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Study of friction stir processing (FSP) and high pressure torsion (HPT) and their effect on mechanical properties

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Abstract

Production of Bulk Nano-structured Materials (BNM) using Severe Plastic Deformation (SPD) is currently being pursued by researchers all around the world. Recently FSP has gained prominence on account of its ability to create BNM in the processed specimen. In the present study an improvised Vertical Milling Machine is designed that can perform FSP on thin metallic sheets. Al6061 sheets of 2mm thick are subjected to FSP and its effect on microstructure is studied. It is observed that very fine grains are formed in these sheets. Further effect of FSP on hardness is studied with the help of micro hardness tester. It is found that the hardness has increased by 50% on the processed AL6061 sheets on account of FSP. The study clearly brings out the advantage of severe plastic deformation caused on account of FSP and HPT and is a step forward in developing Bulk Nano-structured Materials (BNM) materials in future. Another important SPD process is High Pressure Torsion (HPT). In this work Finite element (FE) modeling of HPT of a circular disc of commercially pure aluminum (Al99) is also attempted to illustrate the advantage using FEM in evaluating equivalent strain and hardness numerically prior to experimentation.

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Keywords: SPD, FSW, HPT, BNM, FEM

1. Bulk Nanostructured Materials (BNM)

Bulk Nano-structured Materials (BNM) are defined as solids with nano-scale (typically 1-1000 nm) substructures. The processing of metals has a long history dating back to 300 BC. The legendary steel from Ancient India, known as “Wootz Steel” is characterized by a pattern of bands or sheets of micro carbides within a tempered martensite or pearlite matrix. It is believed that Damascus blades were forged directly from small cakes of Wootz Steel. Reibold et al. [1] have used high-resolution transmission electron

microscopy to examine a sample of Damascus sabre steel from the seventeenth century and found that it contains carbon nano-tubes as well as cementite nano-wires. The first work reported in modern times on SPD is credited to P. W. Bridgman who proposed High Pressure Torsion [2]. Since then many different SPD processes are discovered and analyzed. Last century, BNM have been the subjects of intensive research due to their superior physical and mechanical properties [3-5]. These include a combination of high strength and ductility at room temperature, high strain rate and low temperature super-plasticity. These superior mechanical and physical properties make BNM attractive for numerous advanced applications in medical, aerospace, sporting goods, and transportation industries. Various methods for producing BNM have been developed, which, based on their approaches, can be classified into two categories. The first is the "bottom up" approach, which builds materials atom by atom. Methods in this category include inert gas condensation [3], high-energy ball milling [6], spray conversion processing [7], sputtering [8], physical vapor deposition [9], chemical vapour deposition [10], and electrodeposited nano-crystals [11]. So far, only penny-sized BNM have been produced, which are too small for any structural applications. Other problems with powder consolidation methods include high cost, contamination, and porosity. The second approach for producing BNM is the "top down" approach, which refines coarse-grained metals through severe plastic deformation (SPD).

2. Severe Plastic Deformation (SPD)

Severe plastic deformation (SPD) is a generic term describing a group of metal-working techniques involving very large strains which are imposed without introducing any significant changes in the overall dimensions of the specimen or work-piece. Processing by SPD provides the opportunity to achieve remarkable grain refinement in bulk crystalline solids. Typically, materials processed by SPD have grain size in sub micrometer and nano-meter range [12–15]. Number of SPD techniques are available for producing UFG [18] material like Equal Channel Angular Pressing (ECAP) [19], Accumulative Roll Bonding (ARB) [16], Repetitive Corrugation and Straightening (RCS) [17] and High Pressure Torsion (HPT) [20].

In the present study an improvised Vertical Milling Machine is developed that can perform FSP on thin metallic sheets. AL6061 sheets of 2mm thick are subjected to FSP and its effect on microstructure and hardness are studied. It is found that the hardness is increased by 50% on the processed AL6061 sheets on account of FSP.

The basic principle of FSP in the present research is schematically illustrated in Fig. 1. Cold-rolled plates of aluminium alloy (AL6061) are used as starting materials (work pieces).

