Experimental Investigation of the Addition of Scandium on the Microstructural and Mechanical Properties of Friction Stir Welded AA5083 Aluminium Alloy

K. Shine[*1] and K. Subbaiah[2]
[1] *Department of Mechanical Engineering, MES College of Engineering, Kuttippuram, Kerala, India*
[2] *Department of Mechanical Engineering, Sri Sivasubramaniya Nadar College of Engineering, Kalavakkam, Chennai, Tamil Nadu, India*
E-mail: [1]shinekunnath.phd@gmail.com, [2]subbaiahk@ssn.edu.in

Abstract

The effect of Al-Mg-Sc interlayer on friction stir welding of non heat treatable aluminium alloy AA5083-H111 is studied. A 1.5 mm thick Al-Mg-Sc alloy was used as an interlayer. The microstructural analysis on the friction stir welded sample was carried out using optical microscopy and scanning electron microscopy. The mechanical properties were analyzed using the tensile tests and hardness test. Tensile tests were carried out using the universal testing machine and the hardness tests were carried out using vicker's microhardness tester. The addition of scandium has increased the yield stress and the hardness values but it has reduced the % elongation of the welded joint. The more of failure was analyzed by studying the fractured surface using the scanning electron microscope.

Keywords: *AA5083-H111 alloy, Friction Stir Welding, Al-Mg-Sc alloy, Hardness and Tensile Properties.*

1. Introduction

Friction stir welding (FSW) is a new welding technique developed by the welding institute and it has its significant applications in aerospace and automotive industries. Friction stir welding is a solid state welding process in which a rotating tool pin plunges into two adjoining plates, and the plates are welded using the heat produced by the rubbing of tool pin inside the plate and the tool shoulder on the surface of the plate. In this process there is no requirement for special sample preparations also this process produces very little waste and pollution.

Aluminium alloys are very widely used in aeronautical and marine field due to their excellent strength to weight ratio and good corrosion resistance. Joining of materials from the conventional fusion welding process leads to various defects like porosity, solidification cracking, dendrites formation etc. To overcome this problem a solid state welding technique FSW is introduced by the welding institute (TWI) in 1991 [1]. The intermetallic compounds that are formed during the friction stir welding deteriorate the mechanical properties of the welded joint due to the inherent brittle nature of the intermetallics [2]. The right tool offset position must be chosen to obtain proper weld morphology which is very important for the intermetallics to strengthen the matrix to gain good strength at the weld nugget [3]. Also the composition of the intermetallic compounds can be modified by using a third material insert in form of a interlayer to increase the strength of the weld zone [4].

The AA5083 (Al-Mg) alloy has the excellent combination of strength, formability, corrosion resistance, weldability and low cost. This is reason for the extensive use of Al-Mg alloys in various aircraft, automotive and ship building industries [5]. Since all Al-Mg alloys are non heat-treatable, they achieve their high strength through solid solution strengthening using the Mg atoms and through precipitation hardening using the second phase particles [6-9]. The other alloying elements that are present in the Al-Mg alloys, Mn, Ti and Zr, refines the recrystallized grains, whereas the Cu and Mg contributes mainly in improving the strength of the alloy [10]. The increase in the Mg content in Al-Mg alloys helps in the refinement of sub-crystal and grain sizes. Recrystallization promotes the evolution of grain orientation towards high angle grain boundaries [11, 12].

The addition of scandium acts as a strengthening mechanism for the Al-Mg alloy. Addition of scandium in aluminium alloys results in increase in mechanical properties, grain size refinement and improvement in weldability [13]. High resistance to fatigue crack nucleation was exhibited by AlMgSc alloy than compared to the coarse grained 6013-T6 alloy [14]. Another important characteristic of AlMgSc alloy is micro-crack propagation resistance. When scandium is added to Al-Mg alloy it forms Al_3Sc particles which precipitate as spherical and coherent particle. The Al_3Sc particle contributes to the precipitation strengthening, it also stabilize the sub-grain structure in aluminium alloy during processing which increases the yield stress [15]. Scandium is an effective refiner of recrystallized grain structure when compared to chromium or zirconium. The second phase intermetallic compounds are well refined by scandium addition [16].

