HB due to the base material in the retreating side. The hardness value of the stir zone increases as the tool rotational speed increases. This was due to the HAZ region by retreating side, that is, 39 HB, which is 36% higher in the base material of AA6061

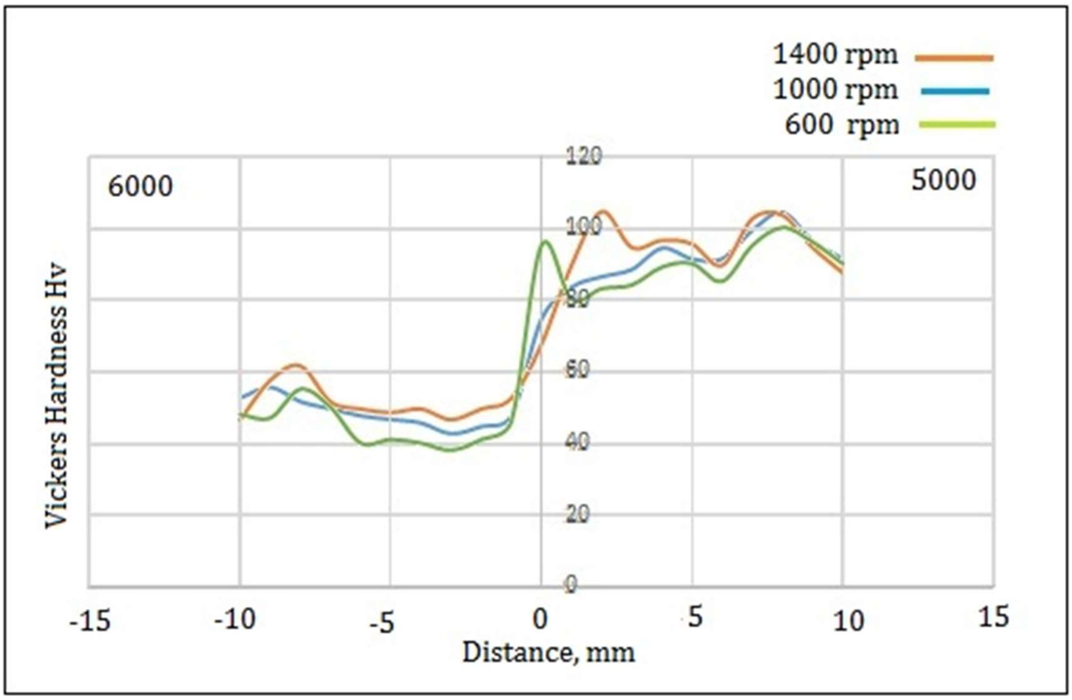


Figure 3.10. Hardness variation from stir zone.

revealing the effect of the tool rotational speed amplifies, the rate of heat input increases, resulting in fine microstructure, in turn increasing the hardness.

3.4.4. Macrostructure

From the macro-graphic studies, different regions of weldments are identified, and it represents the effective stir of both the base material in the nugget zone Fig 3.11. Also, the presence of AA6061 in the stirred zone is more when compared with AA5083, as the former was kept on the advancing side. Defect free welds were produced on using cylindrical with three different tool rotational speed of 600, 1000 and 1400 rpm, keeping the constant welding speed of 40 mm/min.

Figure 3.11. (a) Macrostructure, cylindrical; pin, 600 rpm

3.4.5. Microstructure

The microstructure of the different regions of the welded dissimilar material is shown in Fig. 3.12 (a, b, c). Though the weld undergoes considerable amount of thermal cycle, there is no significant changes in the microstructure of the base metals as we can see in Figure 3.12(a) for AA6061 and Figure 3.12(b) for 5083. On the other hand, the thermal cycle, has considerably influenced the Nugget Zone and Heat affected Zone (HAZ), which is evident from the microstructure (Fig 3.12(c). However, there is no plastic deformation occurring in this area. In the thermo-mechanically affected zone (TMAZ), there is considerable growth in the grain boundaries which could be due to the plastic deformation and the less heat developed during the process. Also, it is evident from the microstructure that a distinct grain boundary separates the recrystallized zone (weld nugget) from the deformed zones of the TMAZ. The dynamically recrystallized zone is the stirred zone, where the material has undergone severe plastic deformation resulting in fine equiaxed grains. The term stirred zone is commonly used in friction stir processing, where sufficient volume of material is processed.

