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Effects of Tool Material and Post Weld Heat Treatment on Mechanical Properties of Friction Welded Joints- AL Alloys (AA6061-T6)

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Abstract- AA6061 alloy has Excellent joining characteristics, good acceptance of applied coatings; this combines relatively high strength, good workability, high resistance to corrosion, and good weldability. H13 Hot Work Tool Steel has High hardenability, excellent wear resistance hot toughness, and good thermal shock resistance all the mentioned properties make it a perfect selection for friction stir welding tool and this material can tolerate some water cooling in service. Nitriding will improve hardness, but can diminish shock resistance if hardened layer is too thick. HSS-M2 and D3 are also similar tool steels which are considered in this study as FSW tool materials for experimentation. Current work deals with the experimental investigation on effects of post weld heat treatment on the mechanical properties of friction stir welded joints of Aluminium alloys. In order to study the effect of post weld heat treatment a design of experiment is conducted and a set of experiments are defined. Experimental trials were conducted with three different tool materials of different hardness with and without post weld heat treatment. Mechanical properties are studied as per the standard procedure defined by American welding society. Post weld heat treatment improves the ductility of the weld joints thus increases the flexibility to use the welded joints in many new applications like explosion forming.

Keywords - Friction stir welding, Heat treatment, Radiography and FSW tool.

1. INTRODUCTION

Friction stir welding (FSW) is a new joining method derived from conventional friction welding which enables the benefits of solid-state welding. This joining technique has been shown to be viable for joining aluminum alloys, copper, magnesium and other low-melting point metallic materials. Shashi kumaret al. [1]presented here, the influence of friction stir welding (FSW) tool material on the mechanical and micro-structural properties of friction stir (FS) welded 316L stainless steel butt joints is investigated. FS welds were produced using two different tungsten based FSW tools having identical tool shoulder and pin profiles. The results showed that the joints produced using the tungsten lanthanum oxide tool are having superior mechanical and micro-structural properties when compared to the joints produced using tungsten heavy alloy tool. Ugender Singarapu et al. [2] have studied the effect of friction stir welding (FSW) parameters such as tool material, rotational speed, and welding speed on the mechanical properties like tensile strength, hardness and impact energy of magnesium alloy AZ31B. The results indicate that rotational speed (RS) and traverse speed (TS) are the most significant factors, followed by tool material (TM), in deciding the mechanical properties of friction stir processed magnesium alloy.

Y.N. Zhang et al. [3] Friction stir welding process constrains the plasticized material around the probe, generates heat through the friction and causes plastic deformation in a relatively thin layer under the bottom surface of the shoulder. Results shows the correlation between the weld speed and the wear rate of the tool material was found that the tools wear by volume increases with the amount of weld length covered by them where as the wear rate decreases with the increase in weld speed. K. Reshad Seighalaniet al.[4] have studied the Friction stir welding (FSW) parameters, such as tool material, etc., Because of excessive erosion, tool material and geometry play the main roles in FSW of titanium alloys. Result of this research shows that Ti can be joined by the FSW, using a tool with a shoulder made of tungsten (W) and simple pin made of tungsten carbide (WC). Ashish Bist et al.[5] have conducted a study on the solid state welding process, which prevents the formation of the intermetallic precipitates responsible for degradation of mechanical properties in fusion welds of these composites. It was found that the total amount of material removed from the tool is in direct proportion to the rotational speed of the tool and the length of the weld butt inversely proportional to the transverse rate.Giuseppe Casalinoet al.[6]

have demonstrated the effect of geometry and surface coating of the tool shoulder on the defectiveness, the microstructure and the micro-hardness of a 3 mm thick 5754H11 aluminium alloy butt weld.

Moreover a tungsten carbide coated was tested. The weld was characterized in terms of the bead morphology and the grain size.Jiye Wang et al.[7] have reported development of equiaxed, bimodal, and lamellar microstructures in FSW of Ti–6Al–4V alloy depending on the peak temperatures reached in the stir zone, which was significantly influenced by the processing parameters.A.K. Lakshminarayananet al.[8] made an attempt to develop the tools that are capable enough to withstand the shear, impact and thermal forces. Five different combinations of self-fluxing alloy powder and 60% ceramic reinforcement particulate mixtures are used for coating. The normalized wears of the PTA hard-faced tool material were reduced by more than 80%, over a given length compared to WC, CrC, TiC and B4C tools.The effect of heat treatment on FSW joints byP. Sivaraj et al.[9] have reported the effects of post weld heat treatments, namely artificial ageing and solution treatment followed by artificial ageing, on microstructure and mechanical properties of 12 mm thick friction stir welded joints of precipitation hardenable high strength armour grade AA7075-T651 aluminium alloy.

