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Analysis of the reciprocal wear testing of Aluminum AA1050 processed by a novel mechanical nanostructuring technique

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Abstract. This research aims to investigate the impact of a novel technique in mechanical nanostructuring on the wear resistance of materials. This technique with the name of High Pressure Torsion Extrusion (HPTE) can produce bulk nanostructured materials with enhanced mechanical properties. Results of microstructural analysis and microhardness testing showed significant enhancement in materials after HPTE. Microstructural characterization by using Electron Back-Scattered Diffraction (EBSD) method illustrated the presence of Ultra-Fine Grained (UFG) materials in the specimens Analysis of the wear by implementing reciprocal wear testing revealed that the amount of displaced volume markedly decreased after processing. This change in the wear behavior can be explained by referring to the hardness increase and the reduction of plasticity in materials which confined the plastic shearing and diminished the built-up edge around the wear track.

1. Introduction

The scientific study of wear and tribology has a long history. The modern development of tribology dated back to the 15th century initiated by Leonardo Da Vinci [1]. However, understanding the mechanism of wear and selecting a strategy to reduce it or to improve the tribological properties have always been a challenge for engineers. It is believed that harder materials generally provide lesser wear and lower friction coefficient [2]. Several mechanical nanostructuring techniques have been employed to enhance the mechanical and functional properties of metals and alloys [3]. Severe Plastic Deformations (SPD) are renowned for their impact on the grain refinement in metallic materials and have become more famous during the past years because of their significant contribution to the enhancement of mechanical properties [4]. Ultra-fine grained (UFG) materials processed by SPD proved to demonstrate better mechanical and functional properties as compared to their coarse-grained counterparts [5]. In the case of tribological properties, several studies evaluated different SPD techniques including High-Pressure Torsion (HPT) [6], Equal Channel Angular Pressing (ECAP) [7], and Accumulative Roll Bonding (ARB) [8] in terms of the wear and friction coefficient. The enhancement of wear resistance in SPD induced materials is a controversial subject among scientists [9,10]; particularly in aluminum alloys, some studies showed an improvement in the wear resistance of the processed samples [7,11], while others reported a reduction in the wear resistance after processing [12,13]. This work for the first time is going to evaluate the impact of a new technique with the name of High-Pressure Torsion Extrusion (HPTE) on the wear resistance of materials; aluminum series 1050 was selected as model materials in this work.

HPTE is a combination of two processes of HPT and extrusion and is capable of producing bulk samples with UFG microstructure [14]. Figure 1 shows the die and a 3D wireframe model. The HPTE die is composed of an upper die, which is fixed, and a lower die that rotates by an electromotor. Samples are inserted through the upper die, extruded by a punch, and then, exit through the lower die. Two process parameters of HPTE, e.g. the extrusion speed (v), and rotational speed (ω) will dictate the amount of imposed strain and consequently, the level of grain refinement in this technique. Earlier studies about HPTE revealed a considerable grain refinement as well as remarkable enhancement in the mechanical and functional properties of materials after processing. Further details about the process and the die geometry can be found elsewhere [15–17]. Due to the impact of torsion in this technique, materials demonstrate a gradient distribution in grain refinement and hardness at the cross-section of the specimens, from the center to the edge; however, as a general rule, increasing the ratio of ω/v in HPTE increases the amount of strain imposed on the material, and accordingly, boosts the amount of grain refinement [16]. This research will evaluate the wear resistance and friction coefficient of aluminum after HPTE processing by implementing dry sliding wear test.

