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Metallurgical Microstructure Evolution of Friction Drilling with Al6061-T6 at Various Regions of Bushing Formation

N. Srilatha* **and Balla Srinivasa Prasad**

Department of Mechanical Engineering, VNR VJIET, Hyderabad - 500090, Telangana, India; srilatha.nimmagadda321@gmail.com
Department of Mechanical Engineering, GITAM, Visakhapatnam - 530045 - Andhra Pradesh, India

Abstract

Friction drilling is one of the non-conventional holes making process, it is a clean and chip-less operation which uses the frictional heat to create the hole on base materials. In any kind operations like machining of metal and mining of fuels the microstructure is composed with its various phases of size, variable form, and distribution (dendrites, grains, lamellae, precipitates, spherulites, pores, etc). Friction stir drilling technology is specifically designed for mining operations. The improved microstructure of the drilled holes ensures better load distribution and resistance to wear and tear. This translates into longer tool life, increased operational efficiency, and ultimately higher profitability for mining companies. The microstructure of metals plays a crucial role in the mining industry, primarily in two main aspects- extraction and processing of ores. In this microstructure of friction drilling hole of brittle cast materials like Al6061-T6, has been investigate with the help of optical microscope at various regions like Stirring Zone (SZ), Thermo Mechanical Affected Zone (TMAZ)and Heat Affected Zone (HAZ). Those zones are divided based on tool contact with work piece. It is observed that Al and Si particles are recrystallized structure. Due to thermal energy and forces acting on the material drilled hole contains few adhered at walls. At when compared with the HZA and TMAZ, SZ zone contains smaller mean particles are observed.

Keywords: *Friction Stir Drilling, Microstructure, Mining Industry, Optical Microscope, Thermal Forces*

1.0 Introduction

In industries thin-walled metals are joined usually with bolted joints or welded joints. Generally melting occurred at welding of small thickness profiles relatively compared with other materials[1]. In some industrial applications body structures need good corrosion resistance at the same time high temperature melting or only corrosion resistance at same place with more strength. joining of plastic and metal in automobile industries has become research key, here multiple factors to be consider while joining of dissimilar materials such as potential for corrosion and galvanic coupling in service, formation of inter-metallic consolidation during joining may leads to brittle, cooling rate and heating effects on microstructure of brittle joint, the effects on joining stresses during constraints and fixtures, temperature differences during melting, the above all factors may affects its precision and heat input. Several joining processes are grouped in various categories like adhesive bonding, soldering, and brazing, arc-welding solid-state process and various mechanical joints like fasteners, rivets, and bolts[2]. Researchers are introduced new technique to solve all those problems is called non-conventional drilling process is known as Friction Drilling. Friction drilling is one of the alternative methods to create hole in pipes, thin-walled sheets, and sheet

*Author for correspondence

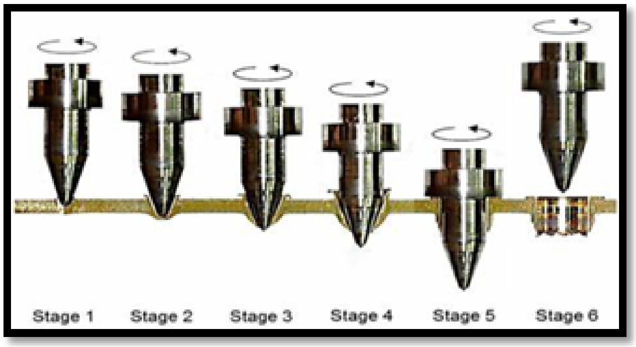

Figure 1. Process of friction drilling.

metals using heat at minimal melting stage of materials. In friction drilling process friction was generated in between workpiece and tool, in the place of drilling operation plastic deformation occurred due to increase in frictional heat[3,4]. When the plastic deformation occurred material is displaced above and below the work piece to form the busing, the length of the hole is significantly extended and formed threaded length. The material which cuts from the hole as donates to create bushing. Due to strain and high temperature microstructure and properties of the material was occurred. Deformed Zone of work material occurred during friction drilling process which will not appear in traditional drilling process. These deformed zone gives the geometry of production next step such as joining process[5,6]. Figure 1 shows sematic representation of friction drilling process. During the friction drilling process is chip less process and there is no wastage in material and no requirement of coolant lubricants, so this process is called green manufacturing process and dry machining. Following figure shows the steps involved in friction drilling process[7]. With the help of this process thread length, stability and safety, complexity, and cycle time such type of problems can be overcome[8].

