Investigating the Mechanical Properties and Ductility of Wrought Aluminum Alloys As a Result of the Mdf Process

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Abstract

The present study was an attempt to examine the mechanical properties and ductility of wrought aluminum alloys as a result of the MDF process. Cylindrical compression samples with a diameter of "6" mm and height of "9" mm were prepared from the central area (dead metal zone) of MAF cubic samples by a wire cutting machine after performing the multi-axial forging process in 1, 2, and 3 passes and at a temperature of 450 ℃, to examine the improved mechanical properties due to the multi-axial forging process. Then, the samples were processed with P2000 sandpaper to remove the effect of stress concentration caused by the preparation. Then, the cylindrical compression samples underwent compression testing by a universal tensile-compression machine with a load capacity of 50 tons and a jaw movement speed of 1 mm/min and at ambient temperature up to a true strain of 0.6. The lubricant was used to reduce the effect of friction between the contact surface of the jaws and the sample. The results revealed that the mean hardness number was calculated at "95 Hv" for the primary sample, "80 Hv" for the solutionized sample, and "90 Hv", "96 Hv", and "99 Hv", respectively, for the samples that were deformed by 1, 2, and 3 passes of MDF process. The compressive strength obtained from the uniaxial compression test was calculated at "1185 MPa" for the primary sample and "1375 MPa", "1435 MPa", and "1470 MPa", respectively, for the samples that were deformed by 1, 2, and 3 passes due to the multi-directional forging process. The increase in hardness and compressive strength after 1 pass deformation was calculated more than the higher passes. The reason for this difference can be related to the interaction of dislocations with each other and the reaching of the flow stress to a saturation limit.

Key words: Wrought aluminum alloy, Friction effect, Compression test, MAF cube samples

1. Introduction

Several methods are currently used for producing ultrafine-grained materials [1, 2]. Selecting an appropriate strengthening method depends on the chemical composition and structure, and the final properties of the alloy [3]. Plastic deformation is considered an effective method to improve the properties and fine-grained structure of materials. To achieve this goal, conventional forming processes such as extrusion, forging, and rolling have been used. Much force is needed for the multi-stage reduction of the cross-sectional area of the piece using conventional methods. It finally leads to non-uniformity of stress and strain in the piece. It is difficult to overcome these problems to produce a high-quality product on a large scale. It is only possible on a limited number of metals and alloys. The conventional processes are not appropriate in this regard and other high-technology deformation methods are required. Studies have proven the capability of the severe plastic deformation method as an appropriate method in creating fine-grained structures at the sub-micron and nano size. These methods are currently expanding rapidly and are moving from laboratory scale to industrial scale. A severe plastic deformation method should have a special feature to be used as a suitable method for producing very fine structures in billets and bulk samples. First, the obtained structure should have grain boundaries with a large angle since a clear and significant change in the properties of the material can be seen only in this state. Second, although the samples have been subjected to severe plastic deformations, they should not have mechanical defects or severe cracks. Multidirectional forging is considered one of the severe plastic deformation processes for producing ultra-fined materials. The MDF process is a repetitive forging process in which the forging direction is changed by 90° in each pass. Among the different SPD methods, MDF can be the most appropriate method for industrial production since it can be applied to relatively large pieces. Moghaddam et al. (2016) [4] examined different SPD methods and investigated their microstructural characteristics and mechanical properties after applying deformation on 7075 aluminum alloy. They investigated MDF, ABE, and FSP methods. Sitdikov et al. (2004) [5] examined the effect of strain on the grain fineness of 7475 aluminum alloys during the MDF process. First, they subjected the billets to a homogenization process at 490 ℃ for 20 hours. Then, they prepared samples with dimensions of 10 x 9 x 5 mm. The MDF process was performed at 490 ℃ with a strain rate of 0.0003/s using a boron nitride lubricant layer, and the force direction was changed by 90° after each deformation pass.

In a similar study, Aoba et al. (2018) [6] examined the effect of strain on the microstructure, texture, and mechanical properties of aluminum alloy 6000. In the mentioned study, the samples were prepared at dimensions of 15.4 x 18.3 x 4.22 mm and subjected to solving operation at 793 K temperature for one hour. After cooling in the salt bath, they were deformed up to the total strain of 16 immediately by the MDF process. Experiments were performed at room temperature and in the primary strain rate of 0.003/s and the strain of 0.4 in each pass. Sajjan et al. (2019) [7] conducted a similar study on LM6 aluminum alloy. In this study, samples at dimensions of 25 x 30 x 30 mm were prepared and subjected to different passes of the MDF process at ambient temperature and with MoS2 lubricant with the help of a 200-ton hydraulic press at a speed of 0.05 mm/s. In this process, after each deformation passes, the sample was rotated by 90° to prepare for the next pass. The amount of strain applied in each pass was 0.18.