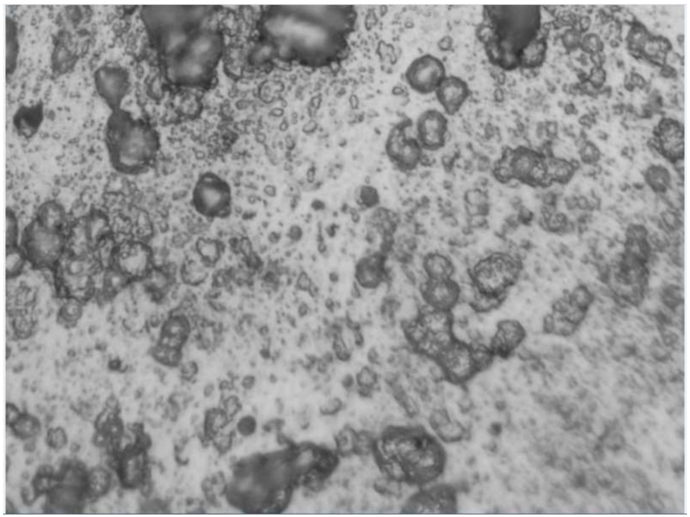


Figure 3.12 (a). Microstructure for AA6061

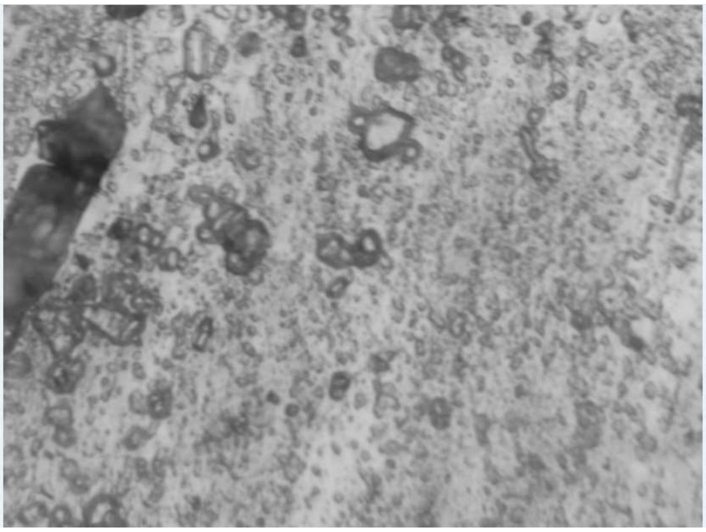


Figure 3.12 (b). Microstructure for AA5083.

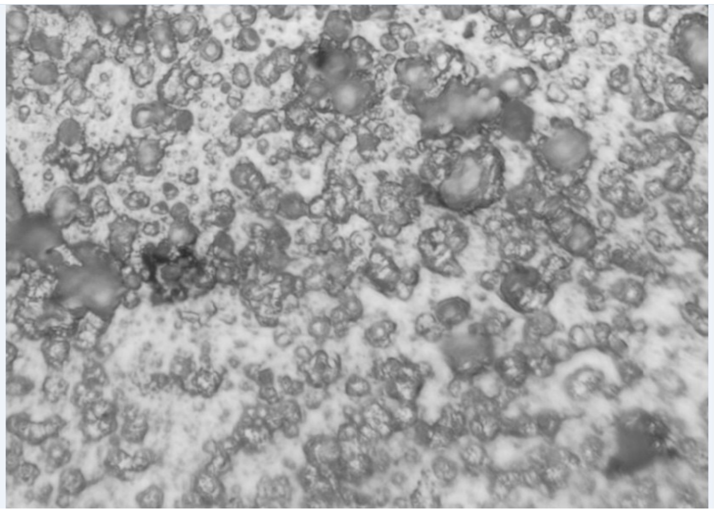


Figure 3.12 (c). Microstructure for Nugget zone (Stir Zone)