In this paper, an attempt is made to study the effect of Al-Mg-Sc alloy interlayer on the microstructure and the mechanical properties of friction stir welded non heat-treatable AA5083-H111 aluminium alloys.

2. Experimental Procedure

The base material used in this study AA5083-H111 is cut into the required dimension of 150 mm x 55 mm x 5 mm using the power hacksaw cutting machine. The cast Al-Mg-Sc alloy insert is cut into a 1.5 mm thin strip using the EDM wire cutting machine. The chemical composition of the base metals AA5083-H111 and Al-Mg-Sc cast alloy are given in Table 1. Table 2 shows the mechanical properties of the base metal used. Two friction stir welding experiments are carried out in this study, one is the simple butt welding of AA5083-H111 aluminium alloy and the second experiment is carried out by keeping the Al-Mg-Sc cast alloy strip as the insert in between the AA5083-H111 aluminium alloy plates. The welding process parameters of the friction stir welding are given in Table 3.

The samples for mechanical and microstructural characterization are extracted from the friction stir welded samples using the EDM wire cutting machine. The tensile samples are extracted as per the ASTM-E8 standards and the tensile tests are carried out using the universal testing machine. Microstructural analyses are carried out on the extracted samples using the optical microscope and scanning electron microscope. The failed surface of the tensile samples is studied using the scanning electron microscope to evaluate the type of failure that has occurred on the welded samples. Hardness evaluation was carried out at 32 spots along the transverse direction of the weld by keeping the weld nugget at the centre. Vickers microhardness tester with a diamond indenter is used for the hardness evaluation.

Table 1 Chemical composition of the base materials (wt%)

Base Metal	Mg	Mn	Fe	Si	Cu	Cr	Zn	Ti	Sc	Al
AA5083-H111	4.25	0.53	0.26	0.98	0.35	0.11	0.10	0.019	-	93.31
Insert Al-Mg-Sc	3.95	0.65	0.36	0.13	0.02	0.02	-	0.023	0.29	94.56

Table 2 Mechanical properties of the base materials

Material	**Yield Strength**	**UTS (MPa)**	**Elongation (%)**
AA5083-H111	197.39	321.34	22.26
Insert Al-Mg-Sc	244	258	11.3

Table 3 Friction stir welding process parameters

Process parameters	**Values**
Tool rotational speed (RPM)	950
Tool traverse speed (mm/min)	28
Tool pin profile	Square
Tool pin length (mm)	4.5
Tool shoulder diameter, D (mm)	15
Tool pin diameter, d (mm)	5

3. Results and Discussion

3.1. Weld Microstructure

The microstructural studies were done on the welded samples to learn more about the grain size, shape, and orientations and also to study about the morphologies of the precipitates and the quantity of precipitates that are present in the welded samples. The optical microscope is used to study in detail about the grains and the scanning electron microscopy is used to study about the precipitates that are present in the weld.

3.1.1. Optical Microscopy

The friction stir welded samples is divided into four major zones they are, the weld nugget (WN), the thermo-mechanically affected zone (TMAZ), heat affected zone (HAZ) and the base metal zone (BMZ). The weld nugget zone is the zone which is directly influenced by the tool pin. This zone has fine dynamically recrystallized grains. The thermo-mechanically affected zone is found next to the weld nugget, it has fine elongated grains that are oriented towards the rolling of the tool pin profile. The heat affected zone is the zone that is present next to the thermo-mechanically affected zone. The grains found in this zone are big in size because of the grain growth that occurs due to the flow of heat during friction stir welding. The zone next to the heat affected zone is the base metal zone, in this zone there is no much changes in the grain structures as the heat flow is in this zone is very minimal during the friction stir welding process.

