Effect of Friction Stir Welding Parameters on the Joint Efficiency of the Weldments for High Strength Aluminum Alloys

Introduction:

Friction Stir Welding (FSW), also known as Friction Stir Mixing Welding in some sources, is a new technique for welding materials in the solid state, meaning that the metal will not approaching the melting case while using the welding process. This method of this technique was discovered in 1992 at the Welding Institute (TWI) at the University of Cambridge in England. Initially, this kind of technique was used for welding aluminum alloys, but it has gradually spread in recent years to be used for welding other metals as well. It is considered a good joining technique, especially for aluminum alloys that have poor weldability with fusion welding methods such as shielded metal arc welding (MIG, TIG) and laser welding, as well as for dissimilar materials welding.

The most important problems encountered in fusion welding for alloys such as (7075) and (2024) are attributed to a decrease in tensile strength for these alloys after welding due to The increase in cell growth resulting from the high amount of heat generated in the welding zone. This also leads to a decrease in hardness value and the occurrence of various metallurgical changes in the heat-affected zone (HAZ) during and after the welding process, resulting in defects in weld like cracks such as solidification cracks, as well as very fine cracks in the melted part of the heating zone.

The presence of copper in alloys such as (7XXX, 2XXX) provides a wide range of melting temperatures with a low solidus temperature, making these alloys highly sensitive to fusion welding cracks. Additionally, it reduces malleability and weldability, making them difficult to weld using fusion welding methods. Friction Stir Welding is a suitable welding technique for aluminum alloys that have poor weldability with fusion welding methods, especially for alloys such as (2024-T351) and (7075-T651). This method is used in their joining process to obtain good mechanical properties with minimal deformation and defects in the weld zone.

The choice of aluminum alloys for this study is due to their use in sheet metal forming processes used in aircraft manufacturing, especially in aircraft bodies and wings, as well as in automotive exterior structures, engine covers, and car pillars. Alloys used in aircraft manufacturing include (7XXX, 2XXX), especially (2024-T351) and (7075-T651), which are high-strength alloys used in the manufacture of wings and commercial aircraft structures. Alloy 2024 is used in the manufacture of the lower surface of aircraft wings, while alloy 7075 is used in the manufacture of the upper surface of aircraft wings.

Other applications of Friction Stir Welding include its use in maritime industries for ship plate and marine structure fabrication, as well as in aircraft and space applications, and in welding fuel tanks for spacecraft. It is also used in high-speed train manufacturing, automotive welding for car structures and wheels, and in electrical and electronic industries.

One of the advantages of Friction Stir Welding (FSW) for aluminum alloys compared to traditional welding methods is that it reduces cracking, porosity, and deformation in the welding zone because welding is performed at a lower temperature than the melting point of the metal being welded. Additionally, it does not use the filler metal during the welding process, making it a clean welding method because it does not use inert gases as a protective cover and does not generate smoke or toxic gases during the welding process, making it an environmentally friendly welding technique.

1.1 Principle of Friction Stir Welding:

Friction Stir Welding employs a non-consumable rotating welding tool with a cylindrical shape called the shoulder or backing, which is the major cause of heat generation resulting from the friction and the plastic deformation. The lower end of the tool has a protrusion or pin that gradually penetrates into the contact area of the welded sheets.

The tool works to mix and form plastic deformation of the metal in the welding zone, continuing the pin penetration until the complete touch is happened between the lower surface of the welding tool's backing and the upper surface of the sheets to be welded. After the pin penetration process is complete, the sheets to be welded are moved linearly relative to the tool, completing the joining process along the weld line. This process is illustrated in Figure (1).

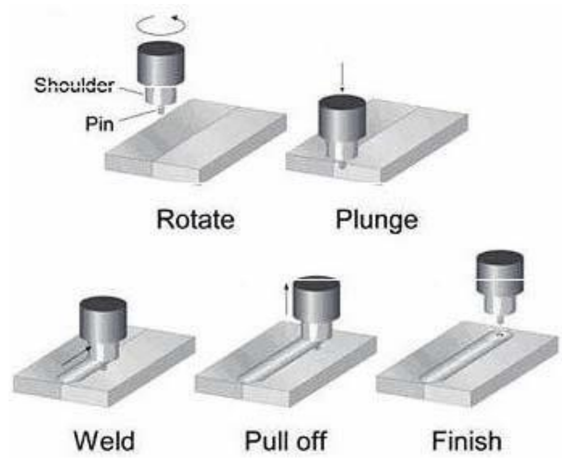


Figure 1: Principle of Friction Stir Welding Process

One of the most important factors in friction stir welding is the variation in the speed of rotation the welding tool and the linear welding r speed. The movement of the rotational welding tool works to mix and blend the metal around the weld nugget, while the linear movement, which is a transitional movement of the metal relative to the welding tool, works to move the mixed metal forward and backward of the weld nugget, completing the welding process. The high rotational movement of the welding tool generates high heat due to friction with the metal, thereby leading to greater mixing and blending of the metal. The speed of rotation of the welding tool also affects the welding temperature, as increasing the rotational speed leads to an increase in the maximum temperature of the welding zone. Similarly, the linear welding speed affects the increasing of the amount of heat entering the welding zone along the weld line, with this heat decreasing as the linear speed increases.

The use of both alloys (2024-T351, 7075-T651) in various fields, as mentioned earlier, emphasizes the importance of studying the impact of friction stir welding factors such as the rotational speed of the welding tool and the welding linear speed on the impact toughness of the welded joints of these alloys. This study aims to investigate the effect of these aforementioned factors, which produce good weld joints, on the impact toughness of the heat-affected zone for plates made of high-strength aluminum alloys such as alloy (2024-T351) and alloy (7075-T651), which have a low susceptibility to fusion welding methods.

2.1 Previous Studies and Research:

There are several studies that have investigated the impact toughness of the heat-affected zone for friction stir welded aluminum alloys. Researchers such as Boromei et al., 2006, studied the effect of friction stir welding on the microstructure and impact toughness of the heat-affected zone for overlapped aluminum alloy specimens (W6A20A), composed of AA6061+20%Al2O3, and for alloy (W7A10A), composed of AA7005+10%Al2O3. They concluded that the of the welded joints impact energy increased with the comparison of the base metal.

Similarly, researchers like Kemal Kulekci et al., 2010, investigated the mechanical properties of joints made of aluminum alloy (EN AW - 6061-T6) connected by gas metal arc welding (MIG) and by friction stir welding. It was concluded that the impact energy of the joints welded by friction stir welding had an impact energy of 30 Joules, which was superior to the impact energy of joints welded by gas metal arc welding (MIG), which was 22 Joules, and superior to the impact energy of the (27 Joules).

As for the researcher R. Jalal, 2010 (Shawnim), he conducted a comprehensive study to test the impact toughness of welded joints by friction stir welding for two aluminum alloy specimens (7020, 7075) under two different conditions (T6, T9), each tested individually. Three different welding tool rotational speeds of the and five different welding linear speeds were used. The results of the study indicated that the increasing in the impact toughness of the welded samples for both alloy specimens and under both conditions (T6, T9) comparing with the original metal. The linear and the rotational speeds had an impact on the impact toughness of the joints to be welded of alloy 7020, while their effect on the impact resistance of the alloy 7075 to be welded was minimal, and there is a high consistency of results in all cases.

Practical Part:

2.1 Fusion Welding and the Friction Stir Welding:

Two types of aluminum alloys were used in this study, both of which have poor weldability using fusion welding methods: alloys 2024-T351 and 7075-T651, which were prepared outside the diameter, and both alloys were heat-treated. For alloy 2024-T351, the heat treatment included solution treatment at a temperature of 495±5°C, followed by a sudden immersion in water to room temperature, then cold working by rolling or drawing, and finally natural aging at room temperature for 48 hours. As for alloy 7075-T651, The aforementioned thermal treatment takes place by treating the solution at temperature of

460±10°C, followed by water quenching to room temperature, then artificial aging at a temperature of 135±5°C for 12 hours.

The symbol (T_51) represents the stress relief process by stretching by a percentage of 13%. Component analysis for the alloys was conducted, and Table (1) shows the chemical analysis of the component ratios compared to the standard ratio values adopted by the European Aluminum Association (EAA).

Table 1: Chemical analysis of the base metal (wt.%).

Alloy	Element	Zn	Mg	Cu	Fe	Mn	Cr	Si	Ti	Al	Another
2024-T351	According to (EAA)	≤0.25	1.2-1.8	3.8-4.9	≤0.5	0.3-0.9	≤0.1	≤0.5	≤1.5	Rem	≤01.5
	Measured	0.0269	1.64	4.41	0.28	0.462	0.006	0.102	0.067	Rem	0.0229
7075-T651	According to (EAA)	5.1-6.1	2.1-2.9	1.2-2.0	≤ 0.5	≤ 0.3	0.18-0.28	≤ 0.4	≤ 0.2	Rem	≤ 0.15
	Measured	6.22	2.3	1.56	0.25	0.024	0.176	0.04	0.0604	Rem	0.0233

Fusion welding was performed for both alloys using TIG (Tungsten Inert Gas) welding technique with argon gas as a shielding gas. After the welding process, Where cracks appeared in the welding area, as illustrated in Figure (2).

To perform the friction stir welding process, a conventional milling machine of the GATE type was used, as shown in Figure (3). Different rotational speeds for the welding tool and three different linear speeds for welding were used. The welding process was successfully conducted for alloys that were difficult to weld using fusion welding methods.

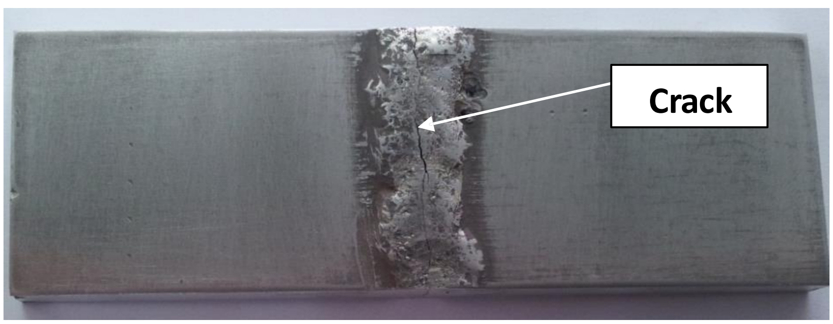


Figure (2): TIG (Tungsten Inert Gas) welding for alloy 7075-T651.

Figure (3): GATE milling machine used in friction stir welding.

For the purpose of studying the effect of welding factors on impact toughness, two plates of each aluminum alloy - 2024 (T351) and 7075-T651 - were prepared with dimensions of (130556.1 mm), arranged in a butt joint configuration and securely fixed on sanding blocks manufactured for welding, ensuring that the weld line is perpendicular to the rolling direction. This setup is illustrated in Figures 4 and 5.

Three linear speeds with two rotational speeds where used for the welding tools, as shown in Table 2.

Figure 4: Clamping of the plates and the friction stir welding process

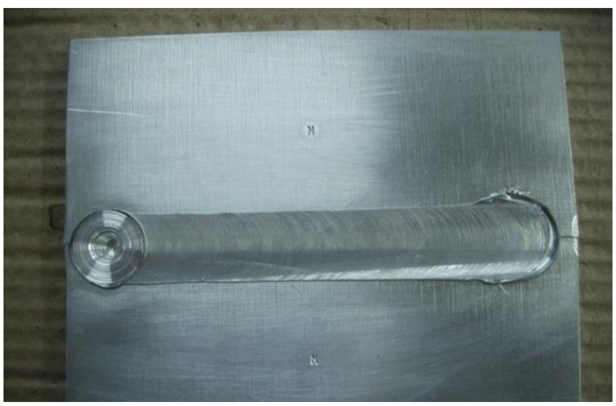


Figure 5: Friction stir welding of alloy 2024-T351

Table 2: Used rotational and linear speeds

alloys to be welded	rotational speeds	Linear speed (mm/min)
2024-T351	900,1120	28,40,56
7075-T651		