There is no cutting edge for friction drilling tool, based on geometrical model of the tool has been divided into five stages, canter region, conical region, cylindrical region, shoulder region, and shank region. Plastic deformation of the work material is formed in friction drilling process because of its high-speed tool, it extrudes material above and below of work piece and gradual increment of feeds, whereas extruded material below work material is called petal and above material is called Collar formation. Lastly the work material is penetrated to create hole[9,10]. This process is suitable to almost all drill sizes, and quick process, it will not create any environmental effect. It's a chip less process because of this no chip process it could be increased quality of hole surface and life of tool, at the same time machining time and cost will be decreases[11,12].

1.1 Force Model of Friction Drilling

In this machining process changes in tool geometry may occurred due to increase in feed rate and temperature between tool and work material. In this work piece pressure P is almost all equal to yield strength. When developing of friction drilling model majorly considering two parameters i.e., pressure (p) and friction coefficient (μ). In friction drilling process more temperature has generated, that will influence the yield strength of work material. When yield strength influenced with temperature, which will influence friction coefficient.

Here there is two contact surfaces involved of tool in friction drilling. i.e. cylindrical region and conical region. So that force models can be written for both the surfaces[9,13].

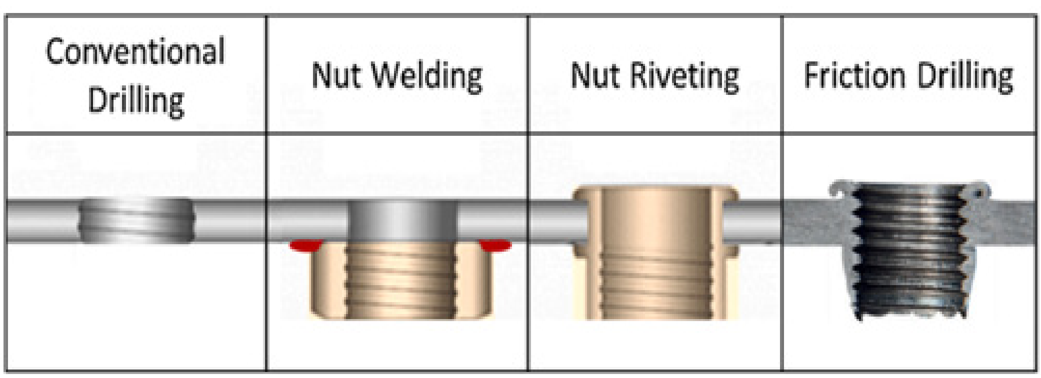

Figure 2. Compression of friction drilling and conventional joints[8].

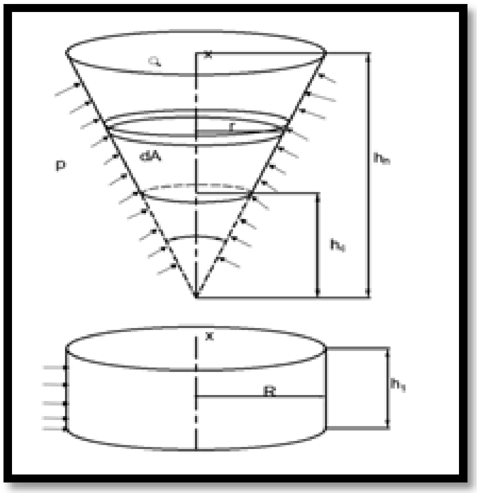

Figure 3. Contact areas of tool with work piece.

From Figure 3. Force model for conical region can be written for Torque (T) and axial Force (F)[13].

$$F = \pi p tan^2(\theta/_2)(h_n^2 - h_c^2) + 2\pi\mu p\frac{v}{\omega}\cos(\theta/_2)\,(h_n - h_c) \quad (1)$$

Here is distance from second contact edge of tool, and is distance from first contact edge of tool, is included angle of conical region, angular velocity [13].

$$T = \pi\mu\rho^{\,2\tan(\theta/_2)}\Big/_{\cos(\theta/_2)} \cdot (h_n^3 - h_c^3) - v^2/_{\omega^2}\,\pi\mu p\cos(\theta/_2)\,(h_n - h_c) \quad (2)$$

Force model for cylindrical region can be written for Torque (T) and Axial Force (F).

$$F = 2\pi R h_l \mu p sin\gamma = 2\pi R h_l \mu p v \Big/ \sqrt{v^2 + \omega^2 R^2} \quad (3)$$

Here is height of contact, R is cylindrical radius

$$T = 2\pi R^2 h_l \mu p cos\gamma = 2\pi R^3 h_l \mu p \omega \Big/ \sqrt{v^2 \omega^2 R^2} \quad (4)$$

1.2 Rotational Speed Effects

Surface roughness, bushing length, microhardness, roundness, and microstructure are the some of characteristics which will be affected by rotational speed and feed in friction drilling of Aluminium alloy were discussed.