WorapongBoonchouytanet al.[10] studied the butt joints of semi-solid metal 6061 in as cast conditions by friction stir welding process (FSW). They were divided into (1) As welded (AW) joints, (2) T6 Weld (TW) joints, (3) Weld T6 (WT) joints, (4) T6 Weld T6 (TWT) joints, (5) Solution treated Weld Artificially aged (SWA) joints and (6) Weld Artificially aged (WA) joints. Rotating speed and heat treatment (T6) condition were an important factor to micro, macro structure of metal and mechanical properties of the weld. P.Vijaya Kumar et al.[11] a study on high strength aluminium alloys exhibits low weldability due to poor solidification microstructure, porosity in the fusion zone and lose their mechanical properties when they are welded by fusion welding. Corrosion resistance of welds gets affected by the microstructural changes that occur during welding. In the present work the effect of post weld treatments viz. peak ageing (T6), over-aging (T73), retrogression and retrogression & re-aging (RRA) on the mechanical properties and stress corrosion resistance is studied. It was observed that Retrogression and RRA treatments improved the resistance to stress corrosion cracking and maintained the mechanical properties.

P.Prasanna et al.[12] made an attempt to study the effect of heat treatment methods like annealing, normalizing and quenching have been applied on the joints and evaluation of the mechanical properties like tensile strength, percentage of elongation, hardness and microstructure in the friction stirring formation zone are evaluated. From this investigation, it is found that the hexagonal tool profile produces good tensile strength, percent of elongation in annealing and hardness in quenching process.Ling Li et al.[13] proposed the effects of heat treatment and strain rate on mechanical behavior and microstructure evolution of aluminium alloy (AA) 6061 have been investigated. It is observed that the additional heat treatment has significantly reduced the yield strength of the material.Stephen J. Hales et al.[14] have made a prototype end domes for cryogenic propellant tanks were fabricated using friction stir welding and spin forming technology.M. FarahmandNikooet al.[15] in their present study, 6 mm thick AA6061-T6 alloy was friction stir welded ,the influence of post weld heat treatment (PWHT) on microstructure and wear properties were studied. Solution treatment cycle was applied to FS welded specimens for 1 h at 540 °C then aged for 18 h at 180 °C.

Current work deals with the experimental investigation on effects of post weld heat treatment on the mechanical properties of friction stir welded joints of Aluminium alloys. In order to study the effect of post weld heat treatment a design of experiment is conducted and a set of experiments are defined. Experimental trials were conducted with three different tool materials of different hardness with and without post weld heat treatment.

2. EXPERIMENTAL WORK

2.1 MATERIAL SELECTION FOR WORK PIECE

AA6061 is a precipitation-hardenedaluminium alloy, containing magnesium and silicon as its major alloying elements. It has good mechanical properties, exhibits good weldability, and is very commonly extruded of various extruded forms of AA6061 alloy. It is commonly available in pre-tempered grades such as 6061-O (annealed), tempered grades such as 6061-T6 (solution hardened and artificially aged) and 6061-T651 (solution hardened, stress-relieved stretched and artificially aged) . Fig 1 and 2 shows the FSW machine setup

Figure 1 Work Holding setup used for FSW

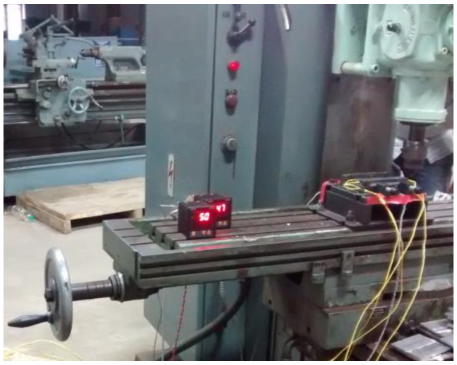

Figure 2 Vertical milling machine used for FSW.

