Experimental Investigation of the Effect of Die Shape on Mechanical Properties of Aluminum Alloy by Hot Direct Extrusion Process

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***Abstract*—This experimental study examined the impact of die shape on the mechanical characteristics of the AA7075, the aluminum alloy, extruded by hot direct extrusion. These characteristics include the extrusion load, hardness and compression tests, and stress-strain curve. Three alternative widths of the extruded metal exit zone (16, 18, and 20 mm) and three different die angles (15°, 30°, and 45°) were considered in the experiments. According to the findings, the extrusion load for the extruded items was the highest at an angle of 30° and the lowest at an angle of 15°. In terms of the hardness test of extruded materials specimens, the hardest areas were located at the outer circumference for all extrusion diameters and angles. Although the extruded samples' compression test results showed variations in the samples' loads before and after extrusion, it was also noticed that some of the other samples' stress and strain curves converged while others had only slight differences.**

***Keywords*—hot extrusion, Al-alloy, mechanical properties, process parameter, die angles**

I. Introduction

Extrusion is a type of plastic deformation when a metal billet (billet) is forced to flow through a die opening with a smaller cross-sectional area than the initial billet [1]. Due to its high productivity, low cost, and improved physical properties, extrusion is one of the most important metal-forming processes. Recent years have seen a significant increase in the use of the extrusion method in the production of components for the aerospace and machinery industries, as well as in mechanical manufacturing [2]. In order to accelerate the movement of the material through the die and avoid work hardening, hot extrusion is performed above the material recrystallization temperature [3]. Through this study, we seek to reduce the forming load and metal losses by changing the design of the extrusion dies. We designed and manufactured nine different dies in terms of the die angle and the exit area of the extruded metal. Three different angles were chosen (15°, 30°, and 45°) for the internal extrusion dies and three different diameters (16 mm, 18 mm, 20 mm) for the extruded metal exit area. We concluded from this study that the precise design of the extrusion die provides strong control over the applied loads and reduces stresses that may cause significant defects in the extruded product structure. This results in a product of high quality, good mechanical properties, and minimal load, resulting in longer extruder life and smaller amounts of metal being dispensed.

II. Literature Review

Many studies and research have been conducted on this subject. Saravanan and Kumar [2] studied the effects of die angle on cold-extruded Nano-Sic reinforced aluminum alloy characteristics, surface polish, and hardness. Qamar *et al.* [3] looked into how profile complexity affects extrusion pressure, