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INVESTIGATION OF PUNCHING PARAMETERS EFFECT ON MECHANICAL PROPERTIES OF Al-1100-O IN INCREMENTAL SHEET METAL HAMMERING PROCESS

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Incremental forming process is an efficient method for rapid prototyping and low-volume production. Recent ideas have been presented for a new type of this process known as incremental sheet metal hammering method. In incremental sheet metal hammering process, a three-dimensional work piece is produced by only moving a hammering punch over a clamped sheet metal without using a special die. In this paper, the effect of diameter and frequency of the punch on the mechanical properties of Al-1100-O sheet will be investigated. To investigate these parameters, the hardness, tensile strength and the grain size and orientation have been considered. Finally, it is indicated that by decreasing the punch diameter and by increasing the punch frequency, the hardness and the tensile strength of the formed material are increased. Two different statistical models were suggested for prediction of mechanical properties after incremental sheet metal hammering process.

Keywords: incremental forming, Al-1100-O alloy, punch diameter, frequency.

Introduction. Incremental sheet metal forming (ISMF) process was introduced by Leszak [1] for the first time about 45 years ago. This process was presented based on industrial research for dieless sheet forming. Nakajima [2] developed the first concepts of incremental forming process by numerical control machines to provide a flexible process. These improvements continued eventually led to the incremental forming machines by Allwood and Utsunomiya [3]. In recent years, assessment of the process parameters has been considered. For example, the influence of parameters on the dimensional accuracy by Ambrogio et al. [4] can be cited. Petek et al. [5] presented the effect of dependent variables on the forces. Ben Hmida et al. [6] presented the effect of initial copper grain size on the mechanical properties in incremental sheet metal forming.

In recent years, incremental sheet metal hammering (ISMH) process as a development of ISMF process was introduced. This process is based on incremental punching where a sheet metal is formed into the final shape by a series of punch impacts as shown in Fig. 1. Available literature in this field is limited and there is still a gap toward its industrial application. Puzik [7] studied on design and construction of several hammering tools. He has investigated different aspect of this method such as tools and advantages of the process. Tanaka et al. [8] studied a new method for rapid-prototyping with a mechanism that uses a servo-motor. A new method has been presented by Luo et al. [9] based on hydraulic mechanism, while the process has been analyzed in study [10] by simulation of incremental sheet metal hammering process.

In the present work, the influence of diameter and frequency of punch on the mechanical properties of the formed sheet is studied. In order to study these parameters, aluminum sheet is clamped and successive blows of punch is applied by a hammering tool. After preparation of the specimens the tensile and hardness tests have been

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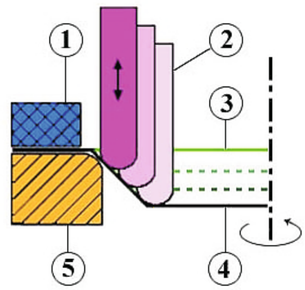

Fig. 1. Schematic of incremental sheet metal hammering process: (*1*) clamp, (*2*) punch, (*3*) initial shape, (*4*) final shape, and (*5*) support.

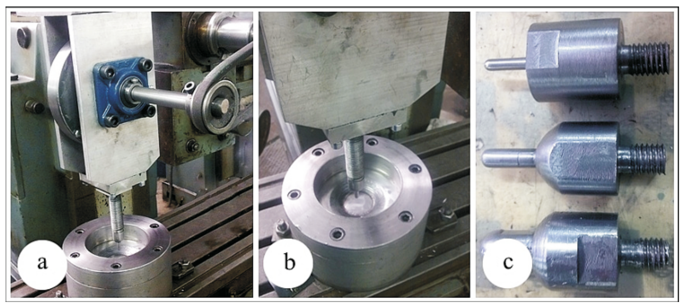

Fig. 2. Testing ring and tools: (a) hammering tools; (b) clamping system; (c) punches with different diameter.

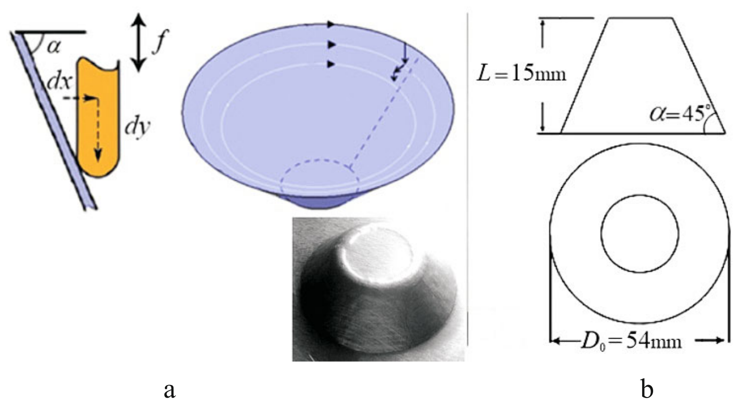

Fig. 3. The forming strategy in ISMH process with forming parameters $dx = dy = 0.1$ mm/s (a) and definition of the cone shape (b).

carried out to investigate the influence of forming parameters. In this paper, firstly the experimental procedure is explained. Then, the results and discussion of the mechanical properties and microstructure are presented.

1. Experimental Procedure. This section introduces the approach, materials and methods for assessment of mechanical properties.

1.1. Process Approach. To remove the effects of rolling process, a number of blanks of sheet is annealed for one hour at temperature 450℃. After that, sheet has been clamped such that no material may flow into the forming area. Then, by applying the successive blows of the punch on the clamped sheet, the ISMH process has been accomplished (Fig. 2a and 2b). In this study, the process was done using different punch diameters (Fig. 2c).

The strategy of sheet forming includes two stages: decreasing cone radius and increasing depth. The hammering frequency has three values of 13, 18, and 25 Hz, the cone angle is 45° and hammering increment is equal to 0.1 mm. Forming strategy and definition of the cone shape is shown in Fig 3.

After the forming process, the specimens have been cut out from the cone wall for tensile test, hardness measurements and metallographic investigations.

TABLE 1. Specimen Dimensions

L_t, mm	L_G, mm	L_U, mm	W_G, mm	W_U, mm	r, mm
30	5	12	5	3	4

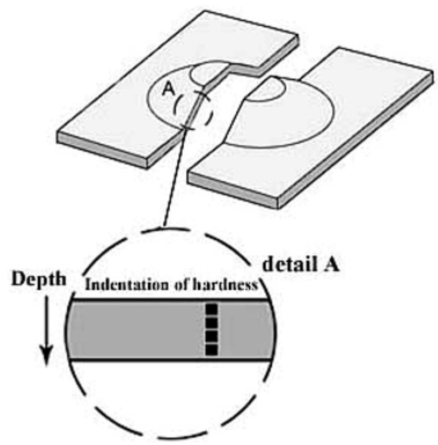

Fig. 4. Schematic of the hardness measurements.

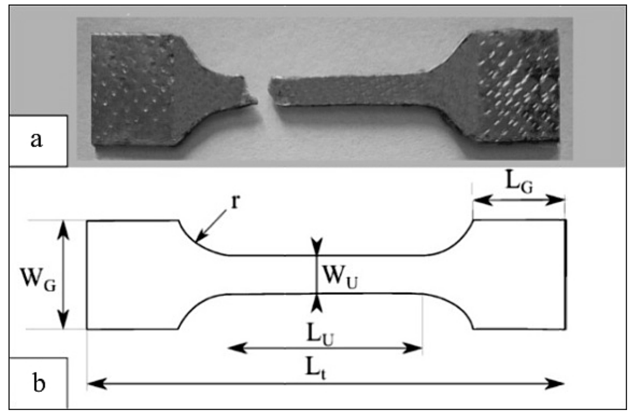

Fig. 5. The tensile test specimen after fracture (a) and its geometry (b).

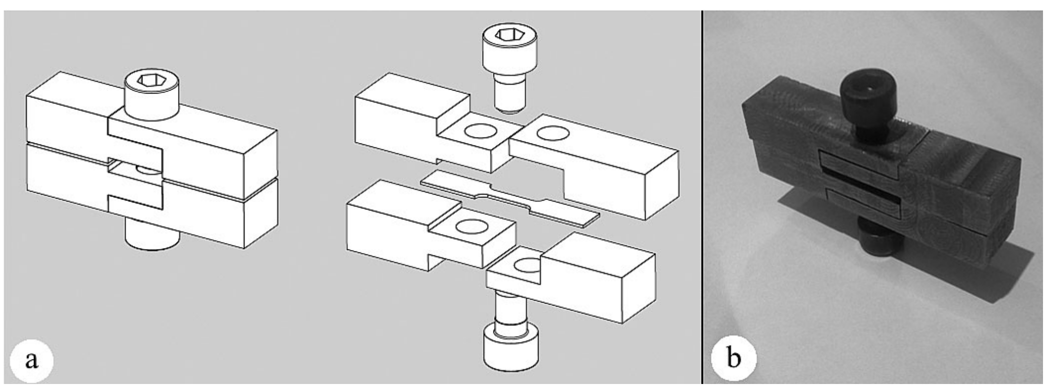

Fig. 6. The schematic of the buckling-preventing fixture.

1.2. Material. The material used in this study is an Al-1100-O blank with an initial thickness t of 0.5 mm and 140 mm in diameter. In addition, the initial hardness of annealed material is 25.7 HV.

1.3. Assessment of Mechanical Properties. This section includes the hardness evaluation, strength of material and investigation of grain size.

1.3.1. Hardness Evaluation. Aluminum sheet is formed by successive blows of punch with diameter of 3, 5, and 10 mm and the frequency of 13, 18, and 25 Hz. The Vickers microhardness measurements were carried out with 2 N load at the cross-sectional thickness shown in Fig. 4.

1.3.2. Strength of Material. The uniaxial tensile tests of the specimens have been carried out using a standard tensile testing machine. The crosshead velocity of the testing machine was 0.0017 mm/s. The reaction force F is measured by the way of load cell with a measurement range of 0–5 kN for all tests. The specimens were elongated up to fracture and the true stress–true strain curves were obtained. The geometry and dimensions of the tensile specimen are shown in Fig. 5 and Table 1.

Some technical problems were encountered in application of the conventional tensile test technique to thin sheets: due to specimen small thickness of 0.5 mm, the buckling has occurred at the first few of the tensile tests. To prevent buckling of a thin specimen, a tiny fixture was designed and manufactured (Fig. 6). When the crosshead jaw moves to clamp the specimen, the fixture bears the load of crosshead and clamping. Then, by rotating the screw, fixture will be opened and the specimen will fully bear the load.

