An Investigation on the Wear Resistance Effects of Severe Plastic Deformation

Mehmet Şahbaz, Erkin Akdoğan

Abstract— In this study, the application of Multi-Directional Forging (MDF), which is a Severe Plastic Deformation (SPD) method, to AA5083 aluminum alloy and, accordingly, the wear resistance of the material was investigated. The workpieces prepared in the form of cubes with a side length of 15 mm were first subjected to homogenization heat treatment and then 1 pass and 4 pass MDF processes were applied on the workpieces. After the process, the Vickers Hardness (HV) test method was applied to the workpieces to have an idea about the change in the mechanical properties of the material. While the hardness value of the material decreased with the homogenization process, it increased in direct proportion to the number of passes of the applied MDF process. In addition, a similar situation was observed in the wear resistance of the material. In materials subjected to wear tests under the same conditions, the highest mass loss was measured in the homogenized one, and the least mass loss occurred in the workpiece with 4 passes of MDF.

Index Terms— AA5083, Abrasion, Multi-Directional Forging, SPD, Vickers Hardness, Wear Resistance,

1 Introduction

ONE of the most important problems encountered in mechanical systems is the wear of moving and contact parts. The tests carried out to determine the friction and wear behavior of the system or system elements are very important in terms of design. One of the most important points in explaining friction and wear events and minimizing the negative effects of these events is the selection and application of test techniques that will provide a clear reveal of cause-and-effect relationships in a tribological mechanism. If a general evaluation is made, it is possible to divide the wear test techniques into two general groups of real systems (operating conditions) and tests using model test setups. Although real system usage is the most reliable method, it is difficult to implement and repeat, it is a time-consuming and costly test. Model experimental setups, on the other hand, are not as reliable as real test setups, but they are preferred in terms of these parameters. The most commonly used model test systems can be listed as follows: pin-on-disc, pin-on-cylinder, pin-on-plate, cylinder-on-plate, etc[1].

In addition, many studies are being carried out and new methods are being developed to increase the wear resistance of materials. One of them, a method that has attracted attention in the last two decades, is to increase wear resistance by improving the material microstructure by severe plastic deformation. Some studies in the literature as examples of these are briefly summarized below.

In order to convert coarse-grained metals into fine-grained microstructured materials, severe plastic deformation (SPD) is applied. Various severe plastic-forming processes have been developed to produce ultra-fine grain (UFG) materials over the past two decades. Equal-channel angular pressing (ECAP)[2]–[5], high-pressure torsion (HPT)[6], accumulative roll-bonding (ARB)[7], and multi-directional forging (MDF)[8] are the main ones. As a result of these methods, the properties examined in the material are mechanical properties, microstructure change, and thermal stability of them. Achieving excellent mechanical properties with the formation of fine-grained internal structures brings along high strength and toughness properties. In addition, good wear resistance, which is one of the most important material properties of UFG materials, is also a significant research topic [9].

Gao et al. (2012) reported that various complex factors affect wear behavior and that the correlation between hardness and wear may be at a certain level. Internal surface material properties such as hardness, strength, ductility, and strain hardening of the material are among the important factors affecting wear resistance. In addition, the importance of surface quality, roughness, lubrication, load, speed, corrosion, temperature and the properties of the opposite surface was also revealed [10].

Moshkovich et al. (2013) made the strengthening of the copper (Cu) surface after friction in different lubrication zones and the determination of the damaged layers. They used different SPD techniques in this study. Friction and wear tests were carried out using a ring block rig. The structure and damage of rubbing Cu samples in Elastic Hydrodynamic Lubrication (EHL) and Boundary Lubrication (BL) were investigated. They found that the strain hardening, grain size, and plastic deformation level under friction in the EHL and BL regions were close to those observed in SPD processes such as ECAP, HTP SMAT, and DPD. They stated that the main damage mechanism in the EHL region is the formation of pores and their coalescence [11].

Karademir et al. (2017) investigated the wear properties of aluminum matrix composites produced by powder metallurgy by applying a surface-severe plastic deformation (SSPD) process. Severe shot peening was used as the severe plastic deformation method. They stated that the applied SSPD method increased the surface hardness and prevented wear loss. They found that the SSPD process creates a layer of higher hardness on the material surface than on the inner surface. They ob-

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served that grain thinning occurred on the surface from the XRD results [12].

Ramos et al. (2021) used the high-pressure torsion (HPT) method as the SPD method in their study. They used high-purity (99.99 wt%) copper as material. They stated that the wear rate decreased by about 75% compared to non-SPD-treated copper. In addition, they observed that the wear resistance was affected by the tensile path and the wear path, as a result of the wear tests performed from different regions on the different sample surfaces. They stated that high strain values do not have an extra benefit on the wear properties of the material [13].