Manjunath et al. (2020) [8] conducted a study on the effect of strain in the MDF process. In this study, cast samples of 7050 aluminum alloy were brought to the dimensions of 30x40x40 mm and underwent the MDF process after heat treatment at 400℃ for 20 hours, at ambient temperature, and a speed of 0.05 mm/s. The samples failed after two passes at most since the number of active slip plates is small at room temperature. In a study by Joshi et al. (2016) [9], the effect of strain rate and forming temperature on the MDF process was investigated. In this study, samples of aluminum alloy 2014 with dimensions of 33x30x27 mm were prepared and subjected to heat treatment at 540℃ for 2 hours and then cooled in water. Then, the samples underwent MDF treatment at room temperature and super-cold temperature (-196℃) with a strain rate of 10/1s. The rate of strain in each pass was 0.2 and after each pass, the sample was rotated by 90°. Thus, the rate of strain in each full cycle of deformation is 0.6, and in the experiments, the samples were deformed by 2, 3, and 4 cycles. In another study, Alyani et al. (2021) [10] examined the effect of temperature and the number of passes on the microstructure and mechanical properties of commercial pure aluminum (AA1050). First, they prepared cubic samples with dimensions of 15x10x10 mm and cooled them in water after annealing at 400 ℃ for three hours. The MDF process was performed at two low temperatures (K200) and ambient temperatures (300K) with 1, 2, 3, 4, and 6 passes, and the rate of strain in each pass was 0.5. The samples were rotated by 90° after each pass. A study by Obara (2021) [11] examined the effect of parameters of temperature, strain, speed, and friction coefficient in the MDF process. The study methods were experimental design by the Taguchi method, simulation of finite elements, and optimization of the results with the help of analysis of variance. Given what was stated, the present study investigates the mechanical properties and ductility of wrought aluminum alloys as a result of the MDF process.

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2. Methodology

The 7xxx series aluminum alloy was used in the present study. It was purchased from Alumtek Company in the form of extruded bars with a diameter of 5 cm. Cubic samples were prepared at the dimensions of "16x16x21 mm" to perform the multi-directional forging process using a wire-cutting machine from the compression test extruded bar. A spark emission spectrometer (SES) was used to determine the primary chemical composition of these samples, as shown in Table 1.

Table 1: The mean primary chemical composition of the alloy (weight percentage)

Al	Zn	Mg	Si	Mn	Fe	Cu	Cr
Base	6.62	2.58	1.03	0.549	0.48	0.298	0.0186

2.1. Mold design

To perform the multi-axial forging process, a mold made of H13 hot-work steel, consisting of two completely symmetrical pieces, with specific dimensions according to the drawn map, was designed by the mold maker. After the cutting, turning, and machining processes, the angles and the internal parts were adjusted using a wire-cutting machine. Finally, heat treatment was performed on the mold to prevent deformation caused by the application of compression during the process of multi-axial forging. Figure (1) shows the image of this mold.

Figure 1. Picture of the MDF mold used in this study

2.2. Multidirectional forging process (MDF)

After preparing cubic samples from the compression test alloy in the form of extruded tubes and performing the solubilization process to improve the ductility and formability of the samples and reduce their brittleness, the multi-axial forging process is used to transform the crystal structure of the samples into an ultrafine-grained structure and improving their mechanical properties without significant loss of ductility, in 1, 2, and 3 passes, each pass consisting of three stages of applying compression around three rotations. It was performed primarily at a temperature of "450" °C and with a spindle movement speed of mm/ 1.26 min with the help of a pre-designed mold and by the SANTAM tensile-compression machine made in Iran with a load capacity of 15 tons and equipped with a resistance furnace with an accuracy of 5°C according to Figure 2. Moreover, the samples were placed inside the oven and between the jaws to make the temperature uniform throughout the samples, before starting loading for each deformation pass, after setting the oven temperature of the machine to "450℃". Then, the samples were kept at the desired temperature for 15 minutes to equalize the temperature of the samples and the furnace environment. Unfortunately, the present study was stopped only by experimenting with the mentioned "450" ℃ temperature due to the evidence of the possibility of cracks in the sample during the process at "200" ℃.

