

Influence of Interlayer Thickness (Zn) on the Properties of Al 7020 FSW Joints

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The use of lightweight materials in the production of cryogenic tanks, spacecraft body etc. are becoming the need to develop dissimilar metal FSW joints. Friction stir welding (FSW) is a novel and inspired light metal joining process since it is not involved with the melting of the parent metal. In this work, two Aluminium 7020 plates were welded with Zn as an interlayer, using friction stir welding method. Different joints were made by varying the thickness of interlayer (Zn) and thereafter the characterization is done against mechanical properties and microstructure of weld nugget. The test result shows that the specimen joint with 10 μ Zn interlayer has higher mechanical properties than samples made with 5 μ , 10 μ , 20 μ , 40 μ and 100 μ Zn interlayer. To analyze the cause, further optical studies (Image analyzer and SEM analysis) were carried out and found the interlayer dispersion plays a vital role in weld strength. As a conclusion addition of Zinc interlayer with preferable thickness (10 μ) in Al7020 FSW joints improve tensile strength and hardness than the FSW joints made with higher and lower interlayer thickness.

Keywords: FSW, Al7020 Joining, Zn interlayer, Microstructure, mechanical Properties, Acoustic Emission

1. Introduction

FSW is a metal joining process produces no fumes, uses no filler material and thereby it makes this process eco-friendly. Here joining takes place below the melting point of parent material this characteristic greatly reduces distortion shrinkage, porosity, eliminates solidification defects. At present, more studies are going on friction stir welding (FSW)¹⁻³ joints in Al/Mg alloys. The major advantages of FSW are a less material loss, high rate of production and can prefer for welding of dissimilar metals or alloys^{1,4-7}. In this process, a rotating tool having larger shoulder attached with a pin is used to make joint. This tool during its path produces frictional heating with low temperature than the melting point and the plastic deformation caused by the stirring of parent metal around the pin, produces the joint. Here, in this study, the tool is made by high-speed steel (HSS) with triangular pin profile as in Figure 1.

Even though FSW produces high strength joints; with poor flexibility. It may cause cleavages and voids in the transition layer and thereby yields deformation in the same zone. To overcome this, it becomes necessary to improve the strength by reducing the transition layer thickness. This can be achieved by providing an interlayer which is softer than the parent metal. This will melt first and ensures the metal dispersion even and reduces the formation of cracks. So this study becomes more important to overcome the defects in FSW joints to make this process more reliable and to improve the application in the field of light metal joining.

In this paper, friction stir welding is carried out between Al 7020 plates with Zinc (Zn) as the interlayer. This study concentrates on the joints made with Al7020 plate's different

interlayer thickness as 5 μ , 10 μ , 20 μ , 40 μ and 100 μ . Finally, the cooling was done by natural free convection. The upper limit for Zn in commercial alloys is 4% (Taylor and Berg L K^{8,9} 1963). The cooling rate plays a vital role on stress corrosion and cracking resistance. It was identified that rapid quenching of Al-Zn-Mg alloys causing failures. While considering Al-4% Zn-2% Mg alloy, the stress corrosion cracking resistance was observed maximum in air cooled samples. Tool rotation and feed rate were maintained as constant throughout the study. After joining mechanical properties and microstructures were studied. This work provides an experience to improve Al7020 FSW joint strength by adding Zn interlayer and in connection with interlayer layer dispersion.