2.2 PROPERTIES OF TOOL MATERIAL

H13: Hot Work Tool Steel. Material Notes: High harden ability, excellent wear resistance and hot toughness. H13 has good thermal shock resistance and will tolerate some water cooling in service.

D3:Tool Steel is a high-carbon, high-chromium, oil-hardening tool steel that is characterized by a relatively high attainable hardness and numerous, large, chromium-rich alloy carbides in the microstructure.These carbides provide good resistance to wear from sliding contact with other metals and abrasive materials.

HSS-M2:High speed steel with an excellent combination of wear resistance, toughness and hot hardness. Suitable for general purpose cutting tool applications, such as boring tools, broaches, chasers, cutters drills, lather tools, and forming dies. The various tool material properties values are given in the table 1.

The schematic representation of the FSW tool is shown in the figure 3. The ramping step finishes when the core of the parts in the furnace reaches the chosen temperature. Then the temperature is maintained constant for a certain amount of time.

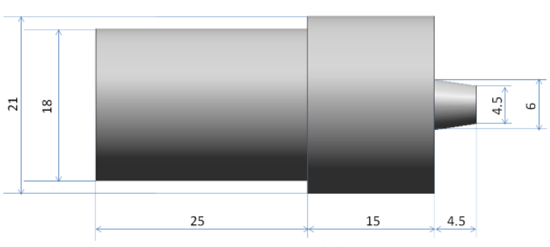

Figure 3 FSW tool for experimentation

This is called holding time. The generally recommended holding time is 30 minutes. In the case of high speed steel, the holding time will be shorter when the hardening temperature is over 1100°C (2000°F). If the holding time is prolonged, microstructural problems like grain growth can arise. The choice between a fast and a slow quenching rate is usually a compromise. To get the best microstructure and tool performance the quenching rate should be rapid. To minimize distortion, a slow quenching rate is recommended. Slow quenching results in less temperature difference between the surface and the core of a part, and sections of different thickness will have a more uniform cooling rate. This is of great importance when quenching through the martensite range, below the M_s Temperature. Martensite formation leads to an increase in volume and stresses in the material. This is also the reason why quenching should be interrupted before room temperature has been reached, normally at 50–70°C (120– 160°F). However, if the quenching rate is too slow, especially with heavier cross-sections, undesirable transformations in the microstructure can take place, risking a poor tool performance.

Table 1 *Al6061-T6-MECHANICAL AND THERMAL PROPERTIES* Tool material properties

Material properties	**H13**	**D3**	**HSS-M2**
Density (×1000 kg/m^3)	7.8	8.1	8.14
Elastic Modulus (GPa)	210	205	200
Tensile Strength (Mpa)	1990	1955	2010
Elongation (%)	9	12	11
Hardness (HB500)	52	64	62
Shear Modulus (MPa)	81	84	82

Aluminium alloy AA6061, plate of 6mm thickness is considered for this study, test pieces of required size and shape is cut with wire-EDM machine for better accuracy. Faces to be welded are then grinded to remove the imperfections due to the erosion by the wire EDM process.**Test plate dimensions:**100 mm (Length) * 50 mm (Width) * 6 mm (Thick).After cutting, the edges (faces) which are going to be welded are grounded to have a better surface contact with the mating faces. Specimens are prepared as per the experimental combination, defined in the design of experiments, variables considered for the experiments are Tool material and Hardness.

2.3 RADIOGRAPHIC EVALUATION

Weld joints are the origins of structural weakness in maximum cases and must be routinely inspected to ensure structural integrity of the fabricated components. Digital X-ray radiography technique is used for evaluation of the quality of the friction stir welded aluminum butt joints and aluminum-zinc coated steel dissimilar lap joints. Fig 4, shows the radiograph equipment.

