Performance of H13 and HCHCR Tool Materials on Friction Stir Welded 6070 Aluminium Alloy Plates Subjected to Different Temper Conditions

M.V.N. Srujan Manohar, K. Mahadevan, A. Aravindan

Abstract—In this study, friction stir welding (FSW) process is carried out on heat-treated 6070 aluminium alloy plates of 10mm thickness in two stages using two different tool materials. Firstly, annealed 6070 aluminium alloy (O-temper condition) is joined with naturally aged 6070 aluminium alloy (T4-temper condition) using H13 (Tool steel) material and HCHCR-D2 (Die steel) material. Similarly, annealed 6070 aluminium alloy (O-temper condition) is joined with artificially aged 6070 aluminium alloy (T6-temper condition) using the same tool materials. Both the stages are welded for two rotational speeds and two welding speeds using cylindrically threaded H13 and HCHCR tools. The effect of these welding parameters are further investigated on tensile behaviour (ultimate tensile strength, yield strength and percentage elongation) and hardness for each welded stage to identify better weld-joint strength. Finally micro-structural examinations are carried out on better tensile responses using scanning electron microscope (SEM) and energy dispersive X-ray (EDX) analyzer.

Keywords—friction stir welding, tool steel, die steel, welding parameters, tensile behaviour and micro-structural examinations.

I. INTRODUCTION

Friction stir welding (FSW) is a solid-state joining technique developed at The Welding Institute (TWI), U.K in 1991 [1]. This technique generates high quality joints for various similar and dissimilar heat-treatable aluminium alloys without reaching their melting-temperatures. Due to high thermal conductivity and high corrosion resistance, aluminium alloys have significant approach in automotive applications, especially for car body structures [2]. In most of the aluminium alloys, work-hardening and precipitation-strengthening are the two main important factors for increasing strength property. These factors are observed due to the influence of magnesium and silicon elements in alloying particularly for 6-series aluminium alloys [3,4].

Based on the observations of tool rotational speeds and tool welding speeds on mechanical properties and micro-structural characteristics for heat treated similar 6-series aluminium alloys, it has been studied that for increase in tool process parameters, tensile strength is increased [5,6]. In FSW-process, selection of tool material and its design have been made a deep impact on performance of tools and their quality made on weld joints. Seven different tools with conical-threaded shape are used to join tough-pitch copper plates and the performance of each tool is evaluated based on the mechanical and wear properties [7,8]. For joining heat treatable aluminium alloys of 6-series, tool steel and die steel tool materials are widely used for identifying better performance on mechanical properties at the weld-joint positions [9]. For fabrication of components and structures, aluminium alloys are generally considered due to their high-joint strength and low distortion properties. Some research studies are investigated on these properties for 6-series aluminium alloys using various stainless steel and mild steel tool materials [10]. Already there are several research studies on friction stir welding of similar and dissimilar aluminium alloys but the work done on joining of aluminium alloys on different temper conditions is observed to be limited.

In this article, FSW-process is carried out on similar heat-treated aluminium alloys (6070AA) with different temper conditions by using two tool materials (Tool steel and Die steel). The chemical composition and tensile behaviour of base-metal, 6070AA is shown in Table I and Table II [2]. Based on the enhancement of studies in automobile applications, the research is carried out to indicate the better results of tool performance on tensile strength properties and micro-structural changes at weld-joints.

### Table I: Chemical Composition Of Base-Metal 6070aa

| Cu    | Mg | Mn  | Fe  | Si  | Zn  | Ti  | Cr  | Other | Al |
|-------|----|-----|-----|-----|-----|-----|-----|-------|----|
| 0.15-0.4 | 0.5-1.0 | 0.4-1.0 | 0.5 | 1.0-1.7 | 0.25 | 0.15 | 0.1 | <0.15 | Balance |

### Table II: Tensile Behaviour Of Base-Metal 6070AA

| Heat-treatment condition of 6070AA | Ultimate tensile strength (MPa) | Yield strength (MPa) | Percentage Elongation (%) |
|-----------------------------------|---------------------------------|----------------------|---------------------------|
| O-temper                          | 145                             | 70                   | 20                        |
| T4-temper                         | 338                             | 207                  | 20                        |
| T6-temper                         | 394                             | 358                  | 10                        |