The welding tool was manufactured from High-Speed Steel (HSS) with a hardness range of approximately HRC (50-52), featuring a shoulder with a diameter of 20mm and a conical toothed seam protrusion with left-hand teeth and a pitch of 1.25mm, with a diameter of 8mm at the base and 4.7mm at the top, and a length of 5.9mm, as shown in Figure 6. A 3º inclination angle was used for the welding tool relative to the perpendicular plan to achieve the quality of welding, and the direction of rotation of the tool was clockwise direction. It must be said that the optimal value for the tool's tilt angle is approximately 2º-4º. In all welding operations, the vertical pressure applied to the welding area is fixed by controlled depth of the penetration of the welding tool's shoulder into the joint area.

(A) (B)

Figure 6: Friction Stir Welding with Toothed Conical Protrusion: (A) Photographic Image, (B) Dimensions in Millimeters.

2.2 Impact Testing:

To assess the impact resistance of the weld zone, standardized test specimens measuring 10555 mm were prepared, containing a V-shaped notch at a 45º angle with a depth of 2 mm, positioned at the center of the weld line according to ASTM E23 specifications (V- shaped samples with sub size), as illustrated in Figure 7.

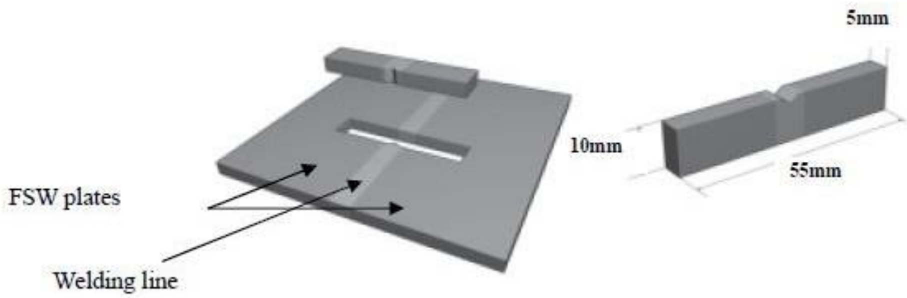


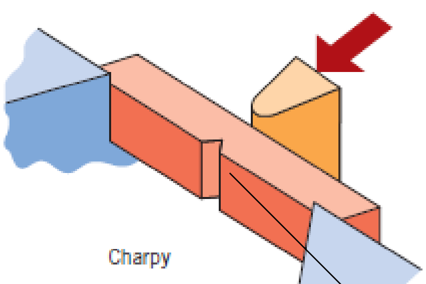
Figure 7: Standard Impact Test Sample

Figure 8: Impact Resistance Test Sample

The test samples were cut perpendicular to the weld joints and parallel to the direction of rolling of the base metal, as shown in Figure 8.

The impact testing was conducted at room temperature using an impact resistance testing device.

Figure 9: (a) Impact resistance test apparatus, sample



Impact resistance test sample.

Figure 9: (b) Fixing the impact resistance test.

Results and Discussion:

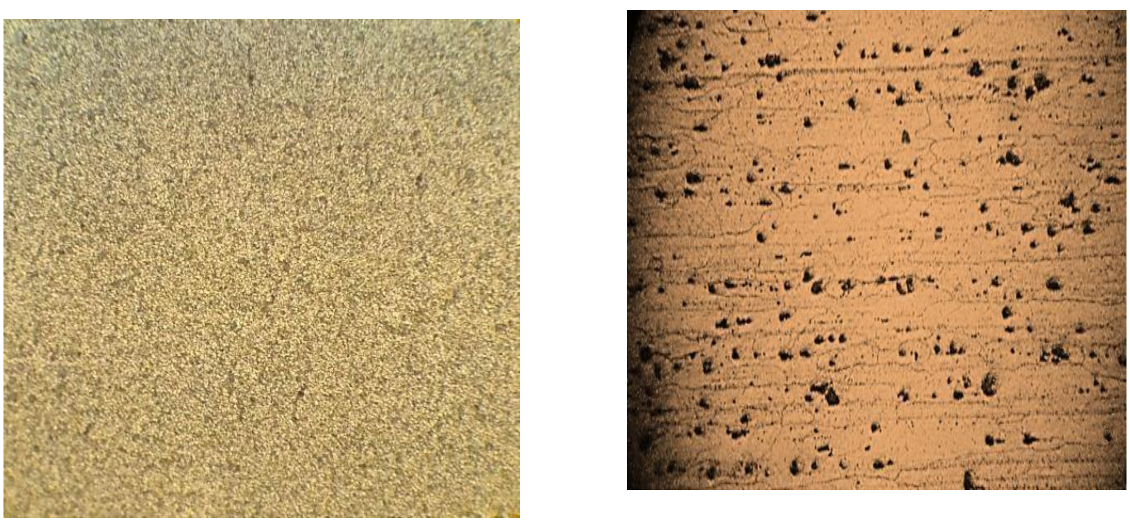
After conducting the impact resistance test for the base metal and the weldments of both alloys, 7075-T651 and 2024 -T351, at the laboratory temperature, results were obtained by averaging the test values for three samples in each case, as shown in Table 3. It is observed from the test results that the base metal of the 2024-T351 alloy has a higher impact energy of 7.2 J compared to the impact energy of the 7075-T651 alloy, which was 4.5 J. Additionally, it is also noted that in most cases, the impact energy of the friction stir welded joints is higher than that of the base metal for both alloys, indicating an improvement in impact resistance.

Table 3: Impact Resistance Test Results

Alloy	**Sample**	**rotational Tool speed (rpm)**	**Traveling speed (mm/min)**	**impact energy (joule)**
2024-T351	Base metal	--------------	--------------	**7.2**
	Weldments	900	28	9.3
			40	9.7
			56	10.2
		1120	28	7.0
			40	7.2

			56	8.0
7075-T651	Base metal	--------------	--------------	4.5
	Weldments	900	28	7.0
			40	7.2
			56	7.8
		1120	28	7.0
			40	7.5
			56	7.7

In the center of the weld zone, the grains are smooth, uniform, and smaller than the base metal grains. This is due to a recrystallization process of the minute precipitates in this area the plastic deformation occurred and caused by the high motion of rotation of the welding tool and the heat generated during the friction caused recrystallization of the pin tool stretching the surrounding metal [1,4]. This is illustrated in the microstructure images of alloy (2024-T351) at a speed rotation of 1120 rpm and a linear speed of 28 mm/min, as shown in Figure (10).



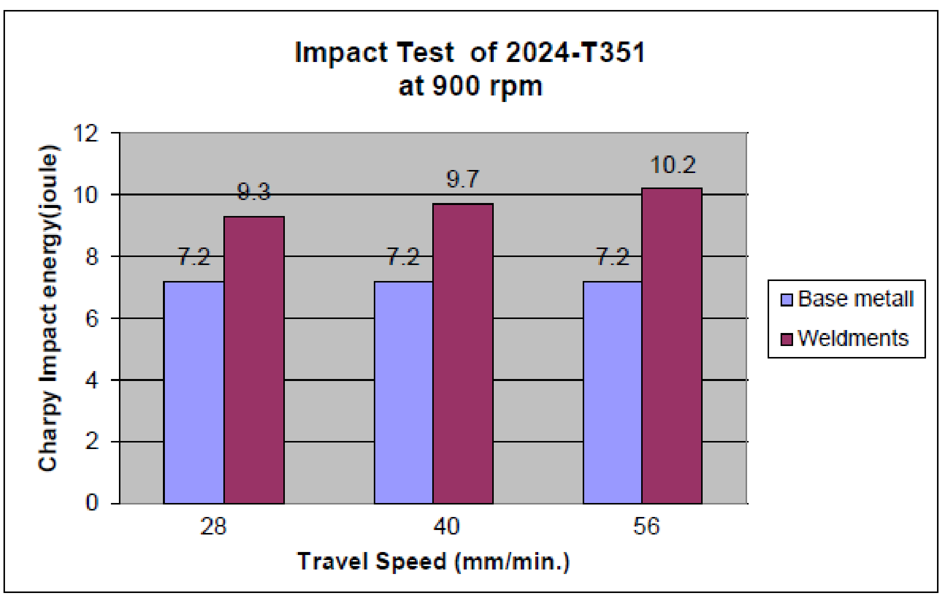
(X160) **(X160)**

(a) (b)