Wang et al. (2010) performed the severe plastic deformation (SPD) process by subjecting the Al-1050 alloy to equal-channel angular pressing (ECAP) and high-pressure torsion (HPT) processes, respectively. A dry abrasion test was performed on the samples with and without SPD treatment. As a result of their study, they determined that the SPD process reduces wear resistance. In their study, they observed two main wear mechanisms. The first of these is the multi-layer wear mechanism at the beginning of the wear and then the oxidation wear mechanism. They observed that the extreme wear phases of the SPD-treated AL-1050 material were longer than the as-received Al-1050 material. They stated that the reason for this is the loss of the hardening capacity of the SPD process[14].

In this study, multi-directional forging (MDF) was preferred as the severe plastic deformation method. After the MDF treatment was applied to the AA5083 aluminum alloy in different passes, the wear resistance of the material was measured. Thus, the effect of this SPD method on the wear behavior of the material was examined, the hardness values were also measured on the same specimens, and a connection was established between wear and hardness.

2 Material and Methods

In this study, MDF treatment, which is an SPD method, was applied to AA5083 aluminum alloy (the chemical compositions is given in Table 1) at approximately 25 ºC. Homogenization annealing was applied to some of the pre-MDF workpieces at 500 °C during 2.5 hours as a heat treatment.

TABLE 1.
Chemical Composition of AA5083

Mg	Mn	Sn	Si	Fe	Al
4.0 – 4.9	0.4- 1.0	0.5 – 0.9	0.0 – 0.7	0.0 – 0.4	Balance

MDF treatment was applied on homogenized workpieces (shown in Figure 1) 1 and 4 passes, and then tests were carried out on 4 different cases as as-received, homogenized and MDF applied workpieces. First of all, Vickers Hardness (HV) test was applied to the workpieces in these four different cases. Afterwards, wear tests were carried out according to the cylinder-on-plate method.

Hardness tests were performed with Digirock brand measuring device according to the HV30 method.
A diamond pyramid tip was used in the tests and a load of 30 kgf (kilo-gram force) was applied for 6 seconds.

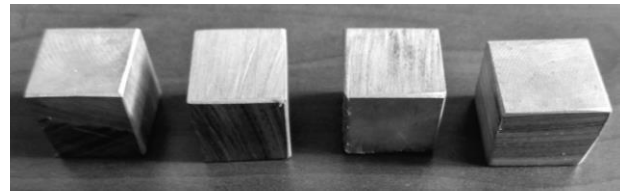

Fig. 1. AA5083 workpieces

Wear tests were carried out using Turkyus brand dry wear test device. In the tests carried out according to the cylindir-on-disc method, 250 meters of wear were achieved under a load of 30 Newtons with 0.5 m/s velocity. Before and after the wear test, the weights of the workpieces were measured with a 4-digit precision scales and the mass loss ratios were measured for all cases.

The multi-directional test was carried out in such a way that 10% deformation occurs on cube-shaped workpieces with a side length of 15 mm. Figure 2 shows the schematic drawing of the MDF method.

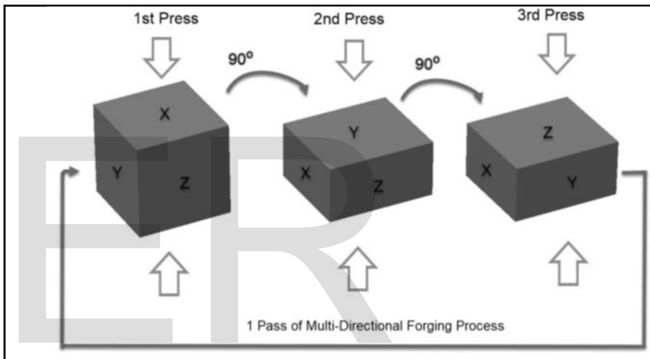

Fig. 2. Shematic shown of one pass od the MDF process [8]

The MDF processes were carried out on a Shimadzu AGS-X 100 kN universal tensile-compression test device at 25 C° and speed of 2 mm/min. Figure 3 shows the 30 N load applied wear test device and the pre-tested workpiece.