2. Material and Methods

Al 7020 samples with a size of 300x100x3.3mm were welded. Tables 1 & 2 illustrate the chemical composition and properties of the base metal used. For processing tool rotation, speed and feed rate were kept as 1400 rpm and 32 mm/min and the FSW tool with 18mm diameter shoulder and 3.2mm probe height with a triangular profile including a tilt angle of 2.5° were used throughout the study. Experiments were carried out with different thickness of 5 μ , 10 μ , 20 μ , 40 μ and 100 μ Zn interlayer and the process parameters were tabulated in table 3. Zinc powder used in the interlayer is expected to act as bonding and filler material to avoid the defects identified by R.S. Coelho¹⁰. When the Al7020 alloy sheet having 5-6 weight % zinc is heated to a temperature just above the solidus line, only one phase is thermodynamically stable. Other solid phases (Zn) dissolve along with interlayer. And this molten phase easily reaches

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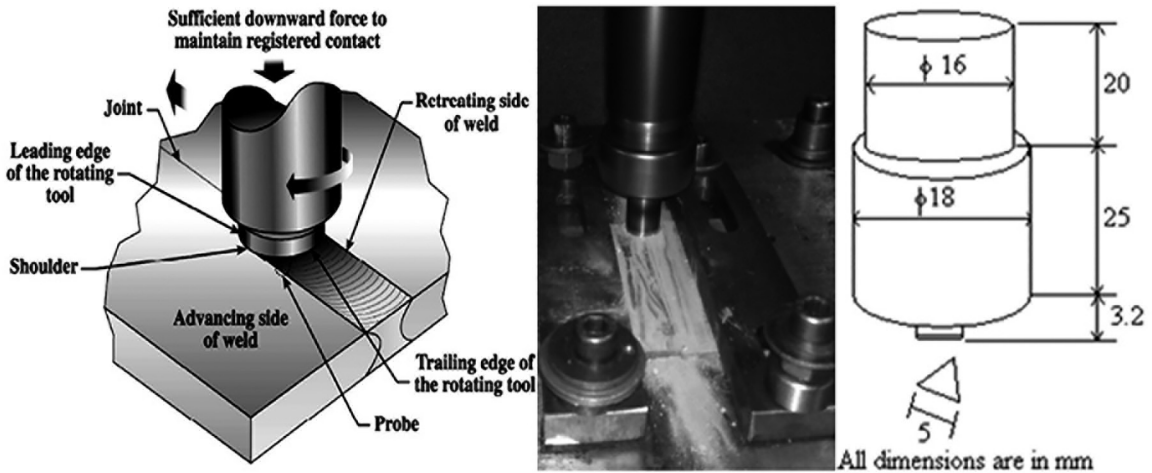


Figure 1: Experimental Setup and Tool profile.

Table 1: Chemical Composition of Aluminium Alloy 7020.

Weight%	Al	Si	Fe	Cu	Mn	Cr
Alloy	Bal	0.35	0.4	0.2	0.050 – 0.50	0.10 – 0.35
7020	Mg	Zn	Zr	Zr + Ti	Other Each	Others Total
	1.0 – 1.4	4.0 – 5.0	0.080 – 0.20	0.80 – 0.25	0.05 max	0.15 max

Table 2: Mechanical Properties of Aluminium 7020.

Material	Temp.	Tensile Strength (Mpa)	Yield Strength (Mpa)	Elongation %
Alloy 7020 Plate	T651	330-350	260-280	10

Table 3: FSW process parameters used in this study.

Material	Tool Speed (rpm)	Tool feed rate (mm/min)	Axial load (KN)	Zn interlayer Thickness (μ)
Al 7020	1400	32	32	05
Al 7020	1400	32	32	10
Al 7020	1400	32	32	20
Al 7020	1400	32	32	40
Al 7020	1400	32	32	100

and fills the gaps or voids present in the metal dispersion zone, hence, it improves the strength (solid-solution heat treatment) and produces the flexible weld.