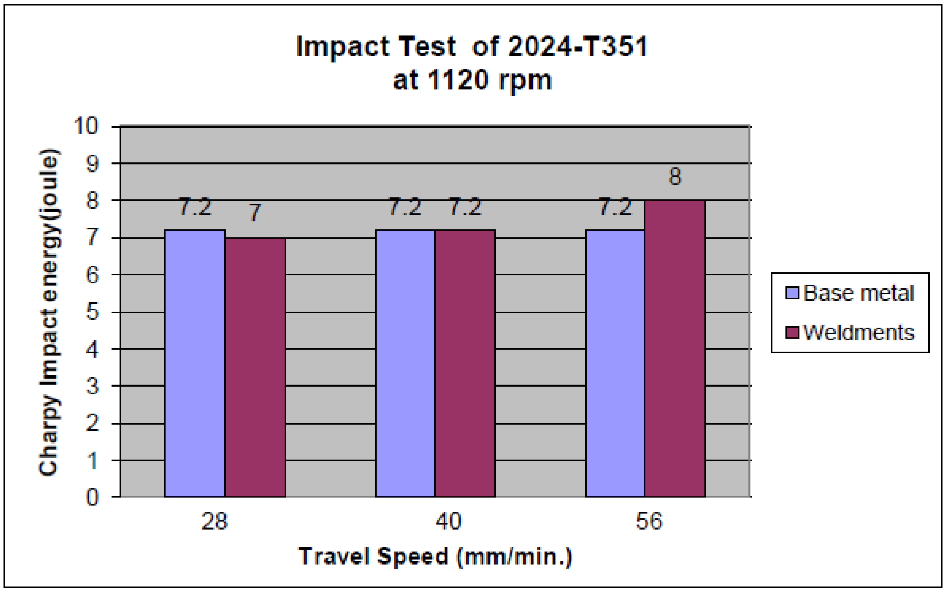
Figure (10): Microstructure of Alloy 2024-T351: (a) Before the welding process, (b) After the welding process.

These results align with those reported in the study [18], indicating that improvement in both impact toughness and elongation can be achieved by reducing the size of the precipitates through controlling the rotational and linear speed in the friction stir welding process of aluminum alloys. Impact resistance testing of the welds of alloy (2024-T351) shows that the highest obtained value is 10.2 joules at a speed of rotation 900 rpm and a linear speed of 56 mm/min. This value is higher than the impact resistance of the base metal, indicating an improvement in weld impact resistance by approximately 42%. Increasing the linear speed at that rotational speed reduces the amount of heat per unit time, thereby increasing resistance and improving impact toughness. Additionally, increasing of the rotational speed up to 1120 rpm generally decreases the impact energy of the welds at the same linear speed, with no tangible improvement in weld impact energy due to the dominant effect of the speed rotation, where most of the frictional heat is generated by the welding tool rotational speed. This causes the increase in the heat input to the weld zone, causing softening of the metal under the welding tool. It is known that increasing the welding tool rotational speed of and decreasing the welding linear speed result in increased friction between the the metal to be welded and welding tool pin, thereby increasing the heat input to the weld zone, leading to the growth of weld zone cells and a decrease in impact energy.

As for the welds of alloy (7075-T651), the examination results also show the improvement in the resistance of impact compared to the base metal, especially at a rotational speed of 1125 rpm and a speed of welding 50 mm/min. However, changes in linear and rotational speed have little effect for the resistance of impact of the welds, as the results were relatively consistent in most cases, as shown in Figure (12).