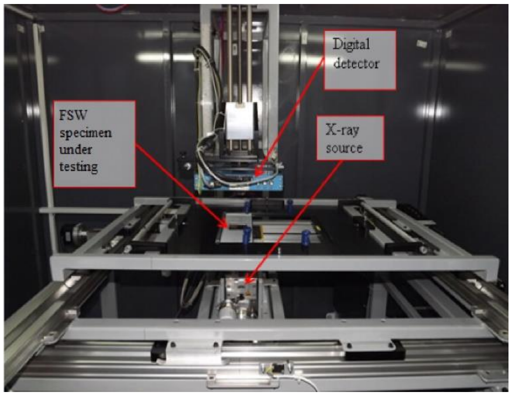

Figure 4 Digital radiography equipment used for checking of FSW weld quality

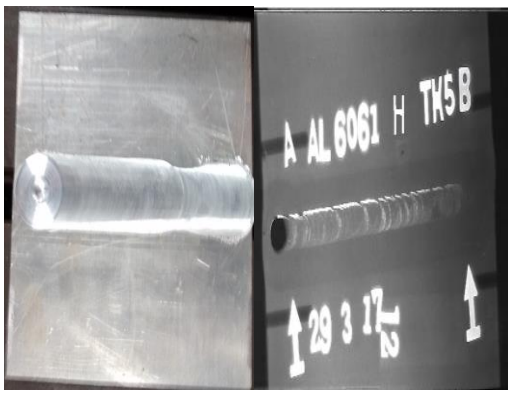

Figure 5 Specimen used for evaluation under X-ray

Similar butt joints (100 × 100 mm) were fabricated using 5 mm thick aluminum (grade 6061). The butt joints were manufactured using a friction stir welder under displacement control mode. The weld joints were produced for a dwell time of 25 s and for depths of 4.5 mm. The dimension of the friction stir welded aluminum butt joint is 100 × 100 × 5 mm. Fig 1.5shows the specimen used for evaluation under X-ray. Figure 6shows the radiography images of test specimens.

A digital X-ray radiography procedure is used to detect micro-pores and voids in aluminum alloy friction stir weld butt joints. This methodology has been successfully used to study the effect of welding parameters like rotational speed, travel speed and penetration depth. A sub-surface tunnel defect along the weld line was detected using radiography and it was observed that the rate of temperature decay was slower for the defect region. Defect depth was quantified from the thermal diffusion length. Internal tunneling defects were clearly identified with the samples, which were not further processed for mechanical testing, radiography evaluation helps in reducing the efforts spent on the specimen preparation for mechanical testing, having the radiograph images for further reference which can be compared.

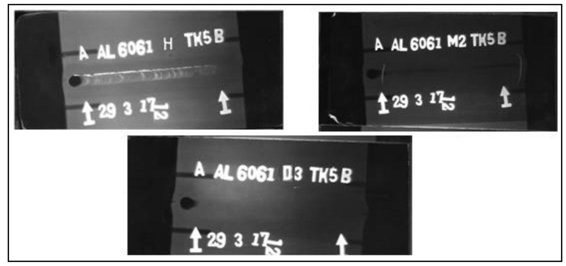

Figure 6 Radiograph images of the test specimen

2.4 MECHANICAL TESTING:

Testing standards such as ASTM E8, ISO 6892, EN 10002-1, and JIS Z 2241 define how to perform proper tensile testing on metallic materials. These standards define critical elements, such as the equipment needed to perform the testing, how to prepare test specimens, proper measurement techniques, testing speeds and control parameters, calculation results, and how to report the results.

Since welded specimens are non-homogeneous over their gauge length, the primary test results of interest are typically the ultimate tensile strength (UTS) and the location of the fracture. However, typical tensile results such as Young's modulus, yield strength, percent elongation, and area reduction may also be recorded for reference purposes.

2.5 MICROSTRUCTURE EVALUATION

The stir zone (also nugget, dynamically recrystallized zone) is a region of heavily deformed material that roughly corresponds to the location of the pin during welding. The grains within the stir zone are roughly equiaxed and often an order of magnitude smaller than the grains in the parent material. A unique feature of the stir zone is the common occurrence of several concentric rings which has been referred to as an "onion-ring" structure. The precise origin of these rings has not been firmly established, although variations in particle number density, grain size and texture have all been suggested as shown in the figure 7,

Figure 7 Specimen used for Microstructure analysis

3. RESULTS AND DISCUSSIONS

3.1 EFFECT OF TOOL HARDNESS ON MECHANICAL PROPERTIES

As defined in the experimental setup, different tool materials are hardened with the same prescribed procedure. Fig 8, shows the various tools used for FSW, and Fig 9, shows the comparison of the hardness values of the tools.