4. Conclusion

Aluminum alloy AA5083 along with AA6061 can be successfully used for friction stir weld for tool rotational speeds ranging from 500 rpm to 1400 rpm; with step variation of 200 rpm the axial load and welding speed is maintained constant. Investigation of the mechanical properties of fabricated joint and its effects are discussed in this paper. The following conclusions can be drawn based on the experiments carried out:

1. The joint fabricated using FSW process parameters 1400 rpm (tool rotational speed), 40 mm/min (welding speed), with the cylindrical tool profile has the highest yield strength and ultimate tensile strength properties compared to the other tool rotational speeds. All the specimens during tensile test failed on the retreating side only.
2. The flexural strength 105 MPa of the weld specimen is lower than the other specimens. Minimum impact strength occurs for the tool rotational speed of 1400 rpm. The brittle fracture is observed on the FSW weld joint. Maximum hardness is achieved for the rotational speed of 600 rpm.
3. Impact strength of FSW weld joints has been evaluated for different tool rotational speeds. These are 0.56, 0.51 and 0.46 J/mm2 for 600, 1000 and 1400 rpm, respectively.
4. The hardness of stir zone is variable for different tool rotational speed, 95 HB for 600 rpm and 75 HB for 1000 rpm. The minimum hardness value (68 HB) of stir zone is observed on the 1400 rpm tool rotational speed.
5. The flexural strength and impact strength and hardness decreases when the tool rotational speed rises, whereas the tensile strength increases.

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Résumé

La technologie d'assemblage de matériaux similaires et dissemblables joue un rôle crucial dans divers domaines, y compris la fabrication. De nombreuses techniques de soudage conventionnelles ont été utilisées au fil des ans pour assembler avec succès divers matériaux. Le soudage par friction-malaxage (FSW) est un procédé de soudage à l'état solide. Cette thèse traite de l'étude des caractéristiques mécaniques des joints soudés bout à bout de l'alliage d'aluminium AA6061 avec AA5083. Une expérience a été menée pour différentes vitesses de rotation d'outil de 600 tr/min, 1000 tr/min et 1400 tr/min. Utilisation de la fraiseuse verticale et vitesse de soudage de 40 mm/min. Des joints soudés par friction-malaxage (FSW) de résistance à la traction plus élevée, de résistance à la flexion plus faible et de résistance aux chocs plus faible avec une dureté maximale, pour la pièce fabriquée à 1000 tr/min à l'aide d'un outil en acier rapide avec un profil cylindrique ont été observés. Une meilleure compréhension de l'effet de la vitesse de rotation de l'outil et des propriétés mécaniques a été illustrée par le résultat expérimental.

Mots-clés : alliage d'aluminium, résistance à la traction, impact, résistance, profil de broche cylindrique.

الملخص

تلعب تقنية الانضمام للمواد المتشابهة وغير المتشابهة دورًا مهمًا في مختلف المجالات، بما في ذلك التصنيع. تم استخدام العديد
هو عملية لحام (FSW) من تقنيات اللحام التقليدية على مر السنين للانضمام إلى المواد المختلفة بنجاح. لحام الدمج الاحتكاكي
AA6061 في الحالة الصلبة. تناقش هذه الرسالة التحقيق في الخصائص الميكانيكية لوصلات اللحام الثنائي لسبائك الألومنيوم
تم إجراء تجربة لسرعات دوران مختلفة للأداة تبلغ 600 دورة في الدقيقة و1000 دورة في AA5083. جنبًا إلى جنب مع
الدقيقة و1400 دورة في الدقيقة. باستخدام آلة الطحن العمودية وسرعة اللحام 40 مم / دقيقة. تمت ملاحظة الوصلات الملحومة
ذات قوة الشد الأعلى، وقوة الانحناء المنخفضة، وقوة الصدمات المنخفضة مع أقصى صلابة، لقطع العمل (FSW) بالاحتكاك
المصنعة عند 1000 دورة في الدقيقة باستخدام أداة فولاذية عالية السرعة ذات ملف جانبي أسطواني. تم توضيح الفهم الأفضل
لتأثير سرعة دوران الأداة والخصائص الميكانيكية من خلال النتيجة التجريبية.

الكلمات المفتاحية: سبائك الألومنيوم، قوة الشد، التأثير، القوة، الشكل الأسطواني.