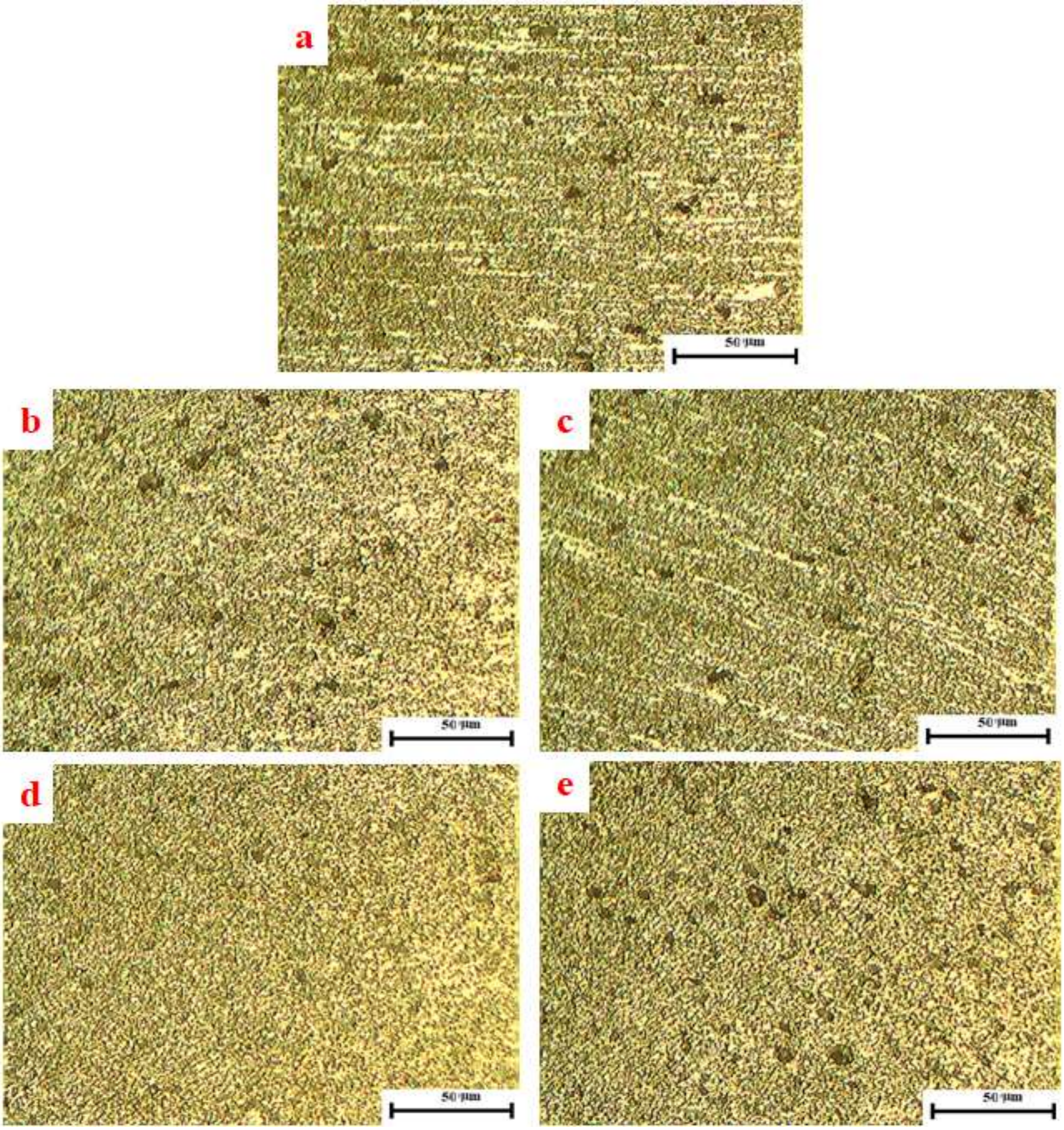

Figure 1. Optical Microscopy images (a) AA5083-H111 BM (b) HAZ (c) TMAZ (d) Weld nugget – w/o Scandium insert (e) Weld Nugget – with Scandium insert.

The microstructural images obtained using optical microscopy is shown in Fig. 1. The base metal microstructure of AA5083-H111 is shown in Fig. 1(a). Fig. 1(b) shows the heat affected zone of the sample welded at 950 RPM and 28 mm/min using the square tool pin profile, Fig. 1(c) shows the thermo-mechanically affected zone of the welded sample. Fig. 1(d) shows the weld nugget of the sample welded without scandium insert and the weld nugget image of the sample welded with Al-Mg-Sc alloy insert is shown in Fig. 1(e). Proper mixing of the materials has been observed on both the welded samples. The dynamic recrystallization that has occurred in the weld nugget zone because of the action of tool pin profile has made the grain size in the nugget zone smaller. The addition of scandium interlayer has also contributed to the reduction in grain growth. This similar phenomenon of grain growth reduction due to addition of scandium has been observed by various researchers [17,18]. This is the reason for the increase in strength at the weld nugget zone in both the cases according to hall-petch strengthening mechanism, whereas due to the heat flow during the friction stir welding process in the heat affected zone there is a increase in grain size. This is the reason why the heat affected zone of the metal is considered as the weakest zone in the welded samples.

