INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

RESEARCH ARTICLE

Mechanical Properties and Microstructure of 7075T6 Aluminum Alloy – DC01 Low Carbon Steel Rod Joints by Magnetic Pulse Welding

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OPEN ACCESS

Received: 21-05-2024

Accepted: 11-07-2024

Published: 26-11-2024

Citation: Gnanamurugan K, Varahamoorthi R, Sundarraj C (2024) Mechanical Properties and Microstructure of 7075T6 Aluminum Alloy – DC01 Low Carbon Steel Rod Joints by Magnetic Pulse Welding. Indian Journal of Science and Technology 17(43): 4470-4475. https://doi.org/10.17485/IJST/v17i43.1728

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Funding: None

Competing Interests: None

Published By Indian Society for Education and Environment (iSee)

ISSN
Print: 0974-6846
Electronic: 0974-5645

Abstract

Objectives: The production of solidification flaws such as porosity, alloy segregation, hot cracking, etc. makes the fusion welding process extremely challenging when joining aluminum alloys with low-carbon steel (DC01). Explosive welding and magnetic pulse welding are two solid-state welding methods that can be utilized to solve these issues. With magnetic pulse welding (MPW), welding can be done more quickly and affordably while creating overlapped joints. **Methods:** In this study, the MPW method was used to join the dissimilar AL 7075T6 aluminum alloy tube and DC01 steel rod. The mechanical characteristics and microstructure of MPW joints were evaluated and observed. The results demonstrate that the metallurgical joints may be formed in the lapping region at a discharge energy of 23 kJ, a stand-off distance of 2 mm, and an working length of 8.5 mm. **Findings:** The joint is made up of a transition zone with varying widths, two matrix metals, and two interfaces between the zone and the two metals. The interface has a characteristic wavy pattern, and mutual diffusion of Fe and Al elements occurs in the zone. The micro hardness of the interface is much higher than that of the matrix metals. The metallurgical joint consists of two interfaces, one transition zone and two basic metals. The mutual diffusion of Fe and Al elements occurs across the interface and in the transition zone. The multi-direction micro-cracks and the micro-apertures present in the transition zone. **Novelty:** Aluminium alloys with low carbon steel joints were developed using MPW for cars and ships applications without fusion welding defects. The microstructural features of Aluminium alloys with low carbon steel tube joints were correlated to the TSFL and Hardness of the joints.

Keywords: Magnetic pulse joining; Dissimilar metals; Metallurgical joint; Aluminum; Alloy; Mechanical properties

1 Introduction

The welding community has become more interested in magnetic pulse welding (MPW), which is recognized as a "solid state welding process" and has similarities to explosive welding [1] because it can join similar and dissimilar materials in microseconds without the need for a contact work piece or welding consumables. Similar to explosive welding, MPW depends on the dynamic effects of high-impact collisions between the joining components. The components to be linked are put concentrically into the coil when utilizing the cylindrical design, creating an acceleration gap. MPW accelerates the flyer work piece in preparation for impact with a target component using an electromagnetic pulse with a duration of less than 100 μs [2]. A high-density magnetic flux is created around the coil when current is supplied, causing currents to flow through the conductive outer work piece. A repulsive force is produced as a result of the eddy currents' opposition to the coil's magnetic field [3]. The outer component experiences high pressure due to the repulsion between the two magnetic fields, which is much higher than the material yield strength. This pressure causes the outer component to accelerate across the standoff gap, producing a highly localized pressure at the collision site [4]. The outer component experiences high pressure due to the repulsion between the two magnetic fields, which is much higher than the material yield strength. This pressure causes the outer component to accelerate across the standoff gap, producing a highly localized pressure at the collision site [4].

The quantity of steel used in the production of automobile bodies has been steadily decreasing over the past several years. As a result, several parts that were formerly made of steel have been replaced with light metals and polymers [5]. Thus, aluminum-steel connecting components are used in automobiles. Although bimetal joining components, such as those made of two different aluminum alloys, steel and aluminum alloy, and stainless steel [6,7], are desperately required and will be widely utilized in the production of aircraft and petrochemical engineering, etc. [8]. However, the mechanical properties of the joint will be weakened by a conventional fusion welding process because of the notable differences in the physical properties of the two dissimilar metals, such as the melting temperatures, which are easily produced [9].