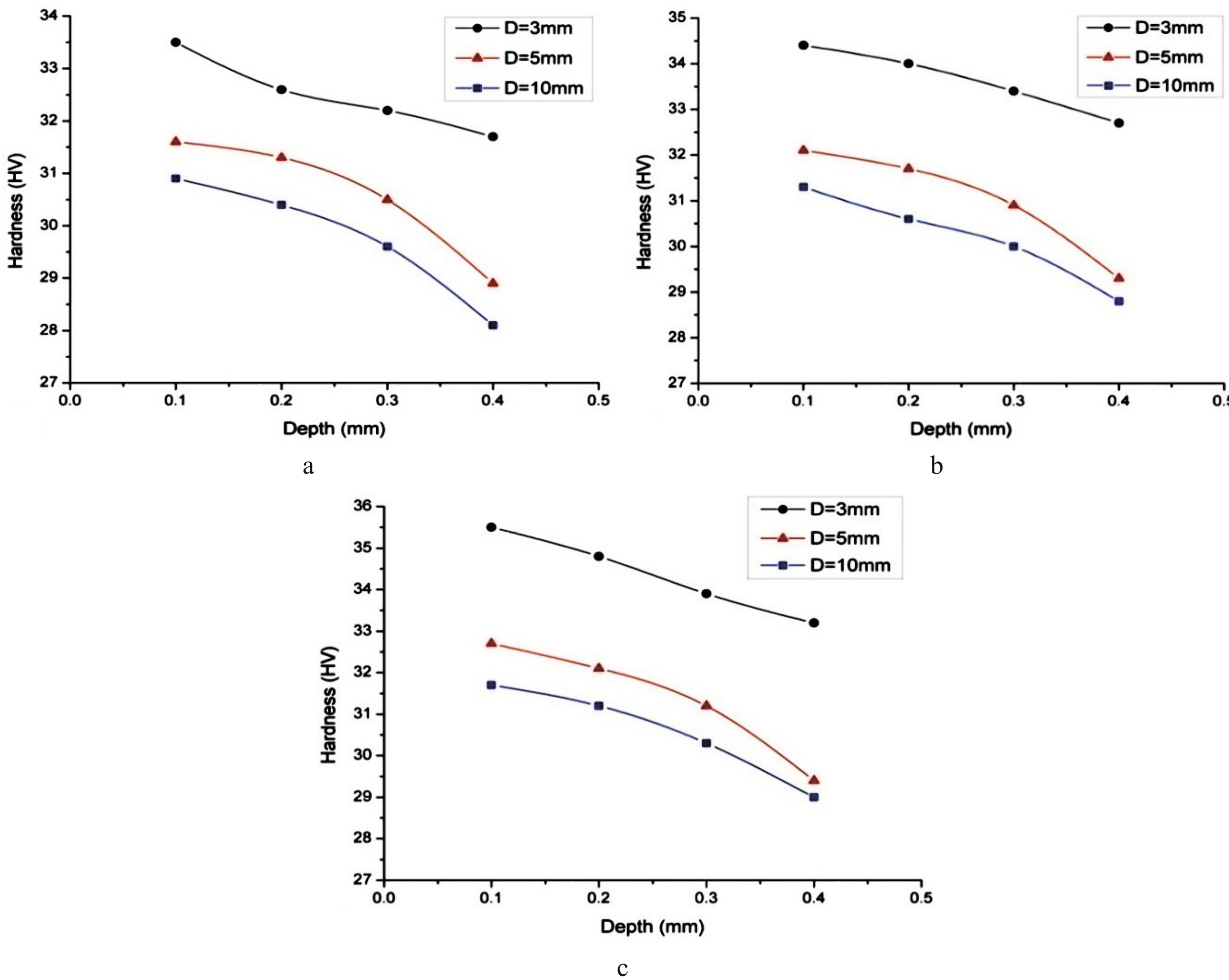

Fig. 7. Hardness vs. depth for different punch frequencies: 13 (a), 18 (b), and 25 Hz (c).

1.3.3. Investigation of Grain Size. After mounting the specimen, it was polished with sandpaper of diminishing roughness to get a flat section. Hydrofluoric was used for etching and grain boundary observation. The microstructure images will be shown in the results and discussion section.

2. Results and Discussion. In this section, the results obtained for hardness behavior, tensile strength and the grain size are presented. Also, two different statistical models were suggested for prediction of mechanical properties after ISMH process.

2.1. Hardness Behavior. The effects of diameter and frequency of punch on hardness are shown in Fig. 7. The hardness of the annealed specimen is 25.7 HV.

According to the plots presented in Fig. 7, the hardness after ISMH processes has increased. The hardness in the areas close to the punched surface is higher than in other points. This variation of hardness is related to the higher strain at the mentioned area. Moreover, since grain size reduction was observed with punch diameter reduction, this fact could also attribute for the increased hardness. The variation of hardness versus depth indicates that the effect of punch impact is less pronounced in the areas located farther from the punched surface. For example, the specimen hardness has increased about 37% for punch diameter of 3 mm and frequency of 25 Hz.

2.2. Tensile Strength. To assess the effect of punch diameter and frequency, the tensile test was used. The variations of stress–strain curves vs. different values of punch diameter and frequency are illustrated in Fig. 8. As shown, the stress–strain curve of annealed specimen is close to that implied by the elastic-perfectly plastic model.