Based on the specific applications of Al7020 like Aircraft structures, heavy trucks, Booster rockets, fuel tanks of space shuttles, power plant heat exchangers etc. it is important to give priority for impact energy. So in this research initially, Impact energy of the welded specimen was tested on Charpy impact tester, of pendulum type, with the maximum energy level of 300 joules. To determine the exact tensile strength; the weld joint is tested using universal tensile test machine with Acoustic Emission setup. The maximum load range of the test machine is 100kN with crosshead stroke of 1000mm. The cross head displacement measurement is 0.1mm with the speed of 0.5mm/min to 250mm/min. Without any surface modification over samples, the tensile test was done. The tensile sample was prepared based on (ASTM E8M-04) standards shown in Figure 2. The hardness of the welded

specimen is investigated by Vickers hardness direct mass loading testing machine. The load limit is 0.1 to 10 Kg of Macro load and 50 to 140 g of Micro load. The indentation time taken by the test machine is 10 sec. with a field illumination of 400 x magnification. For this study, the load applied throughout the test is 0.5 Kg^{9,11,12}. The microstructure of the joint was examined using image analyzer system and interlayer dispersion in different regions (Nugget Zone (NZ), Thermomechanically affected Zone (TMAZ) and Heat affected zone (HAZ)) were studied by SEM analysis and interesting results were found on the joints.

3. Experimental results and discussion

The grain structure and bond nature for Al7020 Friction stir welded joint was analyzed by means of the JSM-6390 scanning electron microscope (SEM). Fine grains than

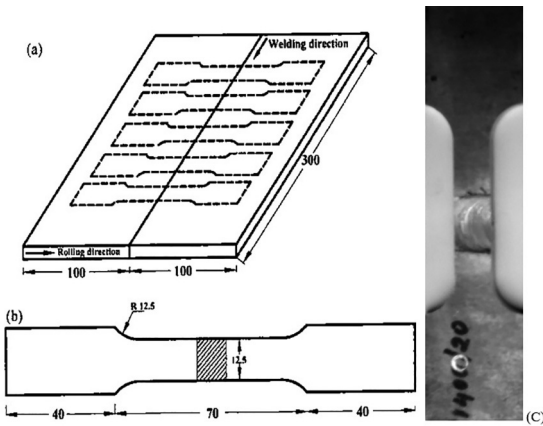


Figure 2: (a) Scheme of extraction¹ and (b) dimensions of tensile specimen (c) Sample specimen.

base metal was present in TMAZ and appeared in dark gray. The Zinc particles shows huge granular and metallic shine in the advancing and retreating sides of the specimen (Figure 4.(a)&(c), 5.(a)&(c), 6.(a)&(c)). It is observed that the flow of interlayer from the retreating side never enters into advancing side. But material from the advancing zone is somehow displaced and that causes a heterogeneous zone and causes a flow variation in the in advancing and retreating sides. The same also evidenced in the microhardness test. I.e., lower hardness in the retreating side.

While studying the weld nugget (stir zone), It is observed that when the interlayer thickness increases the grain size also increased as Shown in (Figure 4. (b), 5. (b)&6. (b)). the grain size was observed by using plain metric methods (a line was plotted with a known length and by keeping this as a reference; the average grain size was measured) and listed in table 4. During the welding (FSW), it is assumed that the heat is generated mainly between the shoulder of tool and parent metal surface. As a result, of this thermal softening will occurs in the edges of the shoulder. So whenever increasing the interlayer thickness the particles having high conductivity and low melting point (interlayer/joining material) will get thermal softening by dissipating the heat faster than the base material. This may lead high grain size as well as high thermal stress formation. From the measured grain sizes in the weld nugget the small grain size in weld zone is spotted in the samples welded with 5 μ Zn interlayer. Also, the metal dispersion is comparatively lesser than the sample made with 10 μ Zn interlayer. This yield softness and poor tensile strength. Maximum strength is observed in the welded joint which is prepared with 10 μ Zn interlayer; here, in this case, the advancing and retreating sides the grains looks huge in size as well as shining. In order to analyze the interlayer flow, a microstructural analysis was conducted. The image taken with different samples shows a drastic difference in metal (interlayer) dispersion and the same is shown Figure 7.