The addition of a third metal element during the diffusion joining process is typically suggested as a solution to these issues. As a result, basic metals like copper and aluminium will lose their single-phase properties. Furthermore, research has been done recently on a number of various approaches, including friction stir welding, magnetic pulse welding [10], delta spot welding, spot friction welds, and friction stir welding. By using the MPW technique and appropriate settings, it is possible to achieve a solid-state metallurgical joining between dissimilar metal tubes with an almost minimal heat-impacted zone. Lightweight, highly robust, and multifunctional tube sections may be manufactured with great efficiency and low cost using this approach to producing dissimilar junctions. A solid coil must have high strength, sufficient mass, and toughness since a joining coil experiences challenging conditions during magnetic pulse joining, such as strong pulse impact loading, vibration, and transient heat cycles for the Joule heat effects . This type of coil, however, is hard to produce since it requires a very intricate design and manufacturing procedure.

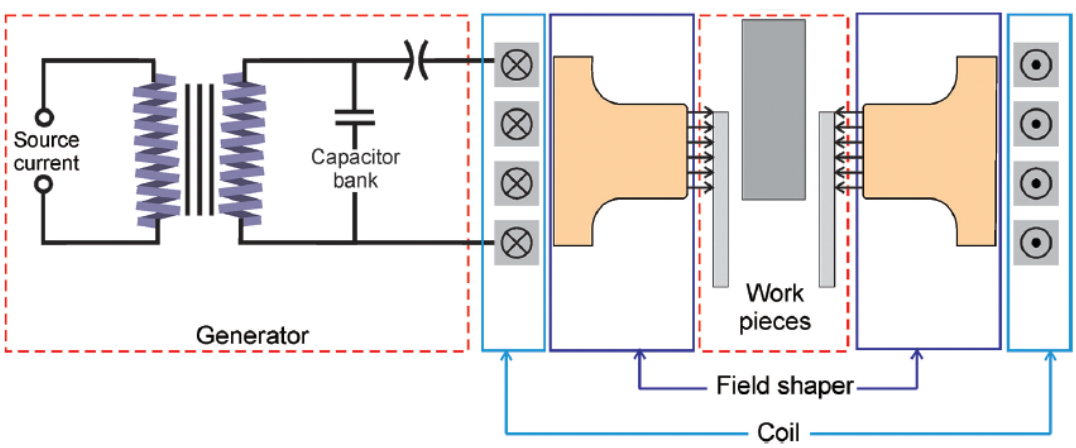

Fig 1. Schematic representation of MPW for tubular parts [3]

It is clear from the literature study that several researchers have looked at the fusion welding procedures used to join aluminium and steel. The joining of DC01 low-carbon steel with AL 7075T6 aluminium alloy utilizing the MPW process has not been studied. As a result, an attempt was made to join the DC01 low-carbon steel with the AL 7075T6 aluminium alloy [11,12]. From the literature review, it is understood that many researchers have studied the joining of the Aluminum with steel using the fusion welding processes. There is no study on the joining of AL 7075T6 aluminum alloy with DC01 low carbon steel using rotary MPW technique. Therefore, aCn attempt was made to join the AL 7075T6 aluminum alloy with DC01 low carbon steel. The primary aim of this research is to analyse the mechanical and microstructural properties of AL 7075T6 aluminium alloy joints fabricated with DC01 low carbon steel by MPW.

2 Experimental Procedure

The experiment was conducted using 100 kJ magnetic pulse welding equipment (available from Magpulse Technologies Pvt Ltd) on a steel coil (EN-8). The solution-heat-treated AL 7075T6 aluminium alloy with a 2 mm wall thickness was used in the experiment. As shown in Figure 1, the diameter was fixed at 66 mm, and the seam-welded DC01 carbon steel pipe with a diameter of 64 mm was used to fabricate MPW joints. Additionally, stand-off distance (SD) was used to manipulate the diameter of the steel tube, which was 60.5, 61, 61.5, 62, 62.5 mm, respectively. High-density polyethylene (HDPE) was used to secure the tubes into place, resulting in the first joint consignment. The direction of the weld was in line with the direction of the aluminium placement. Joints were fabricated with a single pulse. As seen in Figure 2, the manufactured joints were cut from the MPW joint using electron discharge marching (EDM) to achieve the required form size. Table 1 shows the composition of base metals by weight percentage, and Table 2 lists the mechanical properties of base metals. Table 3 displays the welding parameters for the building of joints.