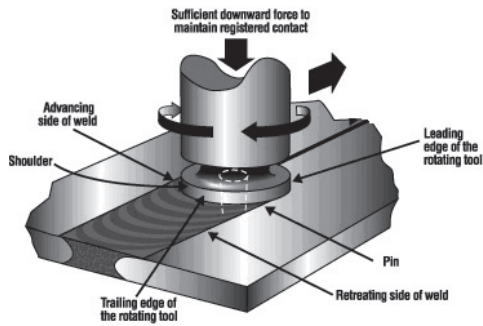


Fig. 1 Friction Stir Processing

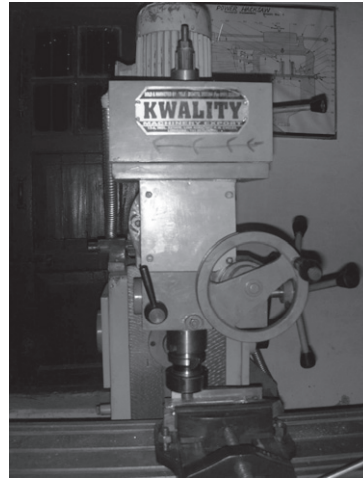


Fig. 2 Friction Stir Processing Machine Setup

In the process shown in Fig. 1, a cylindrical rod rotating at high speed (probe) is inserted into the plate to be processed. The friction of the tool on the part softens the material, which turns into a paste and is stirred. The shoulder that is pressed with a large force on the plates prevents the stirred metal from being expelled and produces a forging effect at the back of the material that was just softened out of shape and stirred. There have been widespread benefits resulting from the application of FSP for example in aerospace, shipbuilding, automotive and railway industries. The benefits of FSP are:

3. Experimentation of FSP with Improvised Vertical Milling Machine

An improvised Vertical Milling Machine (VMM) as shown in fig. 2 is developed modifying VMM with a 3phase 1HP motor with rpm range of 550 to 950 and feed range of 10 to 80 mm/min with “Mild Steel Tool” for doing the FSP experiments. Initially one 77mm long, 34mm broad and 2mm thick aluminium alloy (Al6061) piece is processed using the indigenous setup shown in fig. 2.

Fig. 3 shows the grain structure before the friction stir process of the AL6061 plates. It is explicit that the structure is coarse and unrefined. The grain size of this unprocessed material is found to be in the range of 10 μm . The standard hardness of AL6061 is 95 BHN.



Fig. 3 Grain structure before FSP of rolled AL6061

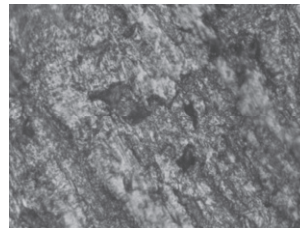


Fig. 4 Grain structure of AL6061 plate after FSP

Fig. 4 shows the grain structure after the FSP of the AL6061 plates. The grain size and the microstructure is in the range of 1 μm . This shows a considerable reduction of the grain size. The hardness after the FSP was found to be in the range of 140 BHN, which clearly indicates an increment of about 50% in hardness in pressed material.

4. Results of FSP

The microstructure of friction stir processed Al6061 plate shows the effect of stirring and formation of smaller grains. The observations by computerized microscope revealed the grain size of processed plate to be approximately 1 μm . The average Brinell-hardness is observed with micro-hardness tester. An increase of 50% is observed in Brinell Hardness Number (BHN) value. This clearly depicts the advantage of FSP on Al6061. The equivalent strain is also a measure of strength of the material and it can be inferred that the hardness and yield strength of AL6061 plates have increased on account of FSP.

5. High Pressure Torsion (HPT)

HPT is a useful process for the investigation of cumulative strain, applied pressure, and rotational speed on the structure and properties of the material concerned. HPT can also be used for the consolidation of nano-structured powders, such as cryomilled Al-7.5wt. % Mg, structure [21]. As pure aluminium has less strength and alloying elements are added to improve their properties of strength, hardness in industries. However the result is loss of some useful properties like conductivity. HPT inducts high strength in pure metals without using alloying elements and hence it is preferred over others. SPD by HPT involves deformation of discs by pure shear between two anvils in which one anvil rotates against the other anvil holding the material as shown in Fig. (5). This method is limited to small discs. The deformation induced during HPT is non uniform from the centre to the outside diameter [22, 23]. In this work a coin-shaped sample is pressed between two anvils under hydrostatic pressure. During the build-up of the pressure, the sample is pressed into the cavities in the anvil and a burr is formed at the edge of the sample. Then one anvil is rotated with respect to the other and the rotation speed can be varied over a large range. This leads to a deformation of the sample by almost simple shear. The equivalent von Mises strain ϵ_{eq} as a function of the number of turns N is then given by equation-1.

$$\epsilon_{eq} = \frac{tg\gamma}{\sqrt{3}} \quad \dots\dots\dots (1)$$

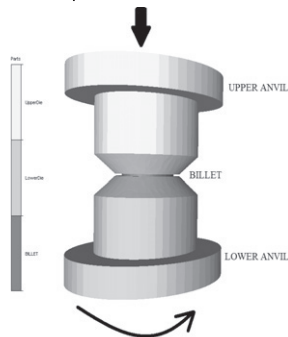


Fig 5: Schematic setup of HPT process used for FE modelling.