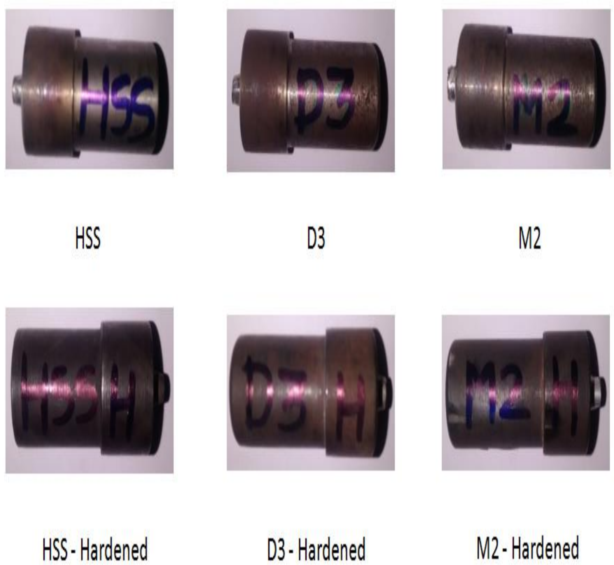

Figure 8 Hardened and unhardened tools

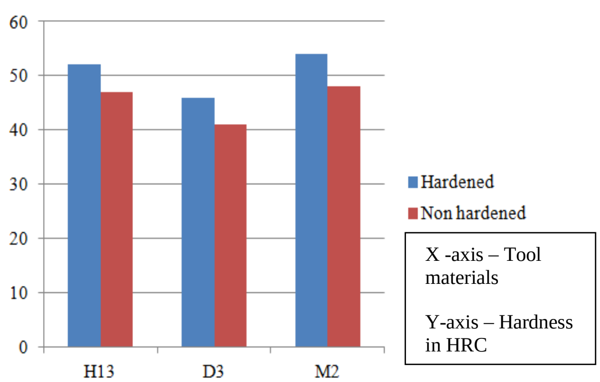

Figure 9 Comparison between hardness values of tools

3.2 EFFECT ON TENSILE STRENGTH

The typical tensile specimen used for experiments and represents the tensile tested specimens according to standards ASTM D 557 M-94. Table shows the micro hardness values in SZ in addition to the tensile test results of all the dissimilar friction stir welded specimens including the tensile failure position. Fig 10, shows the specimens which were undergone tensile testing.

Figure 10 Specimens after tensile testing

Tensile test results of friction stir welded joints of AA6061 without post weld heat treatment is shown in Fig 11., That FSW joints made with D3 unhardened tool has the highest tensile strength. Where as the Hardness of the D3 unhardened tool is the least among the materials taken for study.Fig 12 shows the stres strain curve of welded specimens without post heat treatment.

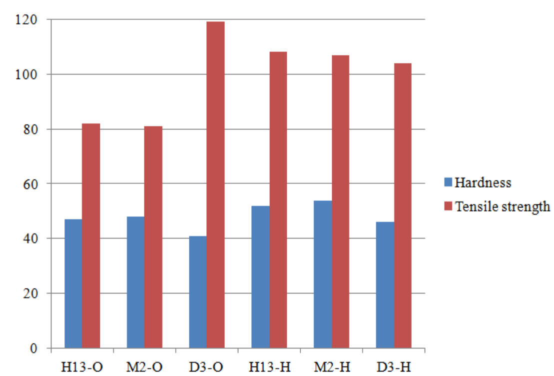

Figure 11 Tensile properties of AA6061 FSW joints without heat treatment

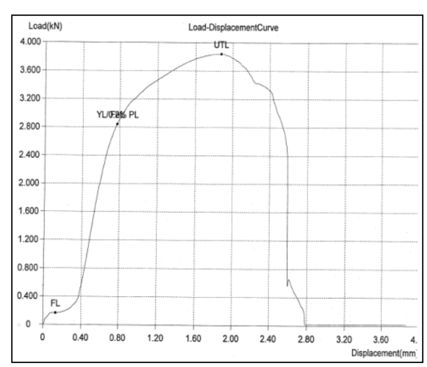

Figure 12 Stress Strain diagram of the specimen welded with D3-O tool

3.3 EFFECT ON HARDNESS OF WELD ZONE

Hardness values on the weld zone for the specimens without post weld heat treatment.