2.0 Experimental Setup

2.1 Material

In friction drilling process tool will play a major role to process performance and form the bushing, so geometry of the tool is important in friction drilling. For this experiment tool is modeled and manufactured by us. In this process two materials are used to fabricate the tool, i.e., HSS and Tungsten materials with 8mm diameter and conical region height as 6.6mm were used and the work material is Aluminium Alloy with thickness of 3mm.

Figure 4. Experimental Setup for friction drilling.

2.2 Drilling Parameters

A CNC mill with adaptive control system machine was used for friction drilling experimentation, Constant force could be used throughout the experiment using adaptive control system which will be maximum peck force were consider, by maintaining the constant force will helps to improve quality of bushing. The rotational speeds 495, 795, 1250 and 1980 rpm respectively. Al having high thermal conductivity, for this maximum amount of frictional heat is shifted into work material and due to low temperature

(a)

(b)

Figure 5. **(a).** Cross section view of friction drilling hole with WC tool. **(b).** Cross section view of friction drilling hole with HSS tool.

insufficient softening and increase in ductility. That causes high force and improving bushing shape. Because of these effects dictated the chosen of rotational speed and feed for al alloy[14,15].

3.0 Microstructure Observation at Inside the Friction Drilling Hole

Generally, microstructure of materials is dependent not only the structure and chemical composition but it also the presence of concentration gradients and atomic mobility during the process. Formation of microstructure is also influenced strongly the amount of force required (energy) to form the new interface. Appropriate heat-treatments such as annealing, and quenching, can form the great variety of microstructures. In case of alloys, and metals, heat-treatments combined with some of the mechanical properties like rolling has reached at very high level of sophistication in order to control the microstructure. The microstructure of metals plays a crucial role in the mining industry, primarily in two main aspects – extraction and processing of ores.

Extraction of Ores: Metals are typically found in ores, which are mineral deposits containing valuable elements. The microstructure of metals helps determine the extraction techniques and efficiency. For example, if a metal ore has a fine-grained microstructure, it would have a higher surface area, making it easier for chemical reactions to occur during leaching or solvent extraction processes. On the other hand, if the microstructure is coarse-grained, it might require crushing, grinding, drilling and additional energy-intensive processes to increase its surface area, thereby affecting the overall energy consumption and extraction costs.

Processing of Ores: After the extraction of metals from ores, further processing is required to purify and transform them into useful products. The microstructure significantly affects the mechanical and physical properties of metals, such as strength, hardness, ductility, and conductivity. The power of enhanced hole microstructure will improve productivity and cost-effectiveness in the mining industry. Understanding these properties is crucial for selecting appropriate processing techniques, like smelting, refining, casting, and forging. Furthermore, the microstructure can also impact the behavior of metals during heat treatments, such as annealing, quenching, or tempering, which are often employed to enhance their properties. These heat treatments modify the microstructure, leading to changes in the material's strength, toughness, and other characteristics. By considering the microstructure of metals, the mining industry can optimize the extraction and processing techniques, resulting in improved efficiency, reduced energy consumption, and enhanced product quality. Additionally, by studying the microstructure, mining companies can better understand the behavior of metals under different conditions, leading to innovation and development of new alloys or materials that can withstand the harsh environments often encountered in mining operations. Ultimately, a thorough understanding of the microstructure of metals enables better utilization and beneficiation of ore resources in the mining industry. Figure 5 represents the cross-sectional view of the friction drilled holes generated by Al 6061-T6 alloy at various tool materials, rotational speeds, and feed rates with 3mm thickness. In this inner surface of the bushing formation various regions are observed. Based on this material flow will be analysed in friction drilling process which simulates the properties of a hot extruded objects. These bushing lengths are divided into various regions in

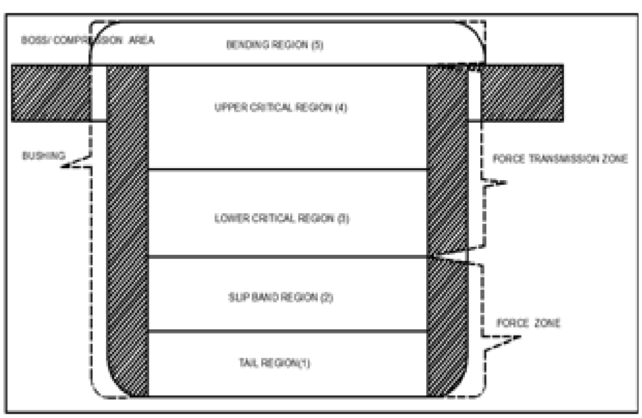

Figure 6. Various region in friction drilling hole.