Table 1. Chemical Composition wt% of the base metals

Material	C	Mn	P	S	Fe	Zn	Mg	Cr	Cu	Al
AL-7075 T6	/	/	/	/	/	5.6	2.5	0.13	1.6	Bal
DC01 steel	0.12	0.60	0.045	0.045	Bal	/	/	/	/	/

Table 2. Mechanical properties of base metals

Materials	0.2% Yield strength	Tensile strength (MPa)	Hardness (HV 0.025 kgf)	Elongation in 50mm gauge length (%)
AA 7075 T6	214	260	87	12
DC01 steel	280	320	125	28

For each specimen three strips (samples) were prepared. Two tensile shear specimens were set to evaluate the tensile shear fracture load (TSFL). Tensile shear fracture test was carried out in an electromechanical controlled universal testing machine and the average values of two results are presented for analysis.

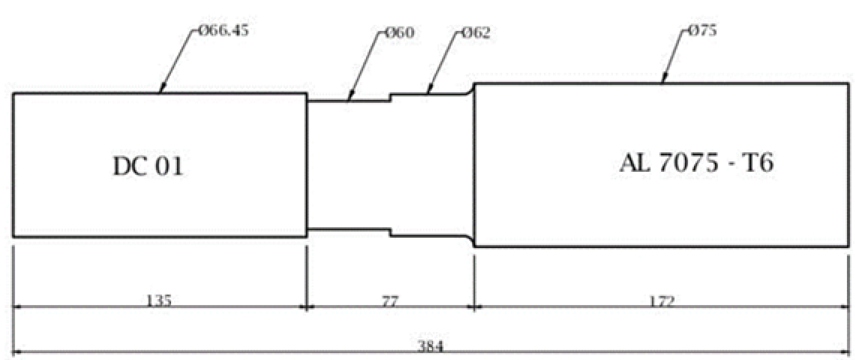

Fig 2. Dimensions of joint configuration (Unit: mm)

One Sample was surface-ground using a 120-grit size belt with the help of a belt grinder, polished using grade 1000, grade 2000 and grade 2500 sandpaper. The specimens were further polished by using aluminium oxide. Macroscopic and microscopic inspections are done by optical microscopy.

Table 3. Optimized MPW pa rameters

No.	Parameter	Notation	Unit	Value
1	Discharge energy	**E**	kJ	23
2	Stand-off-distance	**D**	mm	2
3	Overlap length	**L**	mm	8.5

3 Results and Discussion

3.1 Tensile properties

The average tensile shear force load (TSFL) of the base materials and MPW sample is shown in Table 4. The TSFL of the AL 7075T6 /DC01 MPW joint was 2.4 kN. The observed TSFL is closer to the base material of AL 7075T6, which is confirmed by the MPW joint efficiency of 92.30%. During tensile testing of MPW joints, the samples failed from the heat-affected zone (HAZ) to the base metal (aluminium side). The reduced strength of the MPW joint is mostly due to the lower hardness of the HAZ of the aluminium, which caused the specimen's failure in HAZ. The mechanical and microstructural characteristics of MPW aluminium and mild steel joints are studied in the published data. Because of changes in the microstructural properties of the MPW joint, the authors noticed different strengths in the MPW aluminium and mild steel joints.

Table 4. Th e values of TSFL of base metals and MPW joint

No.	Material/Weld sample	TSFL (kN)
1	AA 7075 T6	2.6
2	DC01 steel	3.2
3	MPW AA 7075 T6/DC01 Joint	2.4

3.2 Micro hardness

The micro hardness of the MPW joint was measured in cross section. Figure 3 depicts the hardness distribution of the AL 7075T6 /DC01 MPW joint's interface. The MPW joint has higher interface hardness. Because of the favorable microstructural properties, the weld interface hardness is 135 Hv, which is greater than that of AL 7075T6 and DC01 steel. Hardness steadily decreased from the weld interface to additional weld zones (HAZ and base metal).