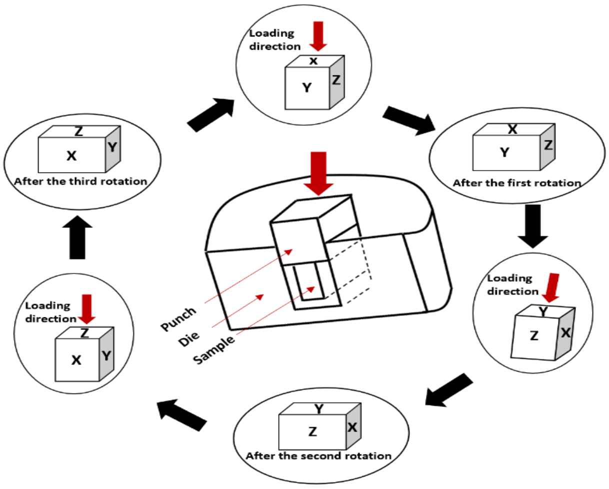

Figure 2. A schematic of the 1 pass multi-axial forging (MAF) process

Figure 3. Resistance furnace equipped with a thermometer of the SANTAM tensile-compression machine

Figure 4. Complete and optimal filling of the mold after each load application cycle

2.3. Investigating the mechanical properties of MAF samples

After performing the multi-axial forging process in 1, 2, and 3 passes and at a temperature of "450" ℃, cylindrical compression samples with a diameter of 6 mm and height of 9 mm were prepared from the dead metal zone of MAF cubic samples by a wire cutting machine to investigate the improved mechanical properties due to the multi-axial forging process. Then, the samples were processed with P2000 sandpaper to remove the effect of stress concentration caused by preparation. Then, the cylindrical compression samples underwent a compression test by a universal tensile-compression machine with a load capacity of 50 tons and a jaw movement speed of 1 mm/min and at an ambient temperature according to Figure 5 up to a true strain of 0.6. The lubricant was used to reduce the effect of friction between the contact surface of the jaws and the sample.

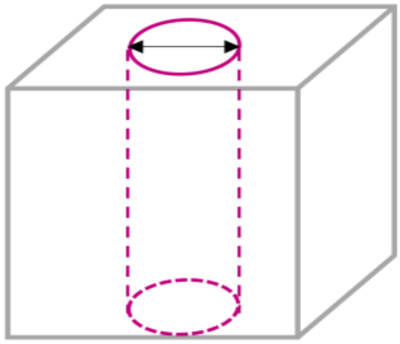

Figure 5. A schematic of compression samples cut from the central area of MAF samples

Figure 6. The compression samples cut from the central area of the MAF samples

Figure 7. Image of samples after uniaxial compression test

2.4. Analyzing compression test data and drawing flow curves

The data relating to the momentary displacement of the jaws and the momentary force applied to the cross-sectional area of the samples were recorded during the compression test. Equations (1) and (2) were used to convert the output data into stress and strain.

Equation 1

$$\frac{F(h_0-d)}{\pi {r_0}^2 h_0}\ \sigma =$$

Equation 2

$$\frac{h_0-d}{h_0} = \ln \frac{h}{h_0}\ \varepsilon = \ln$$

In the above equations, σ is the true stress (MPa), F is the force (N), r_0 is the primary radius of the sample (mm), h_0 is the primary height of the sample (mm), h is the momentary height of the sample (mm), d is the displacement of the jaws (mm), and ε is the true strain. All flow curves and the curves related to structural equations were drawn using Excel 2016 software and Origin software.

2.5. Correction of friction effect in flow curves

Lubricants are primarily utilized to reduce the effect of friction between surfaces in contact with tools and samples. Different lubricants will have different effects on reducing friction. However, the effect of friction will not be eliminated. Thus, to examine the flow behavior of materials accurately, it is necessary to study and eliminate the effect of friction from the flow curves. The effect of friction on flow stress is obtained using Equation 3.

Equation 3

$$\sigma\ \frac{c^2}{2[\exp(c)-c-1]}\ \sigma_F =$$

Equation 4

$$\frac{2\mu R_0}{H_0}\ C =$$

In the above equation, σ_F is the corrected flow stress, σ is the measured flow stress, R_0 and H_0 are the primary radius and height of the sample, respectively, and μ is the friction coefficient, which can be calculated using the following equation.