Figure 3 shows the micrographs taken from the cross-sectional of FSW joints made without interlayer. Based on the microstructural image. There are four zones were observed, namely the Base metal BM, heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) were

identified from both the sides of nugget zone (NZ). Usually, the interlayer is mixed with NZ and there is atomic matching, or coherency, between the precipitate and the matrix.

The microstructure of the weld specimen is obtained by Nikon Image analyzing system from the mid-surface of the cross-section (ie. 1.6mm depth from the top). As suggested by P. Gurusamy et al.¹¹ the microstructure analysis is done in each specimen with various zinc interlayers (5 μ , 10 μ , 20 μ and 100 μ). In the micro analysis the fusion line is clear with nugget zone (NZ), heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and Base metal BM^{12,13}. The shining particles closer to the weld is zinc layer which grew towards the weld. Also, it shows a different structure in stir zone from parent metal since the temperature in weld zone is closer to its recrystallization temperature. Figure 7 shows a typical image of metal dispersion in the joints of samples made with 5 μ , 10 μ , 20 μ and 100 μ zinc interlayer.

From the micro image of joint with 5 μ Zn interlayer, the Zn particle dispersion was not found to be good. It leads uneven as well as irregular weldment and it causes improper stress distribution and poor yield strength. This is the reason for lesser yield strength (525 Mpa) for the specimen made with 5 μ than 10 μ Zn interlayer joint. If proper metal dispersion is assured then the strength also improved further. This is possible if the rpm of the tool is further modified or if the thickness is further improved. This can be achieved by doing further studies with various interlayer thicknesses.

In the micro image of joint with 10 μ Zn interlayer; there could see almost proper metal dispersion takes place in the nugget zone through TMAZ on both sides of nugget zone (advancing and retreating). Since it produces better matrix and with atomic matching. This might be the reason for good microstructure and better strength. To ensure this, it is required to have an analysis on harness across all the zones of the weldment.

The microimages of samples made with higher thickness show high deposition of the interlayer (Zn) over TMAZ. This will reduce the strength especially the sample made with 100 μ interlayer makes a bulk deposition of (Zn) over TMAZ as explained by Tailer⁸ and Caroline Jonckheere¹⁴. This leads poor strength due to lack of fusion between the parent metal and pores formation. All Because of these reasons the strength is gradually getting reduced while improving the interlayer thickness from 10 μ .

If the welding parameters used are appreciated, it is not possible to get defects when making joints by friction stir welding in light metal alloys. But it becomes mandatory to go for further study on fracture morphology which leads corrosion or mechanical failure¹⁵ to ensure the strength and life.

The joint made with 5 μ Zinc interlayer we could see improper or uneven metal dispersion in TMAZ Figure 7.(a) & (c). This leads the joint affected by fractures like cleavage Figure 8 (a) and void Figure 8 (c) failure. This may lead thermal stress accumulation and causes a reduction in strength. While in the case of the sample made with 10 μ (Zn) interlayer all the above said defects were removed and only identified fracture morphology is present in the deformed transition zone. This is caused by the compressive fatigue cycles occurred while welding. The cyclic fatigue failure can be avoided by slightly improving the weld speed,

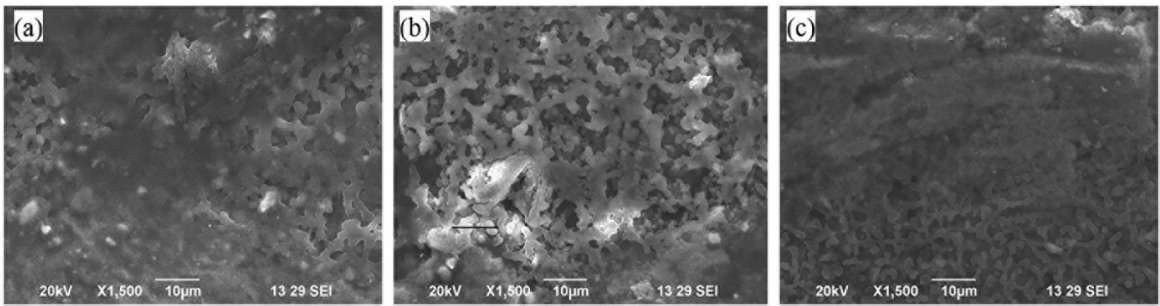


Figure 3: SEM images of (a) advancing side, (b) stir zone and (c) retreating side Al7020 joint with no interlayer.