3.1.2. Scanning Electron Microscopy

The microstructural images that are obtained using scanning electron microscope is shown in Fig. 2. Fig. 2(a) shows the SEM image of the AA5083-H111 base metal. Fig. 2(b) shows the SEM images of the heat affected zone of the welded sample. Fig. 2(c) shows the weld nugget zone of the sample welded without scandium interlayer and the weld nugget of the sample welded with scandium interlayer is shown in Fig. 2(d).

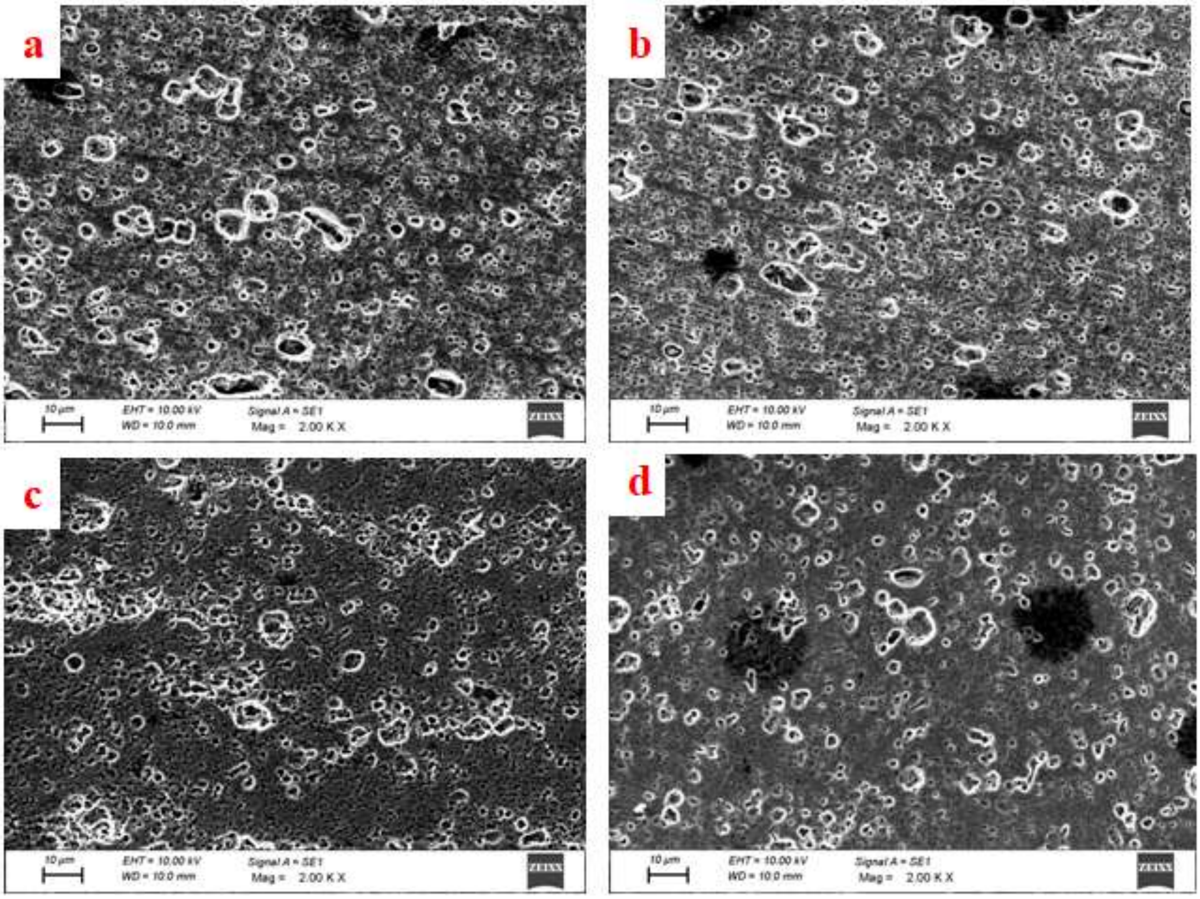

Figure 2. Scanning Electron Microscopy images (a) AA5083-H111 BM (b) HAZ (c) Weld nugget – w/o Scandium insert (d) Weld Nugget – with Scandium insert.