Equation 5

$$\frac{\frac{R}{H}b}{\left(\frac{4}{\sqrt{3}}\right)-\left(\frac{2b}{3\sqrt{3}}\right)}\ \mu =$$

Equation 6

$$R = R_0\sqrt{\frac{H}{H_0}}$$

Equation 7

$$\frac{\Delta R}{R}\frac{H}{\Delta H}\ b = 4$$

In the above equations, R and H are the radius and height of the sample after deformation, b is the Berl parameter, ΔR is the difference between the maximum and minimum value of the radius ($\Delta R=R_M-R_T$), and ΔH is the height reduction due to deformation.

3. Results and Discussion

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3.1. Investigating the results of the hardness test

The Vickers hardness test on the surface of the cross-section of MAF samples was used to investigate the effect of the multi-axial forging process on the hardness of the alloy samples after 1, 2, and 3 deformation passes and to compare the results with the results of the primary and solutionized samples. Table 2 presents these results and their comparison with the results of measuring the mean size of fine-grained samples.

Table 2. Changes in hardness and grain size based on the number of deformation passes in the MAF process

Sample	Mean hardness (Hv)	mean grain size (μm)
Primary	95	27
solutionized	80	40
1 Pass MAF	90	31
2 Pass MAF	96	26
3 Pass MAF	99	23

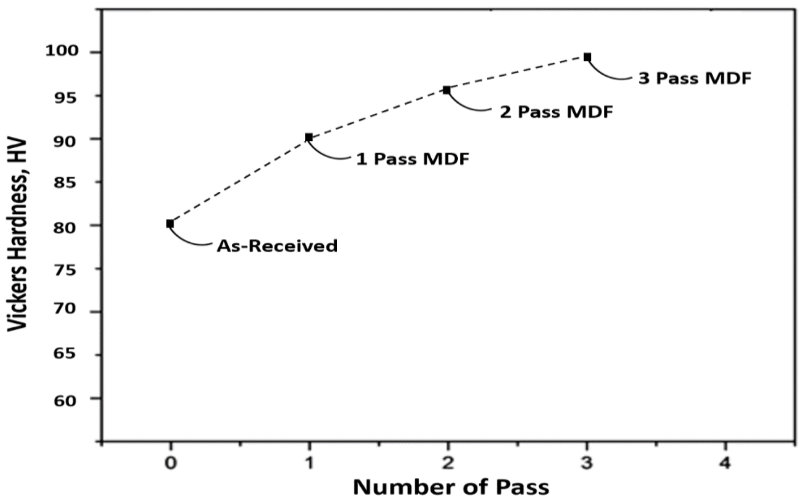

Figure 8. Mean hardness changes based on the number of deformation passes

As shown in Table 2, after the primary samples underwent solubilization treatment, the density of dislocations inside the grains decreased due to heat treatment. Also, the volume fraction of sediments inside the grains decreased due to the dissolution of fine and coarse sediments. Additionally, the growth of the mean grain size up to 40 μm and the reduction in hardness was among the reasons that led to a reduction in the mean hardness of the samples to Hv80 after solubilization processing. Moreover, it was expected that the hardness of the samples to decrease with a greater slope by increasing the time of the solubilization process due to the activation of the recrystallization phenomenon, and after a certain period, the hardness values will show significant changes due to the opposition of sediment dissolution and the recrystallization process. Finally, it was expected that the hardness of the grains and the growth of the grains to decrease by increasing the time and temperature of the solubilization process. The effect of the time and temperature of the heat treatment had not been considered in this project. Hence, these cases were not addressed in the practical results. It is also observed that as a result of performing the multi-axial forging process in 1, 2, and 3 passes, the hardness of the samples has increased due to applying much strain, microstructural changes, reducing the mean size of the grains, and increasing the density of dislocations and the interaction between them. Also, the alloy elements with the regular local arrangement of the atoms and the creation of a short domain order have reduced the movement of dislocations and led to an increase in the hardness of the deformed samples.