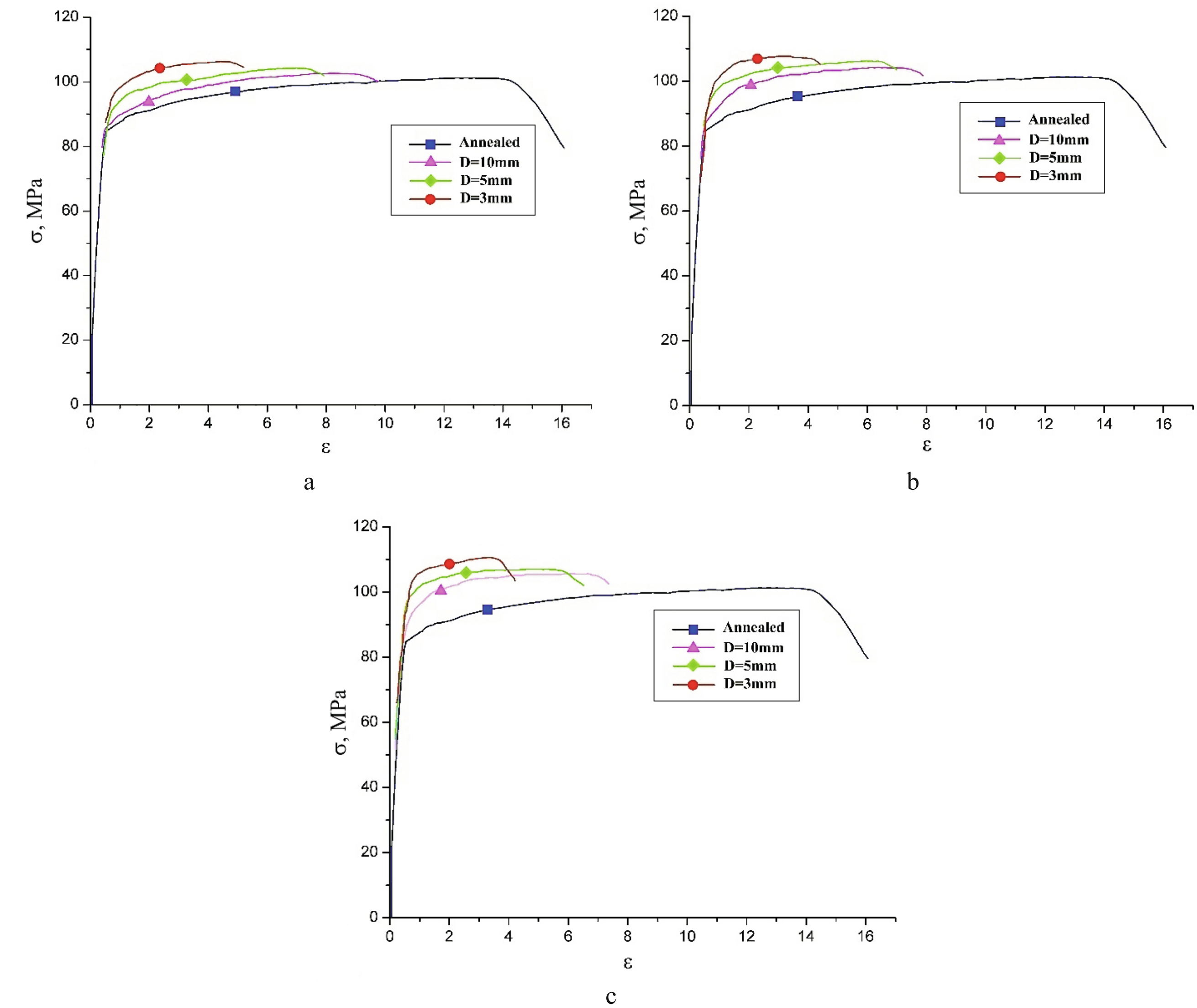

Fig. 8. Stress–strain curves for different punch frequencies: 13 (a), 18 (b), and 25 Hz (c).

By reducing the punch diameter, the trend of local strain increases and by increasing punch frequency, the strain rate increases. This event leads to increasing of strain-hardening rate. In literature, the strain-hardening phenomenon is attributed to:

(i) increased dislocation density at constant volume of microstructure leads to intensifying of intersections between mobile dislocations and some microstructural imperfections, such as, grain boundaries, Lomer–Cottrell barriers and forest dislocations;

(ii) intersection of mobile dislocations leads to formation of pile-ups behind the above imperfections. The dislocation pile-up is a completely different kind of dislocation array that is formed during plastic deformation. In pile-ups, dislocations interact elastically, so that dislocations of a pile-up apply a backward force to the other dislocations. This fact leads to increased resistance to shear stress of the material structure (the so-called Peierls–Nabarro stress) and results in the specimen strain-hardening [11, 12]. The yield stress and the ultimate tensile stress at the maximum frequency and minimum diameter of the punch are increased by 25 and 15%, respectively.