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II. WELDING PROCEDURE

The main intention of the present study is absorbed on FSW of heat-treated 6070AA plates of length 150mm, width 75mm and thickness 10mm. The heat-treatment is carried out in three stages annealed condition(O), solutionised and naturally aged condition(T4), solutionised and artificially aged condition(T6). Wrought alloys(Al-Mg-Si) of 6-series are alternatives to steel materials for fabricating car body applications in automotive industries, since they show good combination of corrosion resistance and weldability properties. During aging treatment, presence of the precipitation-hardening sequence in wrought alloys is found to be difficulty for identifying the chemical composition of fine-scale micro-structures as the precipitation sequence is independent of the composition. The aging condition of precipitation forming sequence is given as [11],

\[
\text{SSS } \alpha \rightarrow \text{GP zones (spheres or needles)} \rightarrow \beta' \text{ (needles)} \rightarrow \beta \text{ (rods)} \rightarrow \beta \text{ (plates, Mg}_2\text{Si or non-stoichiometric Mg}_x\text{Si}_y) \\
\text{where, SSS denotes supersaturated solid solution, } \alpha, \beta', \beta, \alpha \text{ and } \beta \text{ denotes transitional phases}
\]

Hot-working tool steel (H13) and cold-working tool steel (HCHCR-D2) are the two different tool materials used in this experimental work to join 6070AA plates. The chemical composition and nomenclature of both the tools are shown in Table III and Table IV [7]. The profile of the tool shape for both the tools is shown in Figure 1.

![Figure 1. Tool profile of H13 and HCHCR-D2](image)

FSW-process is carried out in two stages using a vertical turret milling machine with a maximum operational speed capacity of 4000rpm and feed capacity of 20–300mm/min. The work pieces should be clamped properly to the welding fixture. Two different tool materials(H13 and HCHCR-D2) are fabricated to make a butt-joint configuration as a weld-profile in each stage. Initially, 6070AA-O is joined with 6070AA-T4 with H13 tool and HCHCR-D2 tool using two sets of rotational-speeds(RS) and welding speeds(WS). Similarly by using the same set of tool parameters, 6070AA-O is joined with 6070AA-T6 with H13 and HCHCR-D2 tool materials as shown in the Table V. The final weld configuration of the work pieces is shown in Figure 2.

![Figure 2. Weld configuration of two stages](image)

### Table III: Composition Of H13 and HCHCR-D2

| Tool-materials | C   | Mn  | Si   | Cr  | Mo  | V   | Ni  | Cu  |
|----------------|-----|-----|------|-----|-----|-----|-----|-----|
| H13            | 0.45| 0.50| 1.20 | 5.25| 1.75| 1.20| 0.30| 0.25|
| HCHCR-D2       | 1.60| 0.60| 0.60 | 13.00| 1.20| 1.10| 0.30| 0.25|

### Table IV: Nomenclature Of H13 And HCHCR-D2

| Tool-materials | Tool-shoulder diameter (mm), D | Tool-pin diameter (mm), d | D/d ratio of Tool | Tool-hardness | Tool-pin profile |
|----------------|---------------------------------|---------------------------|------------------|---------------|-----------------|
| H13            | 20                              | 7                         | 3                | 58HRC         | Cylindrical threaded shape |
| HCHCR-D2       | 20                              | 7                         | 3                | 62HRC         | Cylindrical threaded shape |

### Table V: Tool-Process Parameters

| Welding stages | Tool materials | D/d ratio of tool | RS (rpm) | WS (mm/min) |
|----------------|----------------|-------------------|----------|-------------|
| FSW of 6070AA-O and 6070AA-T4 | H13 | 3 | 1100 | 30 |
|                  | H13 | 3 | 1800 | 50 |
|                  | HCHCR-D2 | 3 | 1100 | 30 |
|                  | HCHCR-D2 | 3 | 1800 | 50 |
| FSW of 6070AA-O and 6070AA-T6 | H13 | 3 | 1100 | 30 |
|                  | H13 | 3 | 1800 | 50 |
|                  | HCHCR-D2 | 3 | 1100 | 30 |
|                  | HCHCR-D2 | 3 | 1800 | 50 |

Totally sixteen experiments are carried out for both the stages for studying the tensile behaviour of weld joints shown in Table VI.
As per ASTM-E8M-16A guidelines, the welded specimen samples were machined for tensile testing in transverse-direction using water-jet machining as shown in Figure 3.