The maximum hardness was related to the sample that has been subjected to three passes of the multi-axial forging process with a value of 99 Hv, and the minimum hardness was related to the primary samples that underwent solubilization processing with a value of 80 Hv. Thus, it can be concluded that the increase in the hardness of the samples is associated with a decrease in the grain size. It was also observed that the mean increase rate of the hardness in the deformed samples decreased or the hardness of the samples increased with a lower slope with the increase in the number of deformation passes, due to the equalization of the rate of generation of dislocations due to the application of strain caused by the MAF process with the rate of loss of dislocations due to the phenomenon of recovery and dynamic recrystallization, so the rate of hardness changes after 1 pass of deformation was 10 units. However, it was 6 and 3 units after 2 and 3 passes of deformation. Thus, the most significant reason for the slight increase in the mean hardness in the deformed samples in the higher passes of the multi-axial forging process is the more uniform distribution of sedimentary hard particles in the whole field.

3.2. Investigating tensile test results

The uniaxial tensile test was used to evaluate the mechanical behavior of the primary alloy sample. After preparing the tensile samples from the primary extruded tube with standard dimensions, the uniaxial tensile test was performed to investigate and analyze some of the mechanical properties of the primary alloy sample. In the uniaxial tensile test, deformation starts from the yield point of the material. The increase in strength in aluminum alloys after deformation has been attributed to three mechanisms, including solid solution strengthening, strengthening by increasing grain boundaries as they become fine in the microstructure, and strengthening through the density of dislocations in the microstructure. In the present study, the tensile test was deleted to examine the mechanical properties of the deformed samples as a result of the multi-axial forging process due to the small dimensions of the deformed samples as a result of multi-axial forging process, and thus, the possibility of errors caused during performing a tensile test on these samples. To examine these properties, the compression test can be used. Thus, the uniaxial tensile test and analyzing the results and mechanical properties in this section were used only for the tensile sample prepared from the compression test alloy sample.

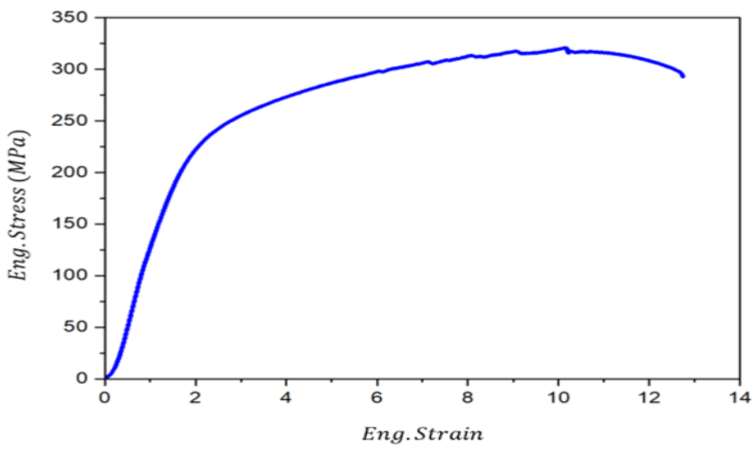

Figure 9. Engineering stress-strain curve of the primary sample

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Figure 9 shows the engineering stress-strain curve of the compression test alloy sample (9). This figure shows the jaggedness of the curve. The jaggedness of the stress-strain curve is attributed to the phenomenon of dynamic strain aging. Dynamic aging is the phenomenon of interaction between mobile dislocations and dissolved atoms during plastic deformation. If the dissolved atoms can penetrate the sample with a speed higher than the speed of movement of dislocations, they will trap and lock them. Therefore, more loads will be needed to continue the deformation .The dislocations are removed from the solution atoms and less force is needed to continue the movement when the load increases. Thus, a load drop occurs, and this process is repeated several times and causes the stress-strain curve to become jagged. To determine the tensile curve constants obtained from the uniaxial tensile test of the primary sample in Figure 9, the VOCE experimental model equation curve was fitted to the tensile curve according to Figure 10. The voce model was presented to justify the phenomenon of isotropic work hardening .Isotropic work hardening is a scalar number that is a function of plastic strain. In this equation, A is the yield stress (σy) of the material, Q is the degree of saturation work hardening, b is the speed of reaching the saturation limit, x is the equivalent plastic strain ($\bar{\varepsilon}_p$), and R is the isotropic work hardening. It should be noted that sometimes the curve does not reach the saturation limit due to the ultimate tensile strength (UTS) inhibition. In these cases, the curve should be brought to the saturation limit by the extrapolation method.