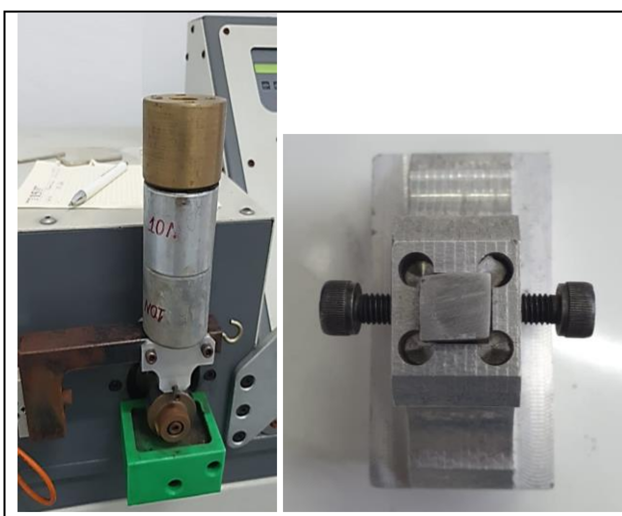

Fig. 3. Wear test device and workpiece

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3 Results

Firstly, information will be given about the hardness results on workpieces prepared in four different conditions. Vicker Hardness (HV) test results applied on workpieces are explained below. The hardness value was high because the as-received workpiece had residual stresses caused by the plastic deformation applied on it before it was supplied.

Since residual stresses are removed in materials subjected to homogenization annealing, the material has softened and its hardness values have decreased.

Material hardness increased as a result of events such as grain size reduction, secondary phase precipitation, and increase in dislocation density occurring in the microstructure of the material after MDF applied to the homogenized workpiece. Although this increase was seen after the first pass, it increased even more after the fourth pass. In addition, in this study, the hardness values of the surface and interior of the workpiece were measured separately, and it was observed that the hardness values were higher in the interior parts than the surface. The graph showing the hardness values is given in Figure 4 and Table 2.

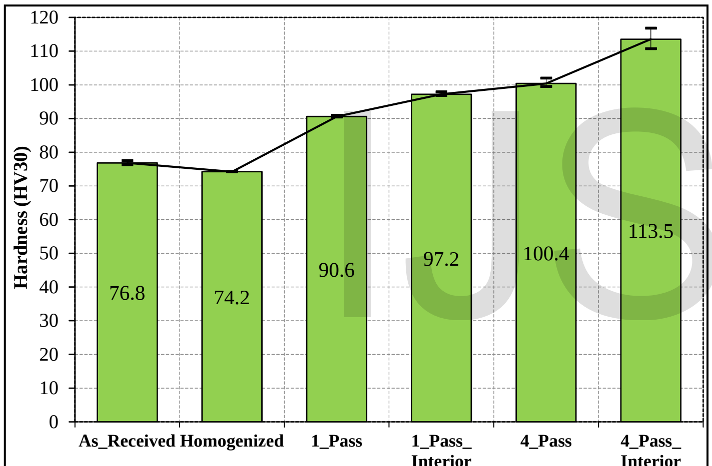

Fig. 4. Hardnes values of workpieces

TABLE 2
Hardness Values of Workpieces at Different Cases

	Hardness (HV30)			
	Avg.	Max.	Min.	SD
As_Received	76.8	77.5	76.3	0.6
Homogenized	74.2	74.3	74.2	0.1
1 Pass	90.6	90.9	90.4	0.3
1 Pass Interior	97.2	97.9	96.8	0.4
4 Pass	100.4	102.0	99.5	1.4
4 Pass Interior	113.5	116.8	110.7	3.1

As seen in Figure 4 and Table 2, the MDF process increased the hardness values of the material. Considering that there is a linear relationship between hardness and strength values, it can be said that the strength of the material increases. This has already been confirmed by the increase in the compressive force required for 10% deformation in each pass during the MDF process. While the compressive strength of the workpiece with one pass was 324 MPa, this value increased to 383 MPa after four passes [8].

In addition, when the standard deviation results from the hardness measurements are examined, information about the homogeneity of the material is obtained. In this case, the standard deviation is seen at least in the hardness measurement of the annealed sample. This shows that homogenization annealing is successful. In addition, when the standard deviations of the MDF applied samples are examined, an increase is seen, and this is because SPD methods increase the inhomogeneity of the material.

It is a known fact that there is a linear relationship between wear resistance and material hardness. It is known that under the same conditions, the soft material exposed to friction will wear more than the hard material. In this case, it is expected that the wear resistance of the materials hardened with MDF will be high. In other words, less mass loss is expected for hard workpieces that are subject to wear under the same conditions, compared to soft ones. In Figure 5, the amount of wear occurring in the materials after the wear test is shown as a percentage. When this graph is compared with the hardness graph, it is seen that the bar corresponding to each case shows an opposite behavior. This shows that, as expected, the loss of mass due to wear decreases with the increase in hardness.