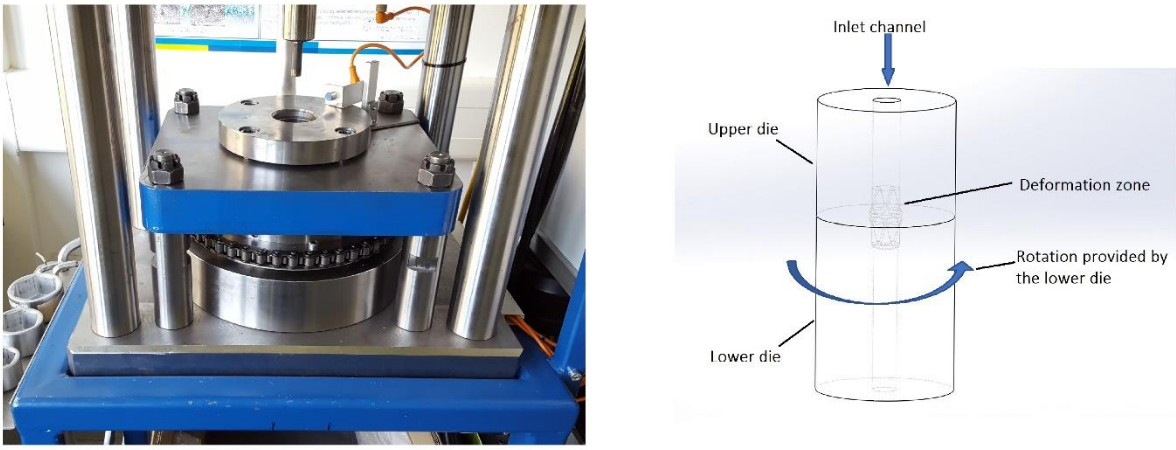

Figure 1:HPTE die; the assembled configuration (left), and 3D wireframe model (right)

2. Experimental procedure

Commercially Pure aluminium (CP-Al) with the following chemical composition was annealed at 350 ºC for half an hour and then processed via HPTE: Al > 99.5 %, Fe < 0.20 %, Si < 0.15 %, Cu < 0.05, Mg < 0.02 % (wt.). Three different HPTE regimes adopting different levels of deformations were selected for evaluation: v= 7 mm/min, ω = 1 rpm (v7w1); v= 1 mm/min, ω = 1 rpm (v1w1); v= 1 mm/min, ω = 3 rpm (v1w3). One sample was kept unprocessed (only annealed) for comparative purposes. The billets after processing were cut, sectioned, and prepared for reciprocal wear testing. A "Buehler Micromet-5104" tester with a load of 0.2 Kg and a dwell time of 15 sec was implemented to apply the micro-indentation at the cross-section of the specimens on several points along the diameter to demonstrate the distribution of hardness in the specimens. The tests were carried out on three specimens in each group to ensure the consistency of the results. The reciprocal wear testing was performed by a Wazau SVT-500 tribometer on the cross-sectional surface of the samples with diameters of 11 mm in dry sliding conditions. Considering the fact that processed materials have a gradient distribution in microstructure and hardness at the cross-section from edge to center, different wear tests were performed at three different sections to study the effect of torsion-induced gradient on the wear resistance of the samples: center zone (r ≈ 0.5 mm), mid-radius zone (r ≈ 2.5 mm), and the edge zone (r

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≈ 4.5 mm). Bearing steel balls made of chrome steel 100CR6 (Redhill balls ™) with a diameter of 3 mm with Vickers hardness of 63±3 HRC were used as a counterpart for wear testing of the samples. The reciprocal sliding wear tests were performed at room temperature (21 °C) and relative humidity of 50 %. Each test was repeated three times. All samples were tested under a load of 0.2 N. Material properties of the aluminum specimens and steel balls are summarized in Table 1. The wear tests were conducted at a frequency of 3 Hz and an amplitude of 1 mm with a sliding speed of 6 mm/s for a total period of 100 min. The mean and maximum values of contact pressure were ~0.16 GPa and ~0.25 GPa respectively for the Hertzian initial point contact in the present tribosysem. The volume loss in the wear tracks was measured using a confocal microscope, Brukers Contour GT-K white light optical profilometer. The microstructural analysis of the samples was performed by using FEI Quanta 3D scanning electron microscope (SEM) operating at 20 kV. The EBSD images were obtained by using the orientation imaging (OIM) software.

Table 1: Mechanical Properties of the specimens and the steel balls

	Yield strength [MPa]	Ultimate strength [MPa]	Modulus of Elasticity [GPa]	Poisson's ratio
AA1050-O workpiece	41	108	71	0.33
100Cr6 steel bearing ball	586	824	203	0.29

3. Results and discussion

3.1. Mechanical and microstructural evolution

Microstructural analysis of the specimens demonstrated a considerable refinement in the grain size after HPTE. Figure 2 shows the SEM investigation of materials. The annealed specimen is shown in Figure 2-a, and the processed specimens are represented by orientation image mapping in Figure 2- b, c, d. The EBSD images were taken from the cross-section of the HPTE specimens near the edge (where the highest amount of strain was imposed on the materials) with an approximate distance of r ≈ 4.5 mm from the center. As illustrated in this figure, the grain size in the annealed specimen with an average value of 120 µm (Figure 2-a) reduced to 1.4 µm in v7w1 (Figure 2-b), 0.9 µm in v1w1 (Figure 2-c), and 0.7 µm in v1w3 (Figure 2-d).