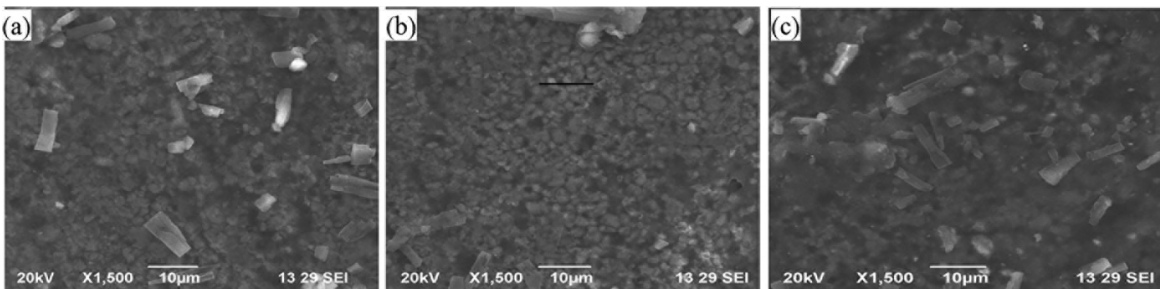


Figure 4: SEM images of (a) advancing side, (b) stir zone and (c) retreating side Al7020 joint with 5µ zinc interlayer.

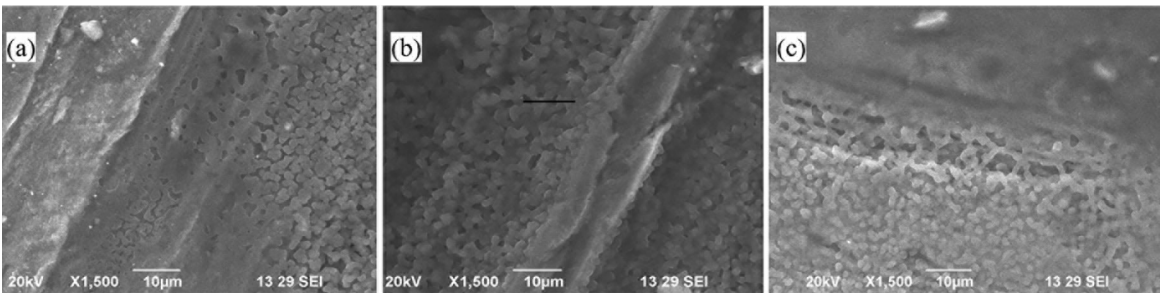


Figure 5: SEM images of (a) advancing side, (b) stir zone and (c) retreating side Al7020 joint with 10µ zinc interlayer.

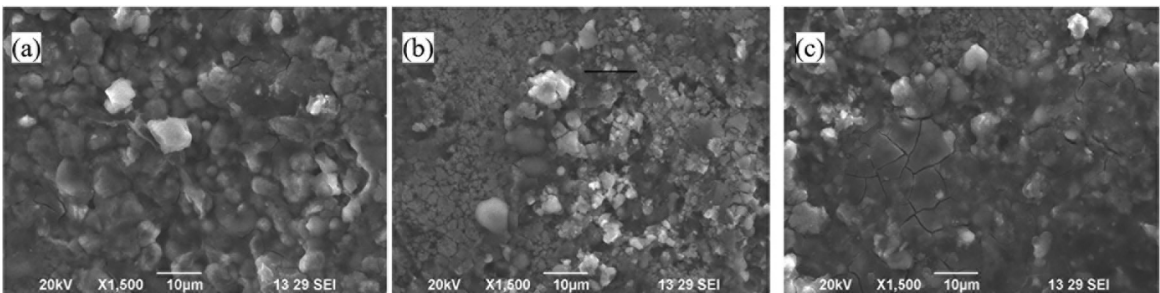


Figure 6: SEM images of (a) advancing side, (b) stir zone and (c) retreating side Al7020 joint with 20µ zinc interlayer.

