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STUDY OF FORMABILITY IMPROVEMENT USING DIFFERENT ANNEALING CYCLES IN INCREMENTAL SHEET FORMING OF AA6061 T6

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Abstract: The formability of AA6061 T6 aluminium alloy is essential due to its high strength and low ductility, posing challenges in forming processes like Incremental Sheet Forming (ISF). Annealing mitigates internal stresses, reduces material hardness, and enhances ductility, thus improving formability. This study investigates the impact of annealing cycles on the formability, microstructure, and micro-hardness of AA6061 T6 sheets during ISF. Various annealing durations (1-15 hours) were tested, followed by ISF experiments. Results demonstrate a significant formability increase with longer annealing, with nearly 40% higher fracture forming height. Micro-hardness decreases with a longer annealing duration (almost 30%), indicating material softening. Microstructural analysis reveals grain growth and recrystallisation, facilitating plastic deformation and enhancing formability. These findings provide insights into the role of annealing in improving formability and mechanical properties in ISF processes, aiding in identifying optimal annealing duration for enhanced performance.

Keywords: Incremental Sheet Forming, AA6061 T6, Annealing, Formability, Micro-hardness, Microstructure.

1. INTRODUCTION

The formability of AA6061 aluminium alloy is a significant concern due to its widespread use in various industries, including automotive, aerospace, and construction. Its excellent strength, corrosion resistance, and weldability make it a preferred material for structural components. However, the inherently low formability of AA6061 limits its ability to undergo complex shaping processes without cracking or failure, particularly in applications requiring intricate geometries or low-volume production. Incremental forming processes, such as Incremental Sheet Forming (ISF), offer a promising solution by allowing the gradual deformation of the material with localised forces, reducing the risk of fracture and enabling the production of complex shapes with minimal tooling requirements. Research in this area is crucial to develop optimised incremental forming techniques tailored specifically to AA6061 to enhance its formability.

Improving formability often involves microstructural modifications through specialised treatments. Wang et al. discussed the efficacy of partial hot rolling (PHR) to enhance the formability of welded joints in aluminium alloys[1]. Similarly, Bian et al. demonstrated the impact of small copper additions on the formability of magnesium-aluminum-calcium-manganese (Mg-Al-Ca-Mn) alloys. These studies highlight the significance of microstructural refinement in enhancing formability by influencing grain structure and strengthening mechanisms [2].

Heat treatment processes offer another avenue for enhancing formability. Xiao et al. investigated the combination of electromagnetic forming (EMF) with heat treatments to improve the formability of aluminium alloys [3]. Additionally, Fan et al. explored integrated heat treatment techniques in hot gas forming processes for Al–Cu–Li alloy, demonstrating the potential for improved formability and microstructural properties through precise heat treatment control [4].

Innovative processing techniques such as friction stir processing (FSP) have also enhanced formability. Lezaack et al. presented a method to increase the ductility of aluminium alloys using FSP, leading to refined grain structures and improved crack deviation behaviour, which is crucial for enhancing formability and crashworthiness [5]. Studies emphasise the importance of understanding the relationship between microstructure, mechanical properties, and formability. For instance, Jeon et al. investigated the influence of recrystallised grain sizes on the mechanical properties and bending formability of aluminium alloys, highlighting the role of grain refinement in improving formability [6].

Advances in heat treatment techniques, such as cryogenic treatment, have shown promise in enhancing the mechanical properties and formability of aluminium alloys. Vijayakumara et al. discussed the effects of cryogenic treatment on Titanium alloy (Ti6Al4V), showcasing the potential for structural changes to enhance formability

[7]. Research efforts have also explored optimising heat treatment parameters to restore formability after cold plastic deformation. Golovashchenko and Krause investigated the impact of heat treatment parameters on the formability of aluminium alloy 6111-T4, aiming to identify treatments that improve elongation and formability [8].

Moy et al. explored the impact of heat treatment on the microstructure, texture, and formability of 2024 aluminium alloy sheets, emphasising the role of ageing treatments in altering alloy properties to improve drawability and reduce earing tendencies [9]. Mohammadi et al. studied the effects of heat treatment conditions and warm forming on the formability and post-forming properties of AA2024-T3 aluminium alloy, highlighting the potential of Laser-Assisted Single Point Incremental Forming (LASPIF) as a method offering a balanced approach to formability, accuracy, and post-forming mechanical properties [10].