AA5083-H111 is a non heat-treatable aluminium alloy it obtains its strength from solid solution strengthening achieved by the magnesium present in the alloys. The other strengthening mechanism of the Al-Mg alloys is precipitation strengthening which are achieved by the precipitates like Al_3Mg_2, Al_6(Fe, Mn), Al_6(Fe,Mn)Cr, Al_6(Fe,Mn)Si and Mg_2Si. The addition of scandium interlayer during the friction stir welding of AA5083-H111 aluminium alloys promotes the formation of Al_3Sc precipitates in the weld nugget zone. These Al_3Sc precipitates that are formed in the weld nugget zone helps in increasing the yield strength and hardness of the welded samples [19].

By comparing the images obtained from the scanning electron microscope, a reduction in the quantity of precipitates are observed in both weld nugget zones (Fig. 2(c) and 2(d)) than compared to the precipitate quantity in base metal (Fig. 2(a)) and heat affected zone (Fig. 2(b)). This phenomenon has been observed because most of the precipitates in the weld nugget zone breaks down into small precipitates because of the stirring action caused by the tool pin, and most of the precipitates gets dissolved due to the high heat flow in the weld nugget zone.

3.2. Tensile Properties

The tensile properties of Friction Stir Welded joints with and without Al-Mg-Sc Insert are evaluated using the universal testing machine and the results obtained are listed out in Table.4. By comparing the yield strength values of both the welded samples, it is clearly evident that the yield strength of the sample welded with the Al-Mg-Sc insert (185.72 MPa) is high compared to the yield strength of the sample welded without the insert (173.16 MPa). By comparing the ultimate tensile strength values of both the welded samples, we can observe that the tensile strength of the sample welded without the Al-Mg-Sc interlayer (252.67 MPa) is higher than the sample welded with the Al-Mg-Sc insert (244.67 MPa). It can also be seen that the addition of Al-Mg-Sc insert reduces the ductility of the welded samples. The similar phenomenon was also observed by few researchers on addition of scandium to the weld [20-22].

Table 4. Tensile properties of the welded samples

	Yield Stress, MPa	UTS, MPa	El, %	Fracture Location
Without Scandium	173.16	252.67	13.52	At the HAZ of the Retreating side
With Scandium	185.72	244.87	9.06	At the HAZ of the Retreating side

3.3. Fractographic study

The fractured surface of the tensile samples is studied using the scanning electron microscope to know about the types of failure that has occurred in the welded samples. Fig. 3(a) shoes the fractographic image of the AA5083 aluminium alloy (base metal). The fractographic image of the sample welded without scandium insert is shown in Fig. 3(b). The fractographic images of sample welded with Al-Mg-Sc cast alloy insert in shown in Fig. 3(c).

Large quantities of dimples are seen in Fig. 3(a), this shows that the base metal AA5083-H111 aluminium alloy is ductile in nature. This proves on the fact that AA5083-H111 is a high ductile material. By comparing the fractography images of both the welded samples it can be seen that the sample welded without scandium interlayer shows dimpled fractured surface whereas the samples welded with scandium interlayer shows no dimples on its fractured surface. This proves that the addition of scandium interlayer reduces the ductility of the welded samples to a large extent.