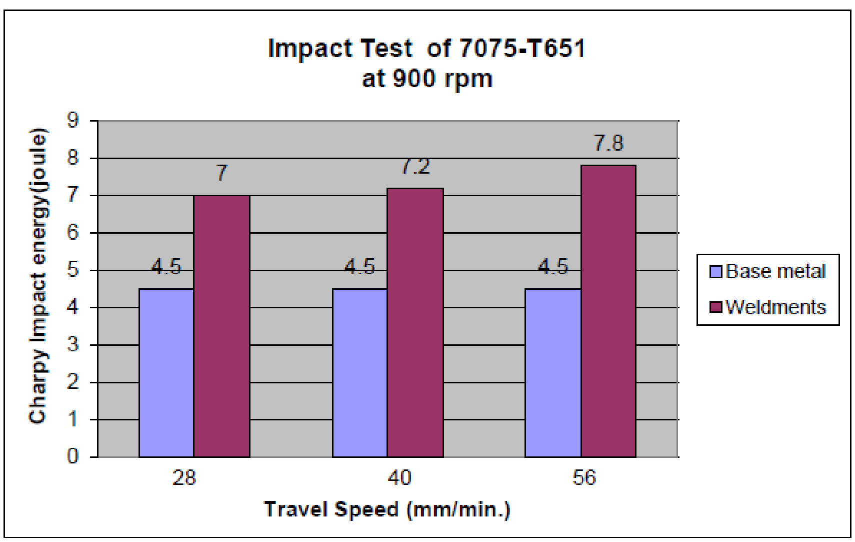
(a) . At rotational speed of 900 rpm.



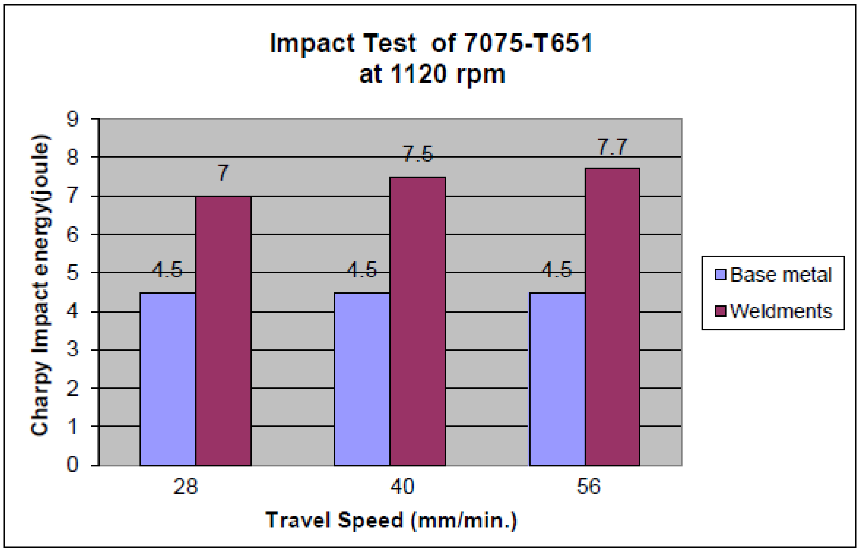
(b) . At rotational speed of 1120 rpm

Figure (11): Impact resistance for alloy (2024-T351):

a. At rotational speed of 900 rpm. b. At rotational speed of 1120 rpm



(a) . At rotational speed of 900 rpm.



(b) . At rotational speed of 1120 rpm

Figure (12): Impact resistance for alloy (7075-T651):

(a) . At rotational speed of 900 rpm. (b) . At rotational speed of 1120 rpm

4. Conclusions:

According to this research study , the following results were appeared :

1. The feasibility of welding aluminum alloys using friction stir welding method (which is difficult to weld using conventional methods, especially high-strength aluminum alloys such as alloys (2024-T351, 7075-T651) which have poor weldability with fusion welding).

2. Most of the impact resistance test results indicate that the impact energy for the welds and for both alloys has increased, indicating an improvement in impact resistance compared to the base metal.

3. For alloy (2024-T351), the research study results could show that the impact energy for the welded joints decreases with increasing rotational speed of the welding tool from 900 to 1200 rpm, and there is no tangible improvement in impact energy with increasing linear speed at the speed of rotational 1120 rpm.

4. The welding tool rotational speed of the and the linear speed of welding have a very limited effect on the impact energy of welded joints of alloy 7075-T651.

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