Table 4: Impact energy results.

Zinc interlayer	Energy(joules)
5µ	1.8
10µ	2
20µ	1.5
40µ	1
100µ	1

hence, it helps to avoid overdrive of the shoulder in the same spot again. In this sample specimen, all the defects were considerably reduced than all other samples made with high or low interlayer thickness.

In the case of the sample made with 20 µ Zn interlayer, all the abovesaid defects are present and especially level of Intergranular fracture is high; this is expected to be the cause of over deposition of Zn than parent material Figure 8. The same is observed in the microstructure also. This is caused due to the

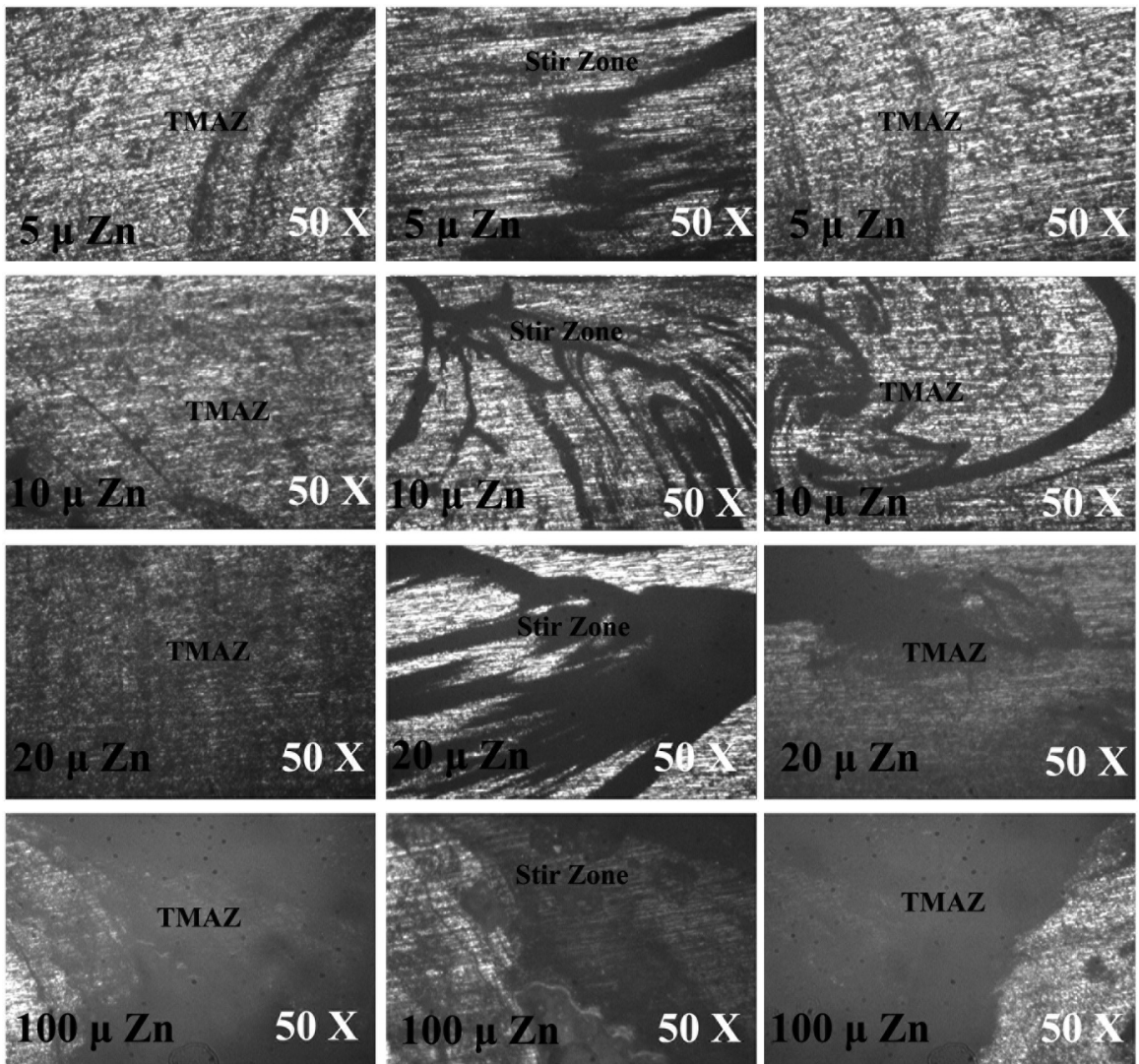


Figure 7: Micro view of joints with the various Zn interlayer.

variation in thermal conductivity and a melting point between interlayer (Zn) and parent metal (Al); so while solidification Zn dissipates more energy and shrink first and yields Intergranular fracture. This shows if the interlayer thickness is further increased that will lead Zn accumulation in the weld nugget and thereby leads poor metal distribution and strength.

From the Microstructure, there is a clear zone between TMAZ and HAZ knowingly mechanical bond zone. In this zone, we could see the interface entirely disappears. It makes more flexible bonding with less stress accumulation than self-metallic diffusion. So always the Joint strength of welding with interlayer is slightly varied from self-diffused joints. While increasing the interlayer thickness, the interface thickness also got improved. This phenomenon leads a reduction in strength and improves the residual stress level. The effect of sintering also plays a role on it and is explained by D. Pereira and other researchers^{12,13,16}.

As a part of failure analysis, impact strength test also carried out. For the testing, a Charpy impact test machine of pendulum type with maximum range is of 300 joules was used

and the results were tabulated in table 5. The result shows that the specimen with 10 μ of zinc interlayer has a maximum impact energy (2 joules). The energy decreases gradually with increase in the zinc interlayer. Hence, it is proved that the improvement in interlayer thickness leads poor impact energy. On comparing with the samples made with 5 μ , 10 μ , 20 μ and 100 μ Zinc interlayer thickness the specimen with 10 μ Zinc interlayer produces high impact strength.

The most required test on mechanical properties is a tensile test, in which the sample shown in Figure 2, is fixed and subjected to an axial load. This leads an axial deflection δ and over a period the test specimen breaks or often fracturing suddenly. The same test is conducted here with a sample made by zinc interlayer of 5 μ , 10 μ , 20 μ , and 100 μ . The results are tabulated in table 6 below. From the results, it is clear that the specimen with 10 μ of zinc interlayer has high tensile strength with a peak load of 5.875kN, the ultimate tensile stress of 122 Mpa, the yield stress of 100 Mpa with 4% elongation. When the interlayer thickness increased from 5 μ to 10 μ the tensile strength is getting improved;