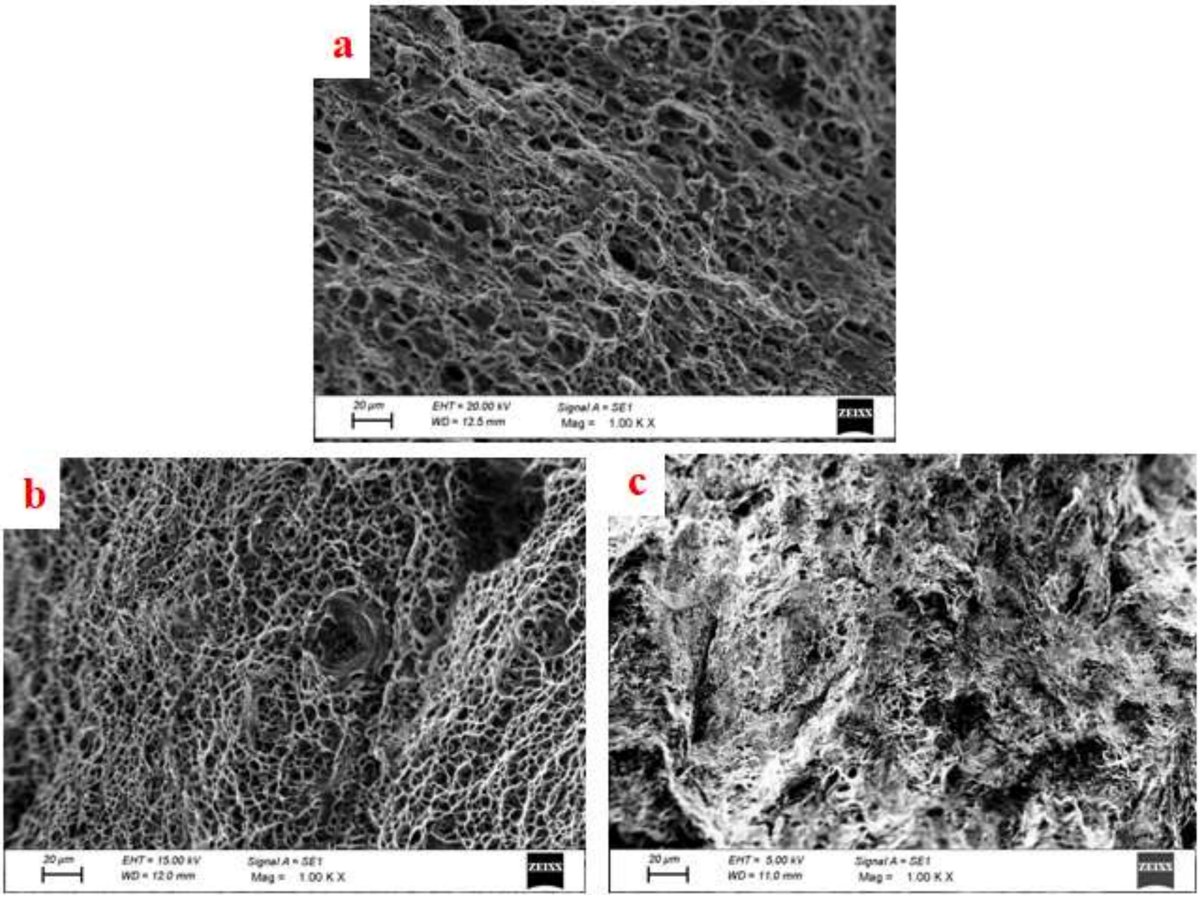

Figure 3. Fractography images (a) AA5083-H111 BM (b) W/o Scandium insert (c) With Scandium insert

3.4. Hardness

The hardness survey of the samples welded with and without Al-Mg-Sc cast alloy was conducted using Vickers Microhardness tester and the graph obtained is shown in Fig. 4. By analysing the hardness graph obtained it is clear that there are no major variations on the hardness peaks in various zones. The high peak is obtained at the weld nugget zone there are two main reasons for this results. One reason is the stirring that is caused by the tool pin and the other reason is the addition of Al-Mg-Sc interlayer. During friction stir welding the tool pin stirs the materials from advancing side to retreating side and from retreating side to the advancing side. The heat input that flows because of the stirring action initiates dynamic recrystallization on the weld nugget zone, also the old grains that are present in the weld nugget zones are broken down into small grain. This increases the hardness values on the weld nugget zone. The addition of scandium to the weld nugget zone helps in the increase of hardness in the weld nugget zone by two ways, one by the formation of solid solution which causes a strong hardening [23] and another way is by the formation of Al_3Sc intermetallic particle which also increases the hardness of the alloy [24].