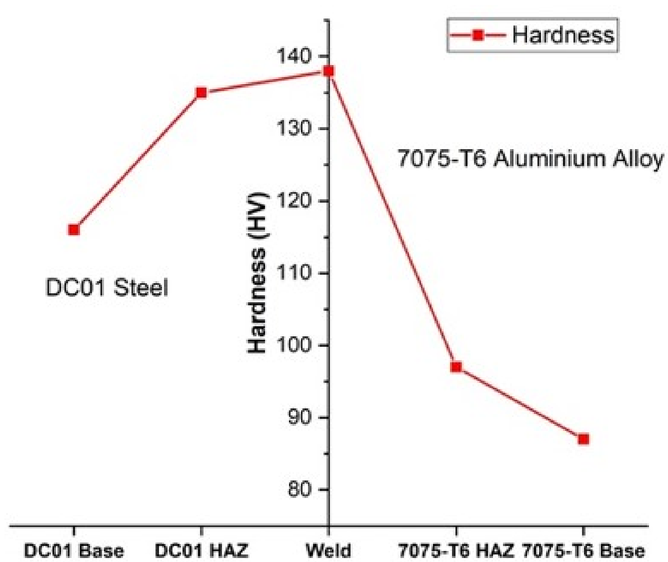

Fig 3. Micro hardness profile

AL 7075T6 aluminium alloy and DC01 steel micro hardness values varied vary from 86 HV to 97 HV, and from 115 HV to 138 HV. This indicates that the amount of deformation of the joint that occurs in the AL 7075T6 is greater than in the DC01 steel. The hardness of the DC01 steel is higher in HAZ. It is mostly due to the increased deformation of the AL 7075T6 aluminium alloy when compared to DC01 steel. The hardness of the MPW interface is 70% higher than that of the base metals (if we consider average hardness of base metals). The greater hardness at the interface is mostly attributable to the mixture structure of the dissimilar MPW joint. The TSFL (described in the preceding section) of the MPW joint is consistent with the hardness measurements. The TSFL of the MPW joint showed lower value than the AL 7075T6 aluminum alloy and DC01 steel due to changes in microstructural characteristics. A similar pattern was reported in a previous study.