According to the above plots, the tensile strength was increased with reduction of the punch diameter: it decreases the material elongation, which naturally causes a higher tendency to the brittle failure. Also, the strength of the material was improved by increasing the punch frequency.

TABLE 2. Variation of Grain Size for Different Diameters and Frequencies of the Punch

Frequency (Hz)	Grain size (μm)			
	Annealed	D = 10 mm	D = 5 mm	D = 3 mm
13	57	55	52	43
18	57	50	44	39
25	57	48	39	34

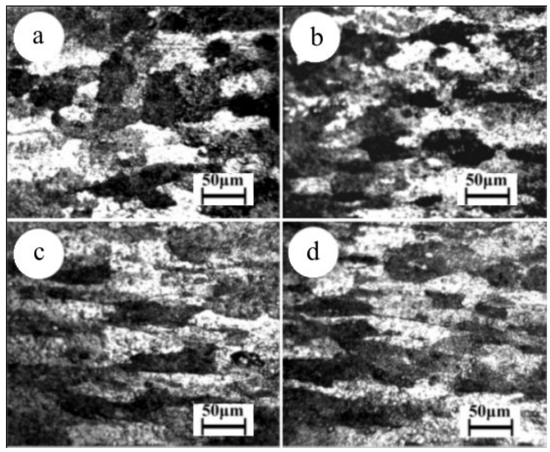

Fig. 9. Variation of shape and grain size in annealed specimens (a) and specimens produced with different punch diameters: 10 (b), 5 (c), and 3 mm (d).

2.3. Grain Size. The microstructure of the formed specimen after ISMH process is shown in Fig. 9. As shown, the grains are more tangibly stretched and become smaller as the punch diameter is decreased. The tendency to punch indentation (smaller punch diameter) induces higher shear stresses in the sheet and, consequently, leads to further grain refinement. In literature, this is related to the generation of sub-grains with a high density of dislocations in the high-Gibbs energy areas in microstructure, such as grain boundaries and twinning boundaries. The mechanism of growing of these subgrains is migration of dislocations from regions of high-density dislocations to lower-density places [11, 12].

The grain sizes for various process parameters are given in Table 2, from which it is evident that the stress applied to the sheet surface increases with punch diameter reduction. The geometry of the formed grains indicates that stress execution occurs in this process: the grains are elongated in the linear direction due to action of tensile stresses.

2.4. Modeling and Prediction. Due to the importance of the prediction of mechanical properties after ISMH process, two models were suggested. These presented models are based on the statistical analysis.

2.4.1. Hardness Variation Prediction. To predict the hardness variation of the surface after ISMH process, a model was presented. This model is based on the curve-fitting of a surface to the results using in Eq. (1):

$$H = 34.83 - 1.32D + 0.18f - 0.02Df + 0.09D^2 + 6.94f^2, \quad (1)$$

where H, D, and f are hardness (HV), punch diameter, and punch frequency, respectively. According to the above relation we can predict the hardness with adjusted R-squared equal to 0.99. The statistical analysis indicates that the hardness is more strongly affected by punch diameter than by punch frequency (see Fig. 10).

The above-mentioned prevalence of the punch diameter effect over frequency can be due to the fact that the applied strain in the ISMH process is related to the punch diameter while the frequency is related to the strain rate. In fact, due to the small strain-rate sensitivity of the material at room temperature, the effect of punch frequency on the hardness is lower than that of the punch diameter [13].