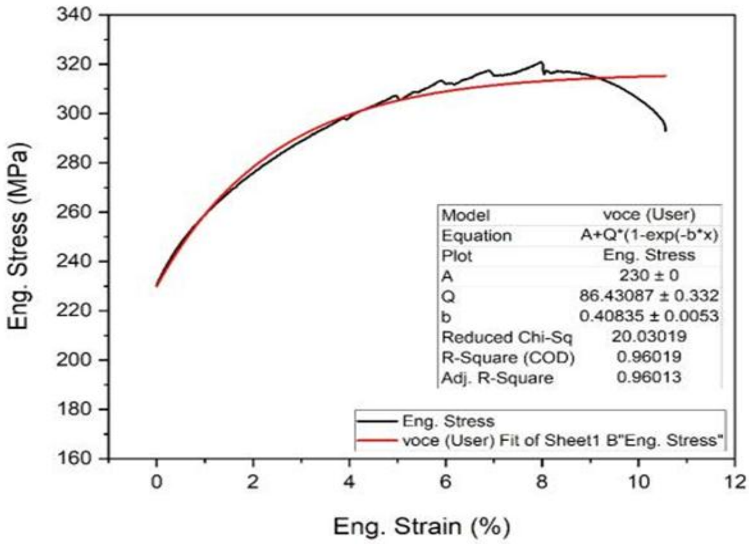

Figure10. The engineering stress-strain curve of the primary sample fitted with the VOCE experimental curve

3.3. Investigating the results of the uniaxial compression test

The uniaxial compression test was performed separately on the primary sample and each of the 1-pass, 2-pass, and 3-pass MDF samples after performing the multi-axial forging process to examine the flow behavior of the MDF samples and the effect of this process on the mechanical properties of the material.

The results obtained from each test were analyzed and evaluated after drawing the flow curves and also compared with each other. Figure 11 shows the true stress-strain curve and Figure 12 shows the engineering stress-strain curve for the primary and MDF samples.

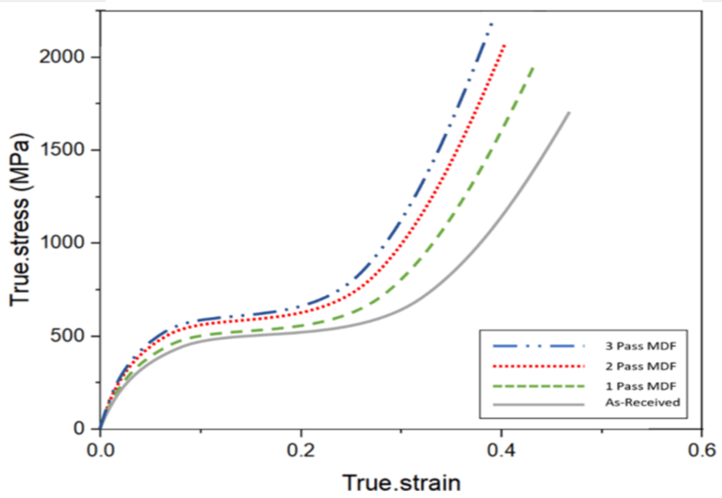

Figure 11. True stress-true strain curve of the original sample and 1-pass, 2-pass, and 3-pass MDF samples

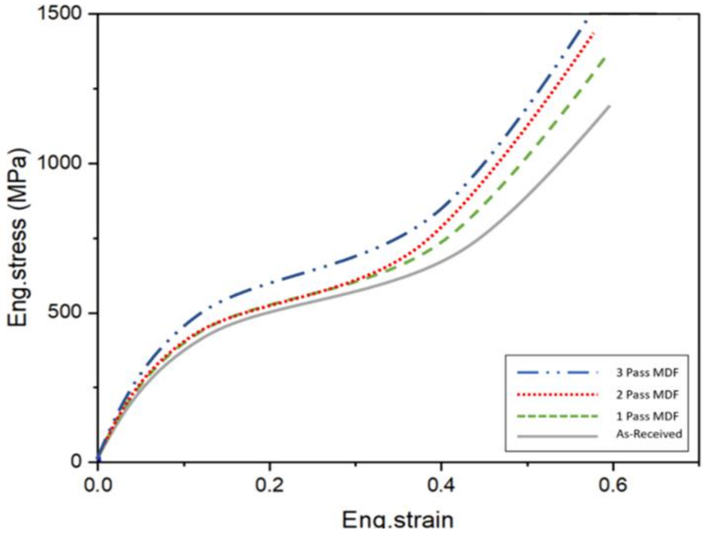

Figure 12. Engineering stress-engineering strain curve of the primary sample and 1-pass, 2-pass, and 3-pass MDF samples