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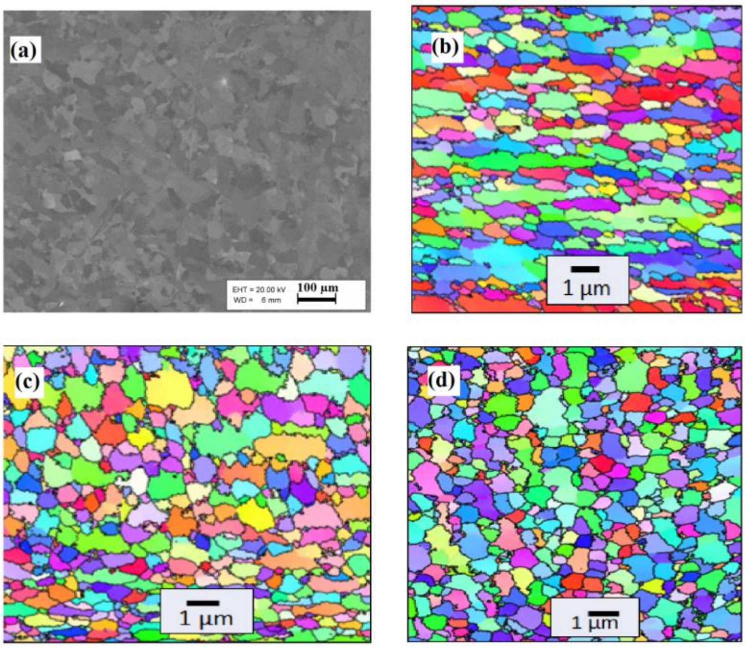

Figure 2: Microstructural evolution of aluminum by HPTE processing; (a) Initial specimen (annealed), (b) v7w1, (c) v1w1, and (d) v1w3.

Results of hardness testing are represented in Figure 3. As a result of microstructural refinement, there is a substantial improvement in the hardness [18]. All the processed samples demonstrated a V-shape distribution as a result of torsion which was applied to the material. As shown in this figure, the initial hardness with an average value of 29 HV0.2 increased to 51, 64, and 67 HV0.2, at the edge zone of v7w1, v1w1, and v1w3, respectively.

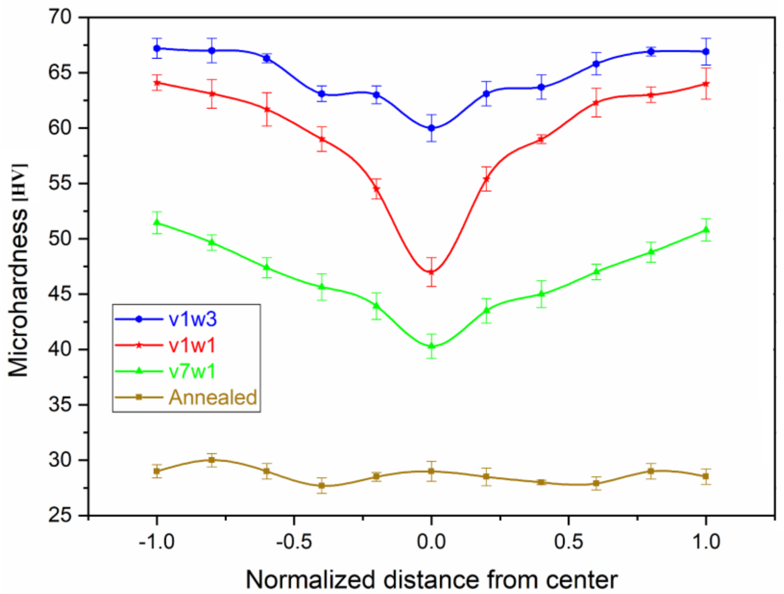

Figure 3:Hardness evolution in the cross-section of HPTE specimens

3.2. Wear test

Evaluation of the coefficient of friction (COF) in the samples showed that HPTE did not make any significant influence on the results; COF in all samples, including the annealed and processed ones, was in the order of 0.31 ± 0.03.