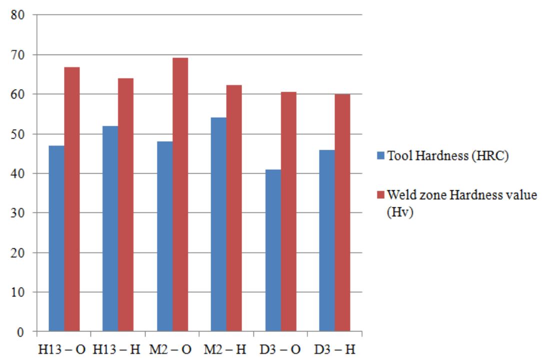

Figure 13 Tool and weld zone hardness comparison without post weld heat treatment

Hardness test results of friction stir welded joints of AA6061 without post weld heat treatment shown in Fig 13. Hardness of the tool material is inversely proportional to the hardness in the weld zone of the FSW sample. Friction stir welded specimens made from D3 hardened tool has the lowest hardness in the weld zone, which corresponds to the tensile strength.

3.4 EFFECT ON ELONGATION

Tensile tests were performed on specimens each of raw material (base material) of Al 6061 T6 and we obtained the results of welding without treatment and welding results with the T6 heat treatment aging variation. The testing data was obtained of the ultimate stress (σ u) and yields stress (σ y). The data was obtained from drawing a line offset 0.2%. The 0.2% offset yield strength was derived from the load–elongation diagram. The percentage of elongation in cross sectional area was evaluated. Figure 14, shows the graph between the tensile strength of the FSW welded joint and the percentage of elongation obtained during tensile testing.

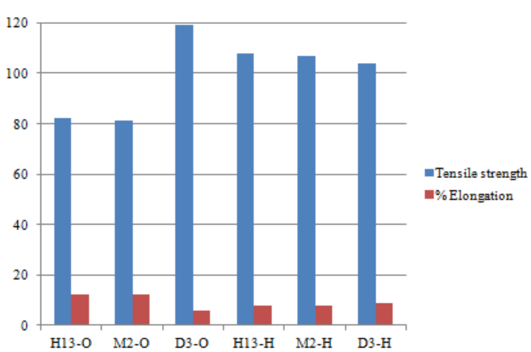

Figure 14 Tensile strength and elongation comparison without post weld heat treatment

3.5 EFFECT OF POST WELD HEAT TREATMENT ON MECHANICAL PROPERTIES

AA6061 alloy is preferred to be treated with Solution heat treatment at 515^{0}C for 1.5hrs with cold water quench and heating at 120^{0}C for 24hr. Figure 15 shows tensile test results of friction stir welded joints of AA6061 with post weld heat treatment .The FSW joints made with H13 unhardened tool has the highest tensile strength.Where as the Elongation of the D3 unhardened tool is at maximum of 20% within the gauge length of 25mm. Figure 16 Stress Strain diagram of the specimen welded with D3-O tool.