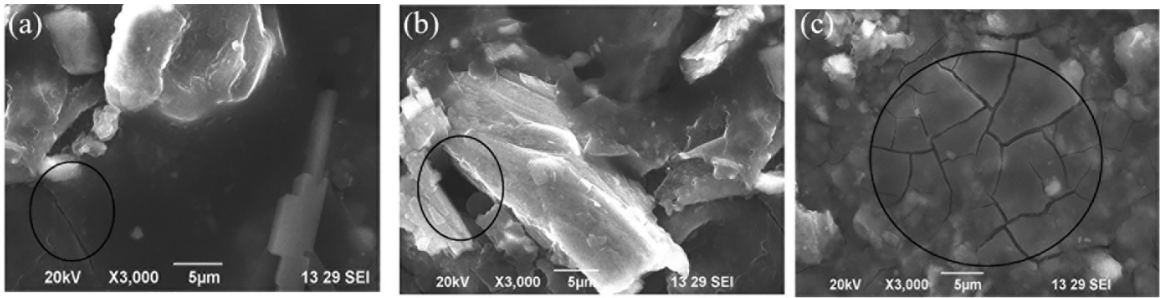


Figure 8: Fracture morphology of Al 7020 FSW joint with Zn interlayer (SEM). (a) Cleavage fracture (b) void growth induced by cavitations/debonding. (c) Crack due to metal deposition.

Table 5: Tensile test results of Al7020 alloy joints with Zn interlayer.

Inter-Layer Thickness	5µ	10µ	20µ	100µ
Peak Load F max (kN)	3.235	5.875	1.64	2.265
UTS(Mpa)	67	122	27	38
Yield Stress(Mpa)	52.5	92.5	26	39
Disp. at F max (mm)	1	1.5	2	2.88
Max. Disp. (mm)	1.5	2	2.63	3.22
Elongation (%)	3	4	5.26	6.44

Table 6: Microhardness results of Al7020 alloy joints with different Zn interlayer thickness.

Interlayer Thickness	HV0.5	Zone
5µ	100	TMAZ.
	110	NZ.
	108	TMAZ.
	130	TMAZ.
10µ	144	NZ.
	141	TMAZ.
	90	TMAZ.
20µ	120	NZ.
	120	TMAZ.

** Parent metal hardness value is HV0.5 =132; A.Z.- Advancing Side, R.S.- Retreating Side, S.Z.-Stir Zone.

thereafter it goes on reduces when the interlayer thickness increases. For better understanding, the values were plotted. From the results, it is very clear that 10µ thickness of Zinc interlayer produces high tensile strength. Also, it shows better improvement while adding Zn interlayer than L. Cecchini's⁶ experimental values.

Vickers Hardness is a very popular test, for measuring surface. The Standard testing methods and theory for Vickers Hardness test are briefed in ASTM E 92 - Metallic Materials. The middle of Nugget (NZ) zone shows an increase in hardness of up to 30% in the joint made with the 10µ interlayer. The lower hardness is obtained from the sample made with 5µ Zn interlayer. It happened due to the poor filler (interlayer) content availability. The region from TMAZ to the interface shows a hardness decrease than the NZ. This decrease in hardness causes more internal stresses and produces large dendritic equiaxed crystals. While Comparing TMAZ zones in Retreating and

advancing sides; it shows high Hardness in the Retreating side due to the better dispersion of metal from advancing side. The results were tabulated in table 7. The hardness test result shows that the test sample done with 10µ zinc interlayer has a maximum hardness as compared to the other specimens. Here the best result lies i.e. 144HV in Nugget Zone (NZ), 130HV and 141HV in Thermo Mechanically Affected Zone (TMAZ) of advancing side respectively.

Table 7: Grain Size in Stir Zone (SZ) measured by the planimetric method.

Specimen	5µ	10µ	20µ	100µ
Grain Size µm (approx)	2	1.67	2.5	--

4. Conclusions

The result of this work shows that joint made with 10-micron Zinc interlayer has higher tensile strength, hardness as compared to another specimen with 5µ, 20µ, 40µ and 100µ of Zinc interlayer due to uniform particles dispersion. An increase or reduction in interlayer thickness yields reduction in strength. Also, the corresponding microstructures displayed fine grains with low fracture morphology.

Therefore, for better results in Al7020 FSW joints it is proposed to make with 10micron Zn interlayer. This will improve joint strength as well as arrest crack propagation. To go further, the research can be extended with pre and post heat treatments to avoid deformed transition zone.

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