As shown in Figures 11 and 12, the compressive strength of the primary sample without deformation was 1185 MPa. However, the compressive strength increased significantly from 1185 MPa to 1375 MPa after 1 pass of deformation due to the multi-directional forging process. It was also observed that with the increase in the number of deformation passes from 1 pass to 2 and 3 passes, the strength increased significantly and the increase in compressive strength compared to the 1 pass deformed sample decreased, so the strength increased from 1435 MPa and 1470 MPa, respectively, after 2 and 3 deformation passes. Thus, it can be predicted that flow stress can reach a saturation limit after some time by increasing the number of deformation passes.

Finally, it can be concluded that the density of dislocations increases as the rate of strain increases. Also, the movement of dislocations is more limited with the formation of cell blocks and sub-grain boundaries and the reduction of grain size, resulting in increased strength of the deformed samples. It is also expected that by reducing the temperature from "450°C" to temperatures lower than room temperature, the strength will increase significantly due to the inhibition of dynamic recovery at low temperatures.

Figure (13) shows the true stress-true strain curve of the original sample and the MDF samples after 1, 2, and 3 passes of deformation after correcting the effect of friction. Based on the studies conducted in this regard, it has been proven that the friction factor will increase with the increase in barreling (the ratio of the maximum radius to the radius of the upper part of the sample after deformation (RM/RT). Figure 13 shows the flow curve of the original sample and the MDF samples at constant temperatures and different strain rates. As shown, at a constant temperature, the difference between the two curves before and after the correction of the friction effect increased with the increase of strain and the number of deformation passes. However, at lower strains, the two curves show a good agreement with each other.

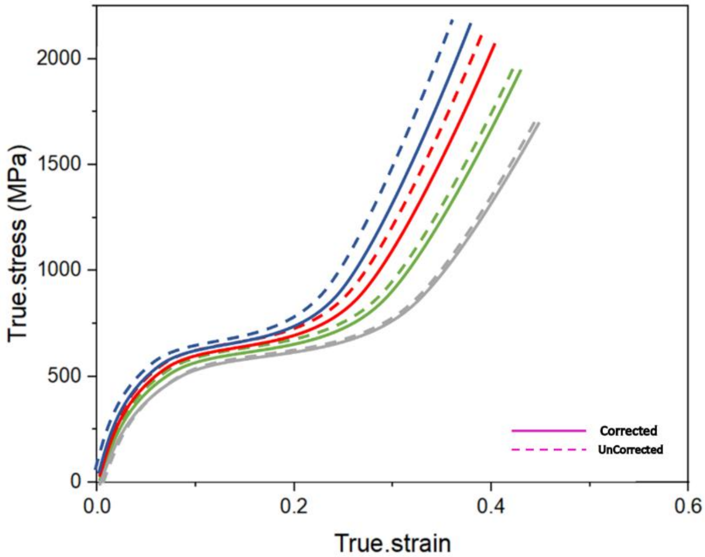

Figure 13. The effect of friction on the flow curve of the primary sample and the 1-pass, 2-pass, and 3-pass MDF samples

Generally, by investigating the flow curves in Figure (13), it can be seen that the effect of friction on the flow stress can be ignored.

4. Conclusion

The present study results revealed that the mean hardness is 95 Hv for the primary sample and 80 Hv for the solutionized sample, and 90 Hv, 96 Hv, and 99 Hv, respectively, for the samples deformed by the 1-pass, 2-pass, and 3-pass MDF process. The compressive strength obtained from the uniaxial compression test was calculated at 1185 MPa for the primary sample and 1375 MPa, 1435 MPa, and 1470 MPa, respectively, for the samples that were deformed by 1, 2, and 3 passes of the multi-directional forging process. The increase in hardness and compressive strength after 1 pass deformation was calculated more than the higher passes. This difference may due to the interaction of dislocations with each other and the reaching of the flow stress to a saturation limit. It is recommended to prepare MDF mold and compression test alloy samples with larger geometric dimensions to perform a uniaxial tensile test after the MDF process and analyze the mechanical properties of the deformed samples in more detail and continue the MDF process until much higher deformation passes, and to reach an ultra-fine grain structure.

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