3.3 Microstructure

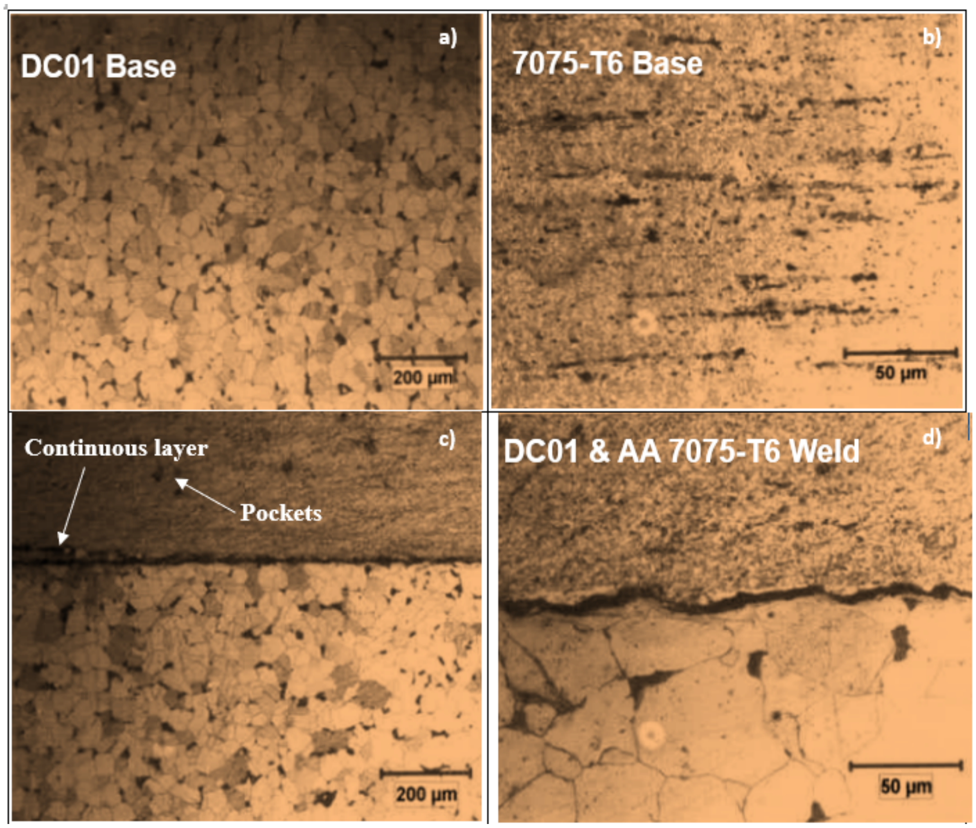

Fig 4. Microstructural characteristics of MPW AL 7075T6 /DC01 steel joint

The MPW joint profile (Micrographs) as shown in Figure 4. The microstructure (see Figure 4**a**) of base metal (DC01 steel) primarily consists of ferrite and pearlite precipitates at the boundaries of ferrite grains. Figure 4**b** shows the α-Al matrix with secondary particles in the base metal of AL 7075T6 aluminum alloy. The deformation was observed in the joint. This deformation affects the interface and vicinity, resulting in a significant temperature increase and strain hardening effect also increases. The temperature rise of the interface softens the metals [13], and in some cases, melts local pockets or a thin continuous layer along the interface (shown in Figure 4 **c**). In some cases, wavy interface morphology appears with short-term periodicity.

At used parameters (due to stand-off-distance), it is directly proportional to the angle of collision and kinetic energy of the flyer (aluminium). The plastically deformed metal, with increasing kinetic energy, increases the shearing effect and decreases the stability of the flyer. At the used parameters (due to overlap length), because the flyer is at the open end and located in the middle of the field shaper or coil (where the magnetic flux density is maximum), this area is subjected to the maximum magnetic pressure, concentrated at the center of the coil, and the collision velocity is higher. It is converted to heat by massive plastic deformation of the flyer metals, as shown in Figure 4**d**.

The element diffusion during the MPW process due to high energy impact is expected. It is mainly due to the sudden transformation from one metal to another one across the interface, that is the primary term for the element diffusion. In addition, the permanent severe plastic deformation for high velocity impact causes the transient process with high temperature and high pressure, which makes for the mutual diffusion of basic elements across the interface. Therefore, more than one factor simultaneously results in the basic elements diffusion during MPW process. The severe shear deformation by the high velocity collision causes high density dislocations and its crossing and irreversible climbing, which produces dense voids and vacancies. A little air in the initial gap is trapped and cannot escape in time during the MPW process, which generates the voids. The transient melt and solidification process because of the severe plastic deformation results in the micro-voids and high impact energy damages the welded interface, as shown in Figure 4**d**.

4 Conclusions

1. The AL 7075T6 /DC01 steel tube joints were successfully welded using MPW. With the working length of 8.5 mm, the metallurgical joints are obtained at a discharge energy of 23 kJ and stand-off-distance of 2 mm.
2. The MPW joint of AL 7075T6 /DC01 showed TSFL of 2.4 kN. The observed TSFL is closer to the base material of AL 7075T6, which is confirmed by the 92.30% joint efficiency of the MPW joint. The TSFL of the MPW joint showed lower value than the AL 7075T6 aluminum alloy and DC01 steel due to changes in microstructural characteristics.
3. The hardness of the MPW interface is 70% greater than that of the base metals. The higher hardness at the interface is mainly due to the mixture structure of the dissimilar MPW joint.
4. The metallurgical joint consists of two interfaces, one transition zone and two basic metals. The mutual diffusion of Fe and Al elements occurs across the interface and in the transition zone. The multi-direction micro-cracks and the micro-apertures present in the transition zone.

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