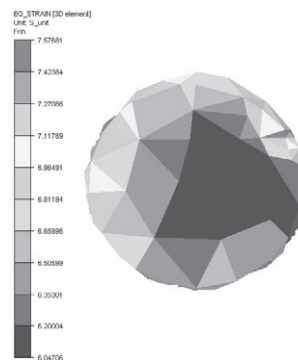


Fig:6: Iso-contour of Equivalent strain in billet after 5 rotation

The shear strain of disk subjected to HPT, γ , can be calculated by using equation 2.

$$\gamma = \frac{2\pi Nr}{h} \quad \dots\dots\dots (2)$$

Where N is the number of rotations, r is the radial distance of site of micro hardness measurement from the centre of the sample and h is the thickness of disk.

6. Finite element modeling of HPT

Pure aluminum (Al99) was selected for this investigation. For FE simulation pure aluminum disk shaped billet sample is taken with 0.8 mm thickness and 10mm diameter. Upper anvil is stationary and lower anvil rotates with a speed of 5 RPM in an anti-clock wise direction and simultaneously billet is pressed hydraulically. Here a cast disc sample is taken as an initial billet. Process parameters used for modeling HPT process are mentioned below: Anvil feed (mm/sec) - 0.66 mm/sec, Lower anvil rotation - 5 rpm, Billet thickness - 0.8 mm, Billet diameter - 10 mm, Running time - 60 sec, Rotation direction - Anti clock wise, Billet material - Al99 (pure aluminum), Initial equivalent strain in billet – 0, Initial temperature of billet - 20°C, Lubrication - Grease MoS2. Figure 6 depicts the equivalent strain contours at the end of the fifth rotation of anvil. The maximum equivalent strain observed is 6.68. The maximum pressure observed is 86 MPa. The various results observed during the current FE simulation are shown in table 1. Average Equivalent strain generated in each turn of HPT Vs estimated Vickers Hardness (running time 60 sec) is plotted in figure 7.

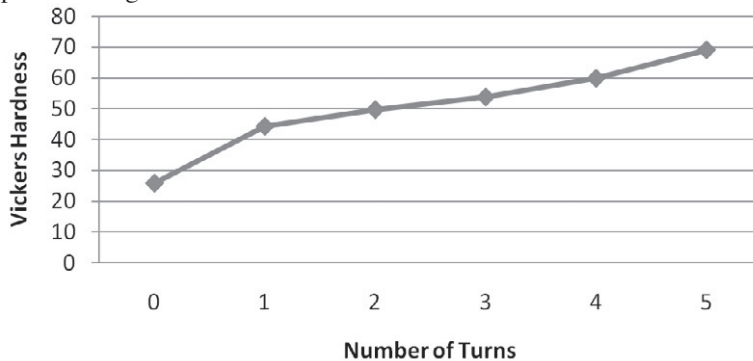


Figure 7: Number of turns Vs Estimated Vickers Hardness based on equivalent strain of HPT specimen.

Table 1: FE simulation results of HPT process using Aluminum disc

Running time	60 sec
Anvil feed (mm/sec)	0.0033 (mm/sec)
Billet material	Al99
RPM	5
Billet thickness	0.8 mm
Equivalent strain	6.68
Temperature	545°C
Pressure	84 MPa

Table 2: The evolution of average equivalent strain and estimated Vickers hardness with number of rotations of tool on HPT specimen.

Number of turns	Average Equivalent Strain	Estimated Vickers hardness
0	0	24
1	0.95	44
2	1.91	49.84
3	2.88	53.90
4	4.23	60
5	6.68	69.19

7. CONCLUSION

Mechanical properties of materials largely depend on the microstructure of processed material. Two approaches are suggested here to study the change in microstructure and its effect on hardness of processed aluminium and its alloy: a. Experimental and b. Finite Element Modelling, by taking two processes of severe plastic deformation i.e. FSP and HPT. In the present study an improvised Vertical Milling Machine is indigenously developed that can perform FSP on thin metallic sheets. Al6061 sheets

of 2mm thick subjected to FSP and its effect on microstructure is studied. It is observed that coarse grains were transformed into very fine grains in these sheets and the hardness has increased by 50% on the processed sheets. The study clearly brings out the advantage of FSP. Another process studied with second approach is High Pressure Torsion (HPT). As observed in the results the equivalent strain has gone up to 6.68. Higher equivalent strain is the pointer for the higher yield strength, higher hardness on account of ultra fine grains in the aluminium disc. The estimated Vickers hardness is found to have increased from 24 to 69. The FE simulation study provides new insights into the HPT process and its effectiveness in developing nano grained pure aluminium alloys for various applications. Both approaches are quite useful in development of BNM in future.

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