Analysis of the wear track using a 3D profiler is shown in Figure 4, and Table 2 collects the results of this analysis. The positive volume in this figure is the transferred material to the edge of the wear track as a result of plastic shearing during the wear test, and the negative volume is the groove that was formed during the test.

The net Missing Volume (M.V.) in Table 2 is the difference between the negative and positive volume, and the total Displaced Volume (D.V.) is the sum of absolute values of positive and negative volumes. As demonstrated in this table, the net missing volume (M.V.) did not decrease in v1w1 and v7w1 regimes; the only reduction of M.V. was found in v1w3 where the highest hardness values were achieved (see also Figure 3). However, all regimes made a noticeable reduction in the Displaced Volume (D.V.). This enhancement is due to reducing the amount of positive volume (built-up edge) forming around the wear track.

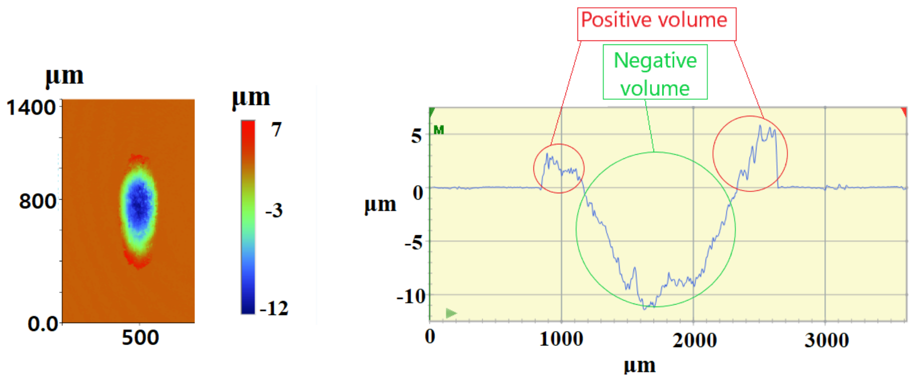

Figure 4: Illustration of the wear track in v1w1 specimen in the center zone; left: 3D-profile analysis of the wear track; right: cross-section of the wear track; the built-up edge was considered as the positive displaced volume, and the groove space as the negative volume.

Table 2: Volume loss of the wear tracks

	Net Missing Volume (M.V.) [$10^6.\mu m^3$]			Total Displaced Volume (D.V.) [$10^6.\mu m^3$]		
Track location	Center	Mid-radius	Edge	Center	Mid-radius	Edge
v1w3	1.08	1.36	1.23	1.15	1.38	1.33
v1w1	2.51	4.92	5.80	3.51	5.20	6.50
v7w1	2.85	4.50	5.95	6.35	6.93	7.75
Annealed	2.06	1.86	2.70	7.80	8.74	8.34

According to the results, the processed samples generated lower amounts of positive volume, and hence, lower D.V. This phenomenon is associated with increasing the hardness and resistance against the plastic shearing in the HPTE samples. As shown in Figure 3, the processed samples showed higher hardness values as compared to the initial one. In the case of the v1w3 regime, materials received the highest amount of strain and accordingly, represented the highest resistance against plastic shearing; therefore, the main portion of the displaced volume was the negative volume which was worn away through abrasion. On the other hand, the annealed sample with the lowest hardness value was mainly worn through the mechanism of adhesion, forming a thick layer of built-up edge (named as positive volume) around the wear track. This positive volume took up a large portion of the displaced volume in the wear. Indeed, the presence of positive volume makes a great contribution to the intensification of adhesive wear. Further investigations will be pursued by the authors to study the effect of this technique on the mechanism of the wear in materials.

4. Conclusion

- A new approach in the microstructural refinement of metals by means of mechanical nanostructuring was examined for the wear resistance and tribological properties of aluminum AA-1050.
- Analysis of the microstructure by EBSD showed remarkable grain refinement in the processed samples.

- Results of reciprocal wear testing at the cross section of the specimens showed that this technique was able to decrease the amount of displaced volume during the wear and thereby, reducing the adhesive wear. This fact corresponds to the enhancement of hardness and increasing the resistance of materials against plastic shearing.

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