Lee et al. explored infrared (IR) local heat treatment on aluminium alloy AA5083, showing significant formability and energy efficiency improvements during automotive part forming [11]. The intermediate heat treatment technique reduced dislocation density, enhancing formability between forming stages. Practical application was demonstrated through the successful manufacturing of a commercial auto part. Similarly, Horikiri proposed strengthening the mechanical properties of semi-solid AA7075 aluminium alloys through various processing methods, including semi-solid casting and Equal-Channel Angular Pressing (ECAP) processing [12]. Subsequent ageing treatment after ECAP processing improved tensile strength and elongation, surpassing conventional wrought AA7075-T6.

Lin et al. introduced a modified two-step Strain-Induced Melt Activation (TS-SIMA) process to improve Al-Mg-Si aluminium alloys' high-temperature compressive resistance and mechanical properties. The TS-SIMA process enhanced formability and mechanical properties, significantly improving post-T6 heat treatment [13]. Bian et al. introduced a novel magnesium sheet alloy, Mg–1.1Al–0.3Ca–0.2Mn–0.3Zn, exhibiting excellent room temperature formability and heat-treatability. The alloy's superior formability and strength were attributed to the distribution of Guinier–Preston zones, influencing its mechanical properties significantly [14]. Chen et al. presented a method to simultaneously improve aluminium alloys' mechanical strength and formability for forming complex parts. This approach increased tensile stress, microhardness, and limiting drawing ratio, indicating enhanced formability and mechanical performance compared to conventional T6-treated alloys [15].

Increasing the formability of AA6061 aluminium alloy through different heat treatment processes, particularly annealing, is important for several reasons. Annealing involves heating the alloy to high temperatures and then slowly cooling it to modify its microstructure, reducing internal stresses and improving ductility. AA6061 is widely used in automotive and aerospace industries due to its excellent strength and corrosion resistance combination. It enhances formability through annealing, facilitating easier shaping and forming processes, reducing manufacturing costs, and improving component reliability. The present study aims to increase the formability of AA6061 T6 alloy by annealing the samples at elevated temperatures for different durations and studying its effect on the formability using the ISF process.

2. MATERIALS AND METHODOLOGY

AA6061 was selected as the base material owing to its extensive utilization across automotive, aerospace, and construction industries [16]. A series of trial experiments were conducted employing various process parameters at multiple levels, as shown in Table 1, through the ISF process to evaluate the forming depth for the base material. Subsequently, the combination yielding the poorest performance in terms of fracture forming depth of 7.02 mm in the trial experiments (Tool diameter = 6 mm, Spindle speed = 500 rpm, Step depth = 0.2 mm, Feed rate = 250 mm/min) was designated as the set parameters for assessing the impact of annealing on forming depth. The remaining operational parameters were constant, such as wall angle at 60°, tool path as spiral and tool profile as hemispherical. The forming experiments were performed on a 3-axes CNC milling machine (make: Batliboi, model: Dart 800), as shown in Figure 1. Each experiment was performed at least twice, and the average fracture-forming depth was reported. The chemical composition of the sheet material is shown in Table 2, while a tool of material Miranda S400 steel was used.

Sheets measuring $150 \times 150 \times 1\ mm$ were precisely cut and subjected to varying heat treatment durations at 210°C [18]. Usually, the annealing temperature ranges between 150° to 300°; however, at higher temperatures, the hardness of the material increases due to precipitation hardening [19]. The alteration in micro-hardness was measured utilising the Vicker's Hardness test at 0.3 Kg of load and 12 seconds of load time (make: Chennai Metco, model: Economet VH-1MDX). At least three readings were taken for micro-hardness measurement, and the average value was reported. Following this, the polished samples were etched for 30 seconds in Kellers etch solution comprising 1% HF, 1.5% HCl, and 2.5% Nitric acid, with the balance being distilled water [17]. Subsequently, changes in microstructure were examined utilising an optical microscope (make: Conation, model: Suxma – Met I).

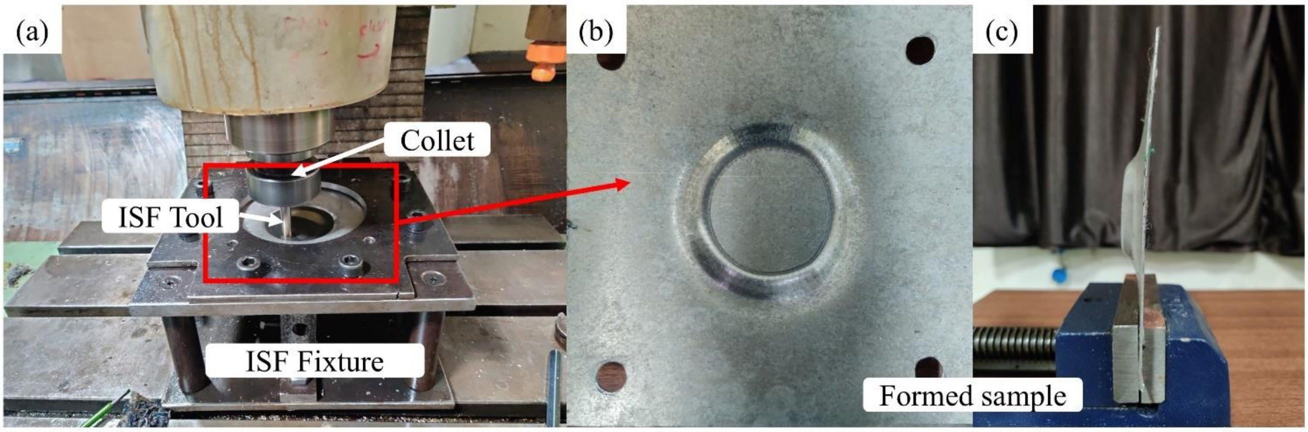

Fig. 1. (a) Incremental sheet forming set up, (b) Top view and (c) Side view of the formed sample

Table 1. Range of individual parameters for trial experiments

Parameter	Range
Tool diameter (mm)	6 – 14
Spindle Speed (rpm)	500 – 1400
Step depth (mm)	0.2 – 0.8
Feed rate (mm/min)	250 – 1250

Table 2. Chemical composition of the base material [17]

Material (%)	Mg	Si	Fe	Mn	Al
AA6061 T6	1.19	0.62	0.172	0.09	Balance

3. RESULTS AND DISCUSSION

The performance improvement of annealing cycles on the formability of the AA6061 T6 is evaluated in terms of fracture forming depth supported by micro-hardness and optical microscopy. The results of ISF experiments are summarised in the following Table 3 and are explained in the following subsections:

Table 3. Change in fracture forming depth and micro-hardness w.r.t. annealing durations

Annealing Duration (Hours)	Base material	1	3	5	7	10	12	15
Hardness (HV)	130.98	118.6	118.2	114.07	108.3	103.47	91.8	90.6
Fracture forming depth (mm)	7.02	7.49	7.5	7.78	8.46	8.43	9.62	9.81

3.1. Effect of Annealing on Micro-Hardness:

The observed microstructural changes induced by annealing have a direct impact on the hardness of the AA6061 T6 aluminium alloy, as seen in Table 3. The base material's microstructure appears uniform, with minimal visible grain boundaries. This uniformity contributes to the material's initial hardness of 130.967 HV, as shown in Figure 2. However, with increasing annealing duration, significant changes occur. Dark spots and localised areas start to appear, indicating the beginning of grain growth or phase separation, as seen in Figure 3. These structural changes reduce hardness as the material becomes more ductile and less resistant to plastic deformation.

The softer microstructure resulting from grain growth and phase separation contributes to the observed decrease in micro-hardness, with values decreasing to 90.6 HV after 15 hours of annealing, as seen in Table 3. Therefore, the evolution of the microstructure through annealing directly influences the material's hardness, with longer annealing durations resulting in softer material properties.

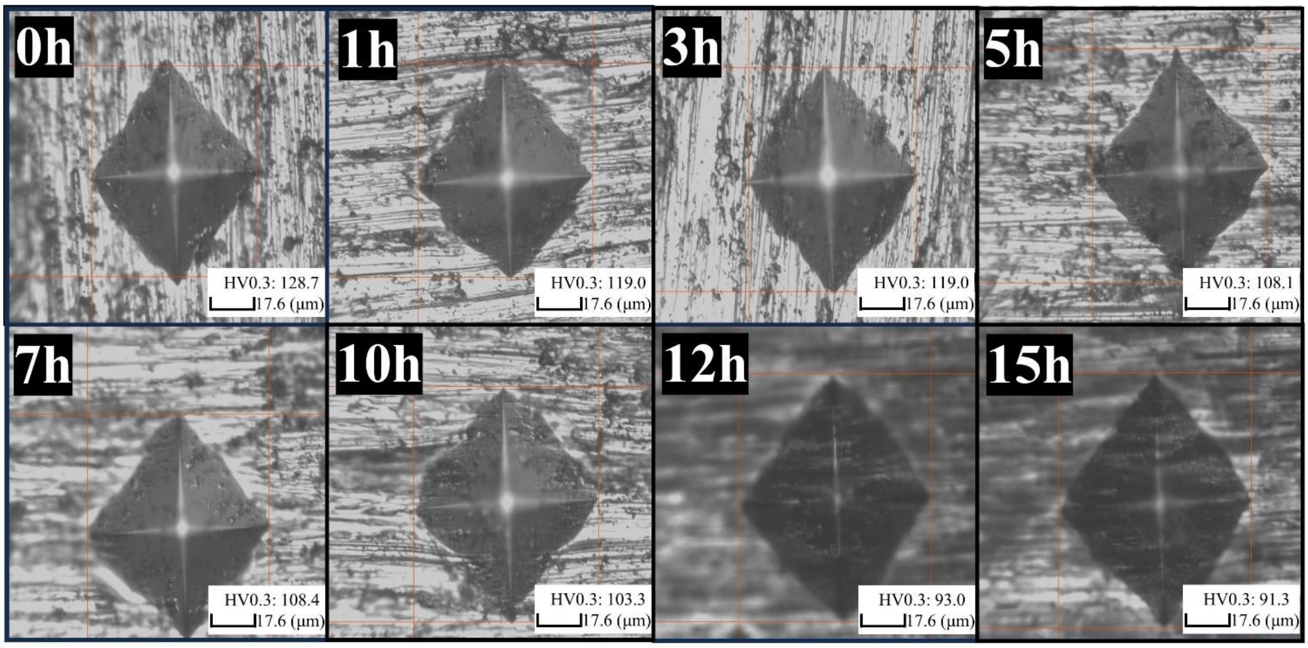

Fig. 2. Hardness value for different annealing duration

3.2 Effect of Annealing on Fracture Forming Depth:

The evolution of the microstructure induced by annealing also plays a crucial role in determining the fracture-forming depth of the AA6061 T6 aluminium alloy. Initially, for the base material, the uniform microstructure limits the material's ability to undergo significant plastic deformation before fracturing. As annealing progresses, microstructural changes become more pronounced, as shown in Figure 3, with dark spots indicating increased phase separation or precipitation of alloying elements.

These changes form distinct grain boundaries and phases within the material, enhancing its ductility and formability. The relief of internal stresses and the reduced dislocation density further enable the material to accommodate more strain before fracturing. Consequently, the fracture forming depth increases with increasing annealing duration, reaching a maximum of 9.811 mm after 15 hours with an improvement of close to 40%, as shown in Figure 4.

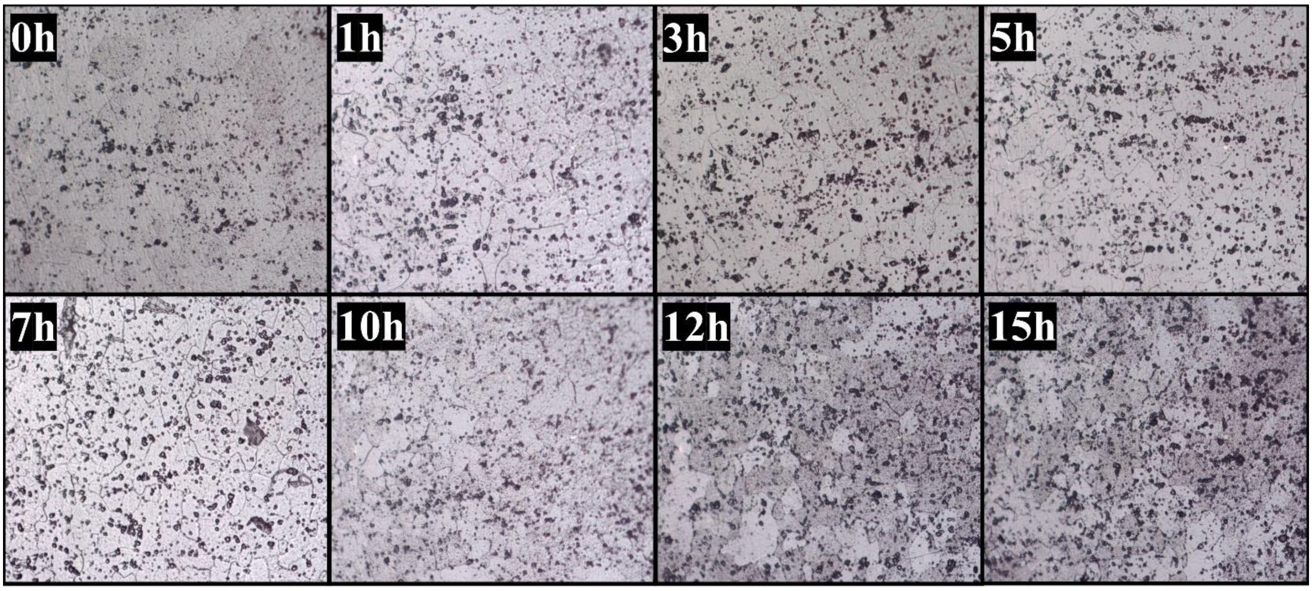

Fig. 3. Optical microscopic image of different annealing durations at 20x magnification

The sudden increase in forming depth and decrease in micro-hardness from 0 to 1 hour of annealing is justified by the increase in grain growth and the presence of Mg2Si precipitates, as seen in Figure 3. A similar sudden jump is also noticed at 12 hours of annealing, where the density of these dark spots increases, reducing the hardness and thus ultimately increasing the fracture forming depth.

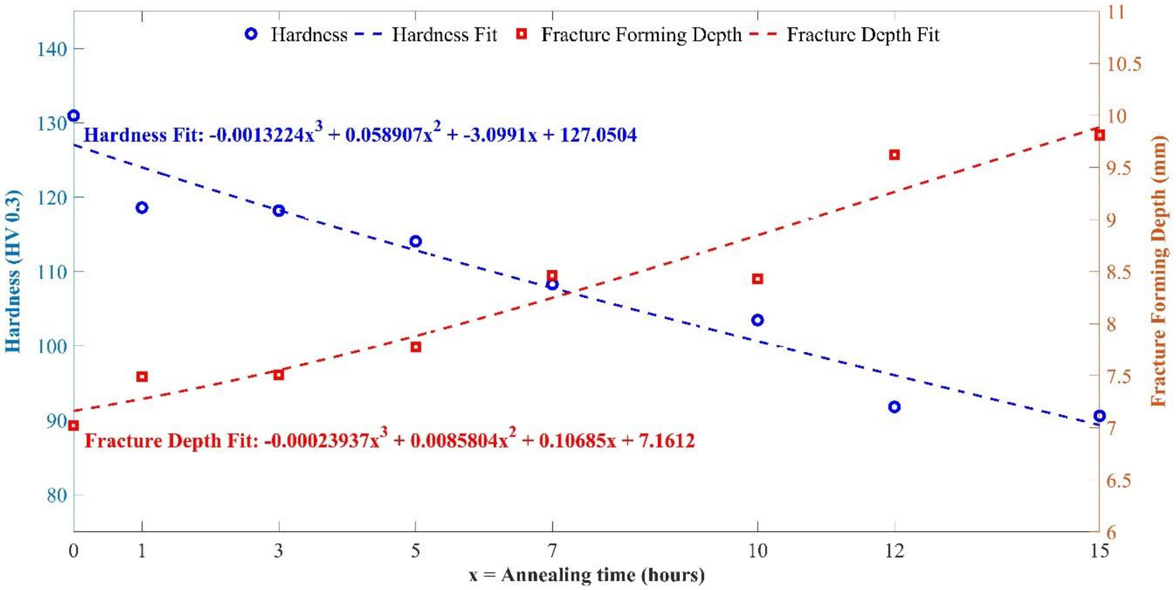

Fig. 4. Change in fracture forming depth and Micro hardness corresponding to annealing

3.3. Negligible Effect of Annealing Beyond 12 Hours

An intriguing observation is a negligible increment in fracture-forming depth from 12 to 15 hours of annealing. While increasing fracture forming depth with annealing duration holds up to 12 hours, the additional 3 hours of annealing yield minimal improvements. This is due to the softening effects induced by annealing approach saturation after 12 hours, with most internal stresses relieved and the material significantly softened. As a result, further annealing beyond this point may not yield substantial enhancements in formability. Additionally, the material may reach a state of microstructural equilibrium, where further annealing does not lead to significant grain growth or dislocation annihilation. This is evident from Figure 5. The microstructure at 12 hours and 15 hours shows similar grain size, shape and distribution, indicating the saturation of the annealing effect. The dark spots in the microstructural images consistently increase from the base material to the 12-hour annealed sample. However, after 12 to 15 hours, the density of these dark spots appears to be similar. These dark spots can be attributed to the Mg_2Si precipitates, which usually occur at 210°. These dark spots near the grain boundaries further solidify the possibility of the Mg2Si precipitates, as shown in Figure 5 [20].

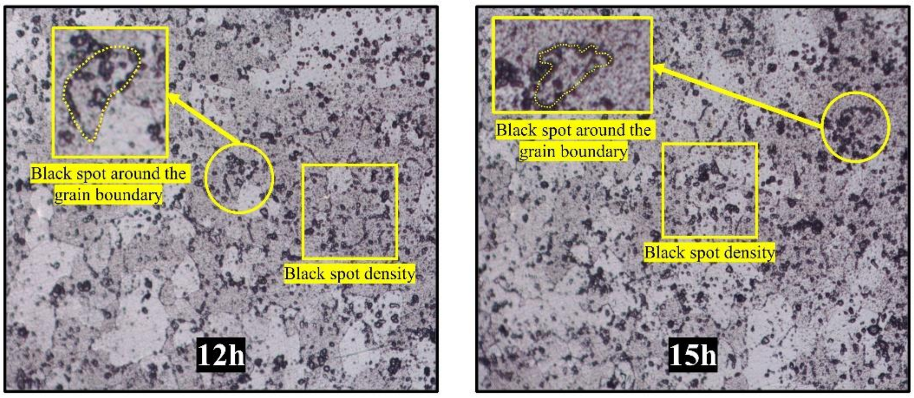

Fig. 5 Saturation of annealing effect at 15 hours

4. CONCLUSION

This article evaluates the effect of different annealing cycles on the formability, especially in the ISF process, for AA6061 T6 material. The following concussions have been drawn:

Annealing cycles significantly enhance the formability of AA6061 T6 aluminium alloy in Incremental Sheet Forming (ISF) processes. Longer annealing durations lead to softer microstructures, reduced material hardness, and increased ductility, resulting in nearly 40% higher fracture forming depth (refer to Table 3).

Microstructural analysis reveals grain growth and recrystallisation induced by annealing, facilitating plastic deformation and enhancing formability. However, beyond 12 hours of annealing, the incremental improvement in formability becomes negligible, suggesting a saturation point in the annealing effect (refer to Figure 3).

These findings provide valuable insights into optimizing annealing parameters for improved formability and mechanical properties in ISF processes, aiding in developing more efficient and reliable manufacturing techniques for AA6061 T6 aluminium alloy components in various industries.

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