Aluminium alloy is shown in Figure 6. In this each region represents with numbers, first region is '1' indicates tail region, second region '2' indicates slip bands region, third region '3' indicates lower critical region, fourth region '4' indicates upper critical region and fifth region '5' indicates bending region. Hear region 1 and 2 comes under Heat affected Zone (HZ), 3 and 4 regions come under Thermos Mechanically Affected Zone (TMAZ) and region 5 comes under Stirring Zone (SZ)[16].

To analyse the material flow and metallurgical structure of the friction drilling of base work material, cross section of drilled holes is prepared, after that emery polishing is done with the help of emery papers with different grades and after that Acetone solution is used on the material to get mirror surface for effective analyzation of the microstructure of material. In this optical microscope is used to test the friction drilled holes at 100X magnification.

Based on the microstructural analyzation of the work piece behavioral changes in the element's defects and cracks are identified. Figure 7 represents the microstructural changes in the Al 6061-T6 at various regions[17].

The inner surface of the friction drilling hole microstructure is observed. It is identified that delaminating and plastic deformation of the surface occurred. The second thing ejection of work material from friction drilling tool also noticed through this analysis, and moreover when heat generation increase with increase of rotational speed and feed at different levels adhering tendency also occurred for aluminium material to tool. Adhesion of tool occurred because of temperature and tedious pressure generated by friction drilling process to work material is higher because cohesive force is less when compared to bonding energy.

4.0 Results and Discussion

The bush formation is initiated when move out centre section of friction drill to the work material. Figure 7(a) represents that microstructural analysis at tail region. In this region there is less contact between tool and work piece, due to this low heat affected zone occurred. In this process there is a continuous forward rotating movement of tool conical section starts after finishing of centre region of tool, due to this thermos mechanical forced action work material becomes softened to form conical cavity at