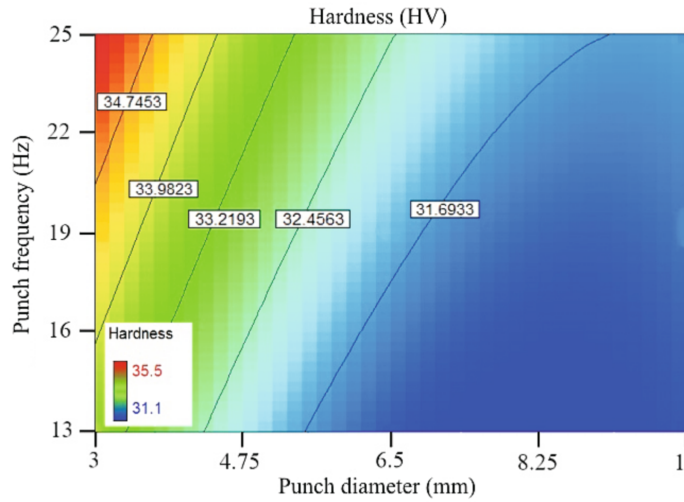

Fig. 10. Variation of hardness versus the punch diameter and frequency.

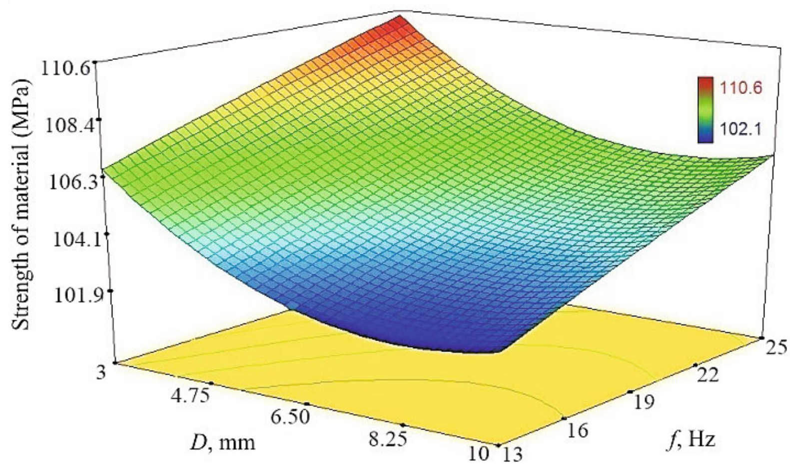

Fig 11. Variation of the material strength versus punch diameter and frequency.

2.4.2. Material Strength Prediction. To assess the effect of punch diameter and frequency on the strength of material, the tensile tests were performed. Since prediction of the material strength after the forming process due to the applied loads is of interest, the statistical analysis was used process the available test data and to achieve a smart model. The obtained model is presented by Eq. (2):

$$S = 108.68 - 2.74D + 0.38f + 3.57Df + 0.16D^2 - 2.08f^2, \quad (2)$$

where S is the material ultimate strength. The presented correlation has adjusted as R-squared of 0.95. For more illustrative presentation of the punching parameters' effect on the material strength, the respective plots in Fig. 11 were also constructed.

As shown in Fig 11, the maximum strength was attained for lower punch diameter (3 mm) and higher frequency (25 Hz). Also, the effect of frequency on the material strength has approximately a linear pattern, while the punch diameter has nonlinear effects on the ultimate tensile strength.

According to the literature, due to the punch diameter increase, the pressure required for the forming process is also increased [14]. In fact, the forming process is completed by one increment (impact) in case of a small punch diameter. As a result, the applied strain is increased by using a small punch diameter, whereas the material strength is also increased.

Conclusions. In this paper, the effects of diameter and frequency of punch on the mechanical properties of Al-1100-O aluminum alloy sheet in incremental sheet metal hammering process were analyzed. To investigate these effects, the hardness and tensile tests were carried out. Also, the effect of the tool parameters on the grain size was studied. Based on the results obtained, the following conclusions can be drawn:

1. The hardness of formed aluminum sheet is increased by reduction of punch diameter and increase in the frequency. The maximum variation of the hardness is about 37%.

2. By reducing the punch diameter from 10 to 3 mm, the yield stress and the ultimate tensile stress are increased about 24 and 7%, respectively.

3. The strength of formed sheet is improved by increasing the punch frequency, which also decreases the elongation values.

4. By decreasing the punch diameter and increasing the frequency, the grain size can be reduced.

5. Two different statistical models are proposed for prediction of the hardness and strength of the material under study after the forming process.

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