The lowest hardness values were observed in the heat affected zone. This is because of the dissolution of the strengthening precipitates and the grain growth that happens in the heat affected zone because of the heat flow during the friction stir welding process. This makes the heat affected zone the soft zone in the welded samples. During tensile loading, the fracture takes place on the soft region of the sample [25]. The soft zone is considered as the weakest zone of the welded samples which in our case is the heat affected zone.

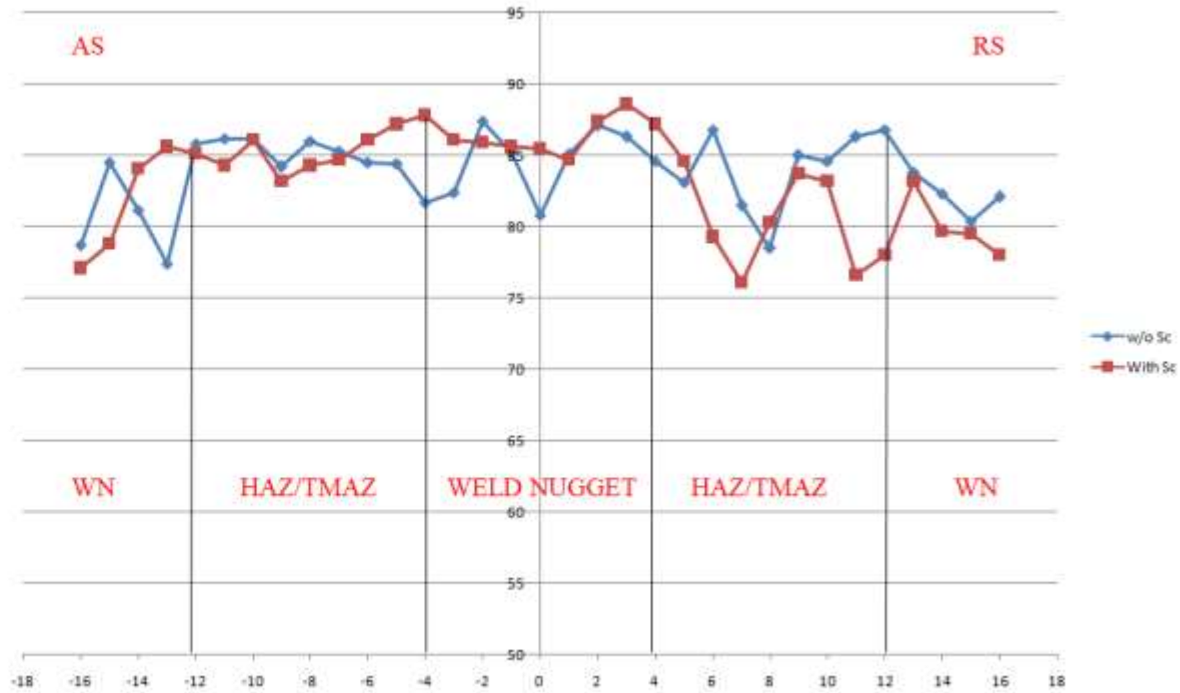

Figure 4. Hardness plot of the welded samples

4. Conclusion

The following conclusions have been drawn on Friction Stir Welding of AA5083 Aluminium alloy with and without Scandium inserts.

1) The microstructural characterization of the welded samples proved that the addition of scandium has reduced the grain growth and has also formed Al_3Sc precipitates which contributed to the strength and the hardness.
2) The weld nugget microstructures of the welded samples with Scandium insert was fine and recrystallized. Fragmentation and nucleation of Al_3Sc intermetallic compounds were observed in the weld nugget of Scandium inserted AA5083 alloy welded joints and was responsible for the enhancement of tensile properties of the welded joints.
3) The tensile test results proved that there was an increase in the yield stress of the sample welded with scandium insert than the sample welded without scandium insert but the addition of scandium has decreased the ultimate tensile strength and the ductility of the material. The fracture location in the Scandium inserted FS Welded joints were observed at the HAZ of the retreating side.

The hardness value of the friction stir welded AA5083 aluminium alloy with Scandium insert was greater than that of the friction stir welded AA5083 plate without Scandium insert.

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