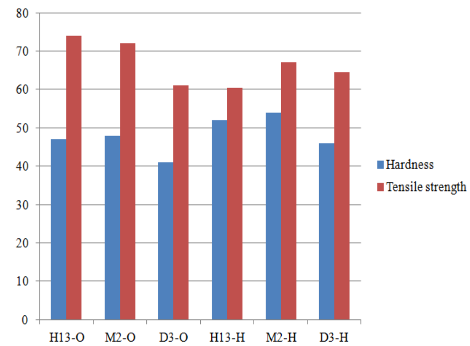

Figure 15 Tensile properties of AA6061 FSW joints with heat treatment

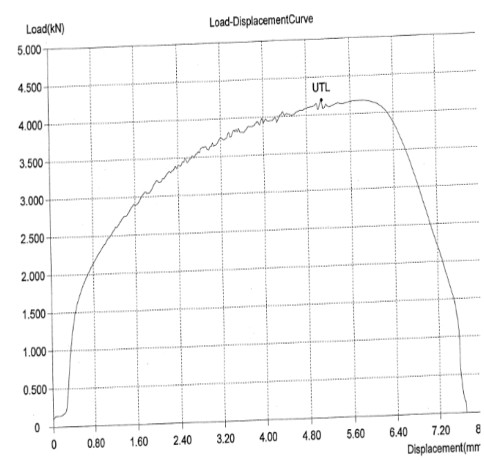

Figure 16 Stress Strain diagram of the specimen welded with D3-O tool

3.6 EFFECT ON HARDNESS OF WELD ZONE

Hardness test results of friction stir welded joints of AA6061 with post weld heat treatment shows, That hardness of the tool material is inversely proportional to the hardness in the weld zone of the FSW sample. Friction stir welded specimens made from D3 unhardened tool has the lowest hardness in the weld zone, which corresponds to the tensile strength.Figure 17, Tool and weld zone hardness comparison with post weld heat treatment.

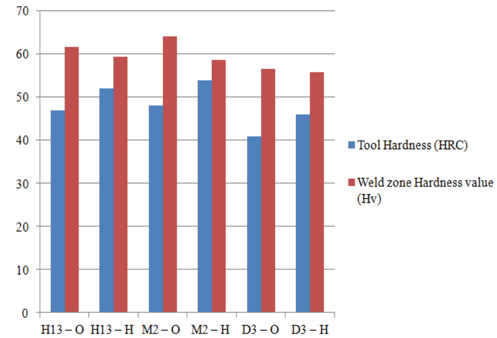

Figure 17 Tool and weld zone hardness comparison with post weld heat treatment

3.7 EFFECT ON ELONGATION

Figure 18 Tensile strength and elongation comparison with post weld heat treatment.The specimens which undergone post weld heat treatment shows a better elongation behaviour when compared with the specimens which did not undergo post weld heat treatment. Maximum percentage of elongation is obtained with the specimen prepared 20 which is obtained with the specimen with the least tensile strength.

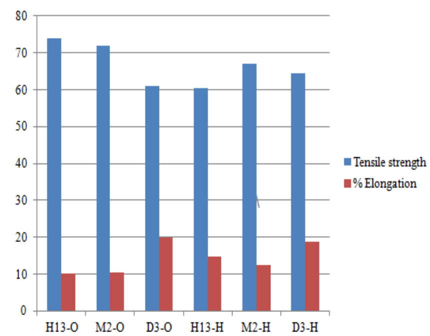

Figure 18 Tensile strength and elongation comparison with post weld heat treatment

4. CONCLUSION

Friction stir welding of AA6061 is carried out with different tool materials including H13, D3 and M2, and also the post weld heat treatment is carried for a set of specimens as defined in the design of experiments. From these experiments and the subsequent tests the following results can be inferred.

Tensile test results of friction stir welded joints of AA6061 without post weld heat treatment shows, That FSW joints made with D3 unhardened tool has the highest tensile strength, this could be due to the grain refinement in the nugget zone and the adjacent heat affected zones.

Where as the Hardness of the D3 unhardened tool is the least among the materials taken for study.Tensile test results of friction stir welded joints of AA6061 with post weld heat treatment shows,That FSW joints made with H13 unhardened tool has the highest tensile strength. This is in contrast to the results obtained with the specimens without post weld heat treatment.

Heat treatment process at higher temperature induces faster kinetics for particles coarsening and grain growth. At 500 deg. C, micro-hardness profiles overlap after 1 hr, even if the microtructure looks very different from the base material to the nugget region. Fracture strain is almost 65% of the joints deformed after heat treatment at lower temperature and failure occurs inside the weld zone.The Elongation observed with the specimen prepared with D3 unhardened tool is at maximumof 20% within the gauge length of 25mm.Hardness is measured along the weld zone to understand the effect of the tool materials and the post weld heat treatment.Post weld heat treatment certainly reduces the hardness in the weld zone as well as the adjacent regions, which in turn makes the material softer thus increasing the elongation.Strain rate of the specimens with post weld heat treatment also two times the rate which is observed with the specimens without post weld heat treatment. Once the FSW joints are subjected to solution heat treatment at high temperature, the welds experience abnormal grain growth within the FSW zone. Moreover, the hardness in the FSW zone of the PWHT joints is lower than that in the BM of the joints. This could be explained by the abnormal grain growth in the FSW zone.T6 (100 °C – 10 h) ageing treatments offered a significant improvement in the elongation compared with the as-welded joint.

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