It is seen that the least mass loss is in the workpiece with 4 passes MDF applied, while the highest mass loss is in the workpiece that has been softened by homogenization heat treatment.

This is an indication that severe plastic deformation methods such as MDF (provided that they are applied in the optimum number of passes) have a positive effect on the wear resistance of the material. When the literature is examined, applying SPD in more than optimum number of passes may decrease the wear resistance as well as decrease the material strength [14].

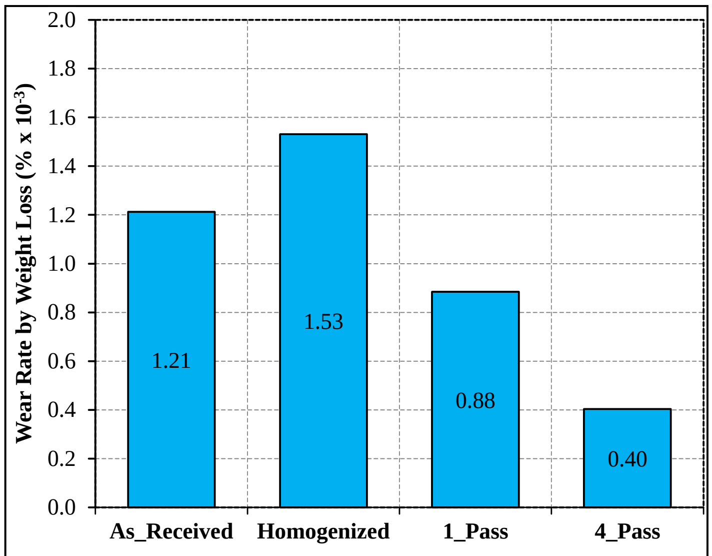

Fig. 5. Wear test results of each case in percentage

Figure 6 shows the deformation on the surface of the workpieces after the wear test. Since the abrasion is made according to the cylinder-on-plate method, the wear trace is also seen in the form of a cylinder.

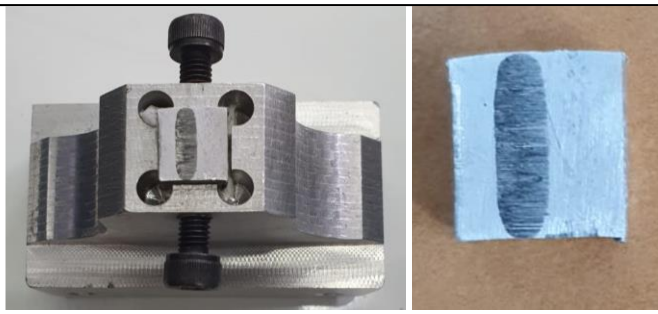

Fig. 6. Surface appearance of the workpieces after the wear test.

In Table 3, the weights of the workpieces before and after the wear test, the mass loss amounts and its percentage rate are given.

TABLE 3
WEIGHT AND MASS LOSS AMOUNTS OF WORKPIECES BEFORE AND AFTER THE WEAR TEST.

	Initial Mass (g)	Final Mass (g)	Amount of wear mass (mg)	Wear rate by Weight Loss (% x 10^{-3})
As_Received	123.6960	123.6945	1.500	1.213
Homogenized	124.0642	124.0623	1.900	1.531
1_Pass	124.3582	124.3571	1.100	0.885
4_Pass	123.8977	123.8972	0.500	0.404

4 Discussion

In this study, it was observed that the SPD method had a positive effect on wear resistance. The reason for this is the improvements in the microstructure of the material such as grain size reduction and increase in dislocation density with the applied SPD. The proof of this situation is the increase in the hardness and strength values of the material. In addition, the increase in the amount of wear as a result of the removal of residual stresses in the internal structure of the material by homogenization annealing also confirms this claim.
In addition, two different measurement results were observed with the applied SPD, where the homogeneity of the material decreased and the inhomogeneity of the material increased. First, the hardness measurements made from the material surface and the inside of the material after SPD showed a difference of around 10%. Secondly, different hardness measurements made from the same surface differed and this caused the standard deviation to be excessive. On the contrary, the standard deviation value of the hardness measurements in the homogenized material without SPD applied was very low.

5 Conclusion

In this study, the effect of multi-directional forging, which is a severe plastic deformation method, on the wear resistance of the material was investigated. It has been observed that as the number of passes of the applied SPD method increases, the hardness value of the material increases and accordingly the wear resistance increases.
In the next study, we plan to measure the hardness values caused by the MDF method on all surfaces and inner section surfaces and map the hardness change.

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The summary of this study was presented at the ICANAS 2022 conference and the full text of the study was selected for IJSER.

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