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### Table VI: Final Matrix Of Tool-Process Parameters

| Welding experiments | Tool materials | D/d ratio of tool | RS (rpm) | WS (mm/min) |
|---------------------|----------------|-------------------|----------|-------------|
| FSW-1 (6070AA-O and 6070AA-T4) | H13 | 3 | 1100 | 30 |
| FSW-2 (6070AA-O and 6070AA-T4) | H13 | 3 | 1100 | 50 |
| FSW-3 (6070AA-O and 6070AA-T4) | H13 | 3 | 1800 | 30 |
| FSW-4 (6070AA-O and 6070AA-T4) | H13 | 3 | 1800 | 50 |
| FSW-5 (6070AA-O and 6070AA-T4) | HCHCR-D2 | 3 | 1100 | 30 |
| FSW-6 (6070AA-O and 6070AA-T4) | HCHCR-D2 | 3 | 1100 | 50 |
| FSW-7 (6070AA-O and 6070AA-T4) | HCHCR-D2 | 3 | 1800 | 30 |
| FSW-8 (6070AA-O and 6070AA-T4) | HCHCR-D2 | 3 | 1800 | 50 |
| FSW-9 (6070AA-O and 6070AA-T6) | H13 | 3 | 1100 | 30 |
| FSW-10 (6070AA-O and 6070AA-T6) | H13 | 3 | 1100 | 50 |
| FSW-11 (6070AA-O and 6070AA-T6) | H13 | 3 | 1800 | 30 |
| FSW-12 (6070AA-O and 6070AA-T6) | H13 | 3 | 1800 | 50 |
| FSW-13 (6070AA-O and 6070AA-T6) | HCHCR-D2 | 3 | 1100 | 30 |
| FSW-14 (6070AA-O and 6070AA-T6) | HCHCR-D2 | 3 | 1100 | 50 |
| FSW-15 (6070AA-O and 6070AA-T6) | HCHCR-D2 | 3 | 1800 | 30 |
| FSW-16 (6070AA-O and 6070AA-T6) | HCHCR-D2 | 3 | 1800 | 50 |

### III. OUTCOMES ON MECHANICAL PROPERTIES OF WELD-JOINTS

#### A. Tensile-Behaviour Test

The tensile behaviour at the nugget-weld zone (NWZ) is tested for all 16 experimental runs using universal-testing machine and the maximum values for Ultimate tensile strength (UTS), Yield strength (YS) and percentage-elongation (%E) of two welding-stages by two (H13 and HCHCR-D2) tool materials are reported in Table VII.

### Table VII: Final-Matrix Of Maximum Tensile Data

| Welding experiments | Tool materials | Maximum Tensile test data at NWZ |
|---------------------|----------------|---------------------------------|
|                     |                | UTS [MPa] | YS [MPa] | %E            |
| FSW-1 (6070AA-O and 6070AA-T4) | H13 | 166.37 | 137.95 | 18.28 |
| FSW-8 (6070AA-O and 6070AA-T4) | H13 | 178.78 | 139.78 | 15.22 |
| FSW-12 (6070AA-O and 6070AA-T6) | H13 | 158.84 | 131.32 | 17.02 |
| FSW-16 (6070AA-O and 6070AA-T6) | HCHCR-D2 | 166.39 | 139.58 | 19.22 |

The maximum values obtained from the tensile data are recorded from the following typical engineering stress-strain curves as shown in Figure 4 to 7.

![Figure 4. Force(N) Vs Stroke(mm) curve for FSW-1 (6070AA-O and 6070AA-T4) using H13 tool material](image)

![Figure 5. Force(N) Vs Stroke(mm) curve for FSW-5 (6070AA-O and 6070AA-T4) using HCHCR-D2 tool material](image)
Performance of H13 and HCHCR Tool Materials on Friction Stir Welded 6070 Aluminium Alloy Plates Subjected to Different Temper Conditions

Figure 6. Force(N) Vs Stroke(mm) curve for FSW-12 (6070AA-O and 6070AA-T6) using H13 tool material

Figure 7. Force(N) Vs Stroke(mm) curve for FSW-16 (6070AA-O and 6070AA-T6) using HCHCR-D2 tool material

B. Hardness-Distribution Test

The hardness-distribution was evaluated for all the welding experiments obtained from maximum tensile data using a Digital Vickers Hardness Tester. The hardness is determined by measuring the depth of indenter penetration. The shape of the tool indenter used in this testing machine is a diamond pyramid with a square base having an angle of 136 degrees. The load used to indent the weld-section is maintained as 1kgf with a dwell time of 10 seconds. The readings of hardness-distribution are carried out along the transverse cross-section of welded parts as shown in Table VIII.