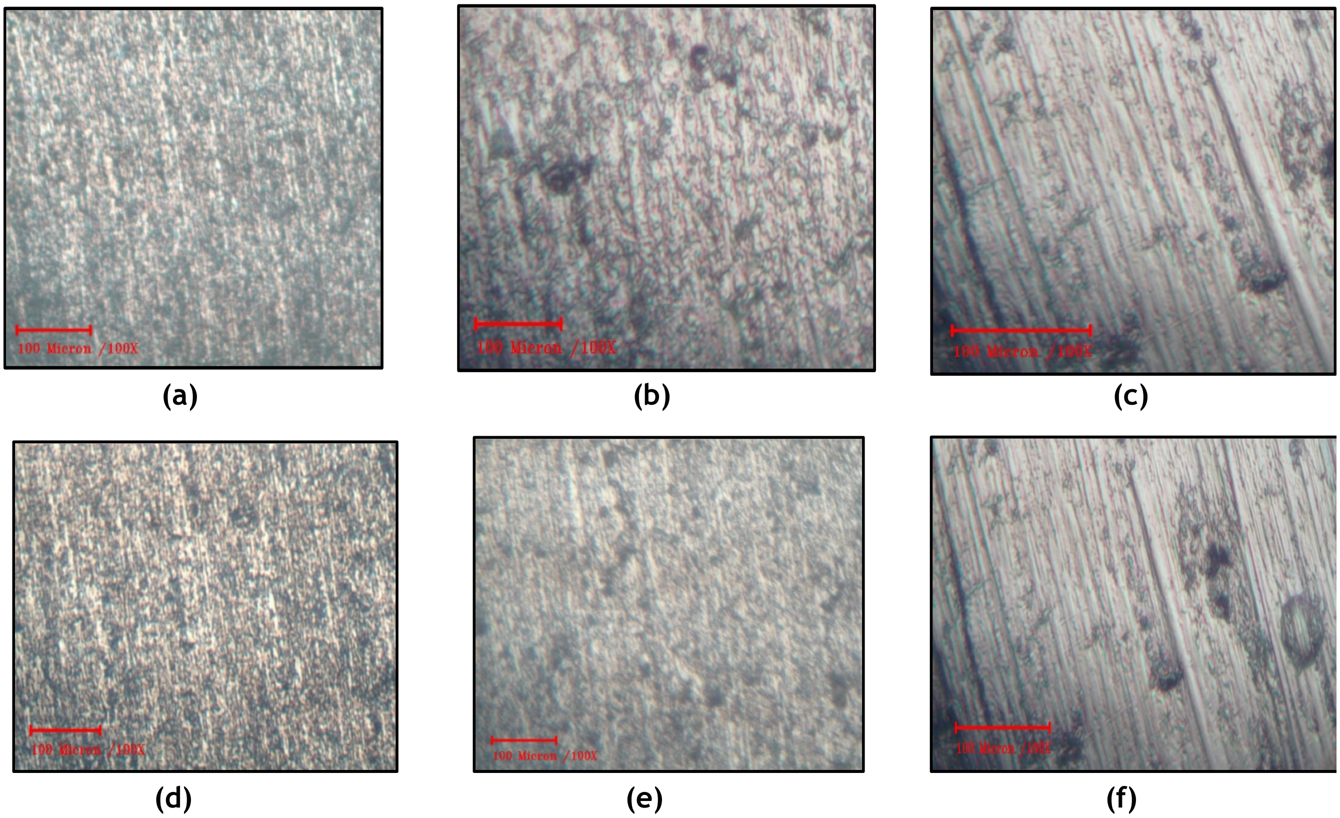

Figure 7. **(a, b, c, d, and e)** Microstructural representation of friction drilling hole at different regions. **(f)** Hole inside surface in the Al 6061-T6 sheet represents plastic deformation, abrasion, and delaminating.

bottom side and some amount of material transferred in top side of material.

Figure 7(b) represents the microstructural analysis of slip band region. Due to occasionally heterogeneous yielding and more frictional heat strain marks wear generated in this region. Hear detached bands of damaged Al alloy sheet are observed. So that this band is called as slip bands which are generally occurred in stamping and drawing operations. When compared with the other three regions the first two regions i.e., tail and slip band regions will create more axial force with maximum rotational speed.

Microstructural representation of lower critical region is shows at Figure 7(c). In this tool passes from conical region to cylindrical region, it enlarges the conical cavity leads to form bushing shape. In this stage axial force is converted into transmission force. Due to this there are drastic changes in grain structure and low strain marks occurred. Figure 7(d) and 7(e) represents the microstructural representation of upper critical and bending region. In upper and bending regions tool pass cylindrical region to shoulder region to level the final shape or extended burr material.

Formability is calculated in terms of bushing height[18,19] this is one of the indirect techniques in production technology. Whereas petal height is proportional to formability. Petal height is measured by using Mitutoyo Digital Vernier Caliper for each experiment as shown in Figure 5(a) and (b). In friction drilling process when low speed is applied maximum petal height wear obtained and similarly petal height is low when moderate speeds are used. Figure 7(f). Represent the microstructure of al 6061-T6 alloy after of friction drilling operation. This indicates that inter dendrites of aluminium and eutectic mixture of silicon are presented. After friction drilling of al 6061-T6 alloy changes in the microstructure is obtained that represents that Al elements leads to recrystallization to improve grain growth tendency and it reveals that dendrites network structure of Al and Si due to impurities while casting.

5.0 Conclusions

In this work Al6061 alloy work material is used to perform friction drilling operation with the help of CNC milling machine with Adaptive control system is used. Friction stir drilling technology is specifically designed for mining operations. The improved microstructure of the drilled holes ensures better load distribution and resistance to wear and tear. This translates into longer tool life, increased operational efficiency, and ultimately higher profitability for mining companies. The power of enhanced hole microstructure will improve productivity and cost-effectiveness in the mining industry. In any kind operations like machining of metal and mining of fuels the microstructure is composed with its various phases of size, variable form, and distribution (dendrites, grains, lamellae, precipitates, spherulites, pores, etc.) when two materials are interacted with each other (metal with fuels or two materials) phase changes of material may occurred. These are distinguished from each other by various semi-crystalline or amorphous, crystalline structures which are observed with electron microscope or optical. The microstructure of friction drilling hole at various regions are observed at different speed, feed rates and tool material and diameters are observed. Microstructure of work material was observed with the help of optical microscope.

- Microstructure at tail region demonstrates that there is due to low friction contact in between the tool and work piece low heat is produced.
- Due to forward movement of tool by thermos-mechanical phenomenon to soften the work material at slip band region.
- Stretched strain marks are produced by high friction heat. Because tool transferred from centre region to conical region. In this time heterogeneous yielding and deformation of work material was generated.
- In the lower and upper critical regions lower stretcher- strain marks are observed.
- In the shoulder part of tool gives forging force it acts in downward direction over extended burr.
- More formability is occurred at high heat generation to make higher material flow it leads to high petal formation.
- Stronger grain orientation was observed in friction drilling when compared with twist drill.

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