Table VIII: Hardness-Distribution Data

| Welding experiments | Tool material | Hardness-distribution test data at NWZ (HV) | Average Hardness-distribution |
|---------------------|--------------|--------------------------------------------|-------------------------------|
|                     |              | Trail-1 | Trail-2 | Trail-3 |                           |
| FSW-1 (6070AA-O and T4) | H13         | 146     | 147     | 147     | 146.66                     |
| FSW-5 (6070AA-O and T4) | HCHCR-D2   | 149     | 147     | 147     | 147.66                     |
| FSW-12 (6070AA-O and T6) | H13        | 149     | 147     | 152     | 149.33                     |
| FSW-16 (6070AA-O and T6) | HCHCR-D2 | 146     | 152     | 147     | 148.33                     |

From Table VIII, the trail runs of Hardness-distribution data based on the welding speeds of two tool materials is shown in Figure 8. The maximum average hardness number from the plotted values are recorded as 147.66HV for 6070AA(O and T4) using HCHCR-D2 tool material and 149.33HV for 6070AA(O and T6) using H13 tool material. From the average hardness-distribution profiles of two welding stages, FSW-5 and FSW-12 experiments exhibits fine grain size at NWZ due to dynamic-recrystallization. Hardness and grain-size relationship at NWZ location is observed as per Hall-Petch effect.

Figure 8. Graphical plot of Hardness-distribution and Welding-speed

IV. OUTCOMES ON MICROSTRUCTURAL OBSERVATIONS OF WELD-JOINTS

A. Microstructural observations using Scanning Electron Microscope (SEM) study

In the present study, joining of 6070AA plates with different temper conditions (O, T4 and T6) are successfully produced. The weld samples are prepared for SEM study and observed for NWZ under a magnification of 250X as shown from Figure 9 to 12.

Figure 9. Microstructure of NWZ for 6070AA-O and T4 joining with H13 material
B. Microstructural observations using Energy Dispersive X-ray Spectroscopy (EDS) study

The results of EDS-study are recorded for obtained SEM profiles and studied about the elemental composition of principal alloying elements present in 6070AA at NWZ location. The EDS mappings provide a good source of information about the atomic structure of NWZ location as shown from Figure 13 to Figure 16.
The elemental composition of principal alloying elements at NWZ location for each welding stage is studied from the results of EDS-mappings as shown in Table IX.

**TABLE IX: EDS-STUDY ON SEM PROFILES**

| Welding experiments | Elemental composition of principal alloying elements at NWZ location |
|---------------------|---------------------------------------------------------------|
|                     | Atomic %           | Weight %            |
|                     | Al     | Mg     | Si     | Al     | Mg     | Si     |
| FSW-1 (6070AA-O and T4) | 90.48  | 1.14   | 8.39   | 0.58   | 0.01   | 0.06   |
| FSW-5 (6070AA-O and T4) | 97.28  | 0.72   | 1.99   | 0.41   | 0.00   | 0.01   |
| FSW-12 (6070AA-O and T6) | 91.54  | 0.49   | 7.97   | 1.43   | 0.01   | 0.13   |
| FSW-16 (6070AA-O and T6) | 86.98  | 0.00   | 13.02  | 0.05   | 0.00   | 0.01   |

V. CONCLUSIONS

Thick 6070AA plates with different temper conditions are successfully welded using H13 and HCHCR-D2 tool materials. Nugget-weld zone location is studied briefly for all possible weld conditions based on the mechanical properties and microstructural examinations.

The experiments are carried out in two stages with two different tool materials. Initially 6070AA plates are welded with O-temper condition and T4-temper condition using H13 and HCHCR-D2 tool materials. Similarly 6070AA plates are welded with O-temper condition and T6-temper condition using H13 and HCHCR-D2 tool materials.

The maximum tensile behaviour in first stage is observed for HCHCR-D2 tool material with 178.78Mpa UTS and 139.78Mpa YS. Similarly for second stage the maximum value is observed for same tool material with 166.39Mpa UTS and 139.58Mpa YS. The values of UTS and YS are increasing with increase in RS of tool.

The average hardness number at NWZ location is found to be more in second stage by H13 tool material than HCHCR-D2 tool material. This shows weld portions of H13 tool material has fine and small grain structures at NWZ location due to dynamic-recrystallization. These predictions conclude that HCHCR-D2 material has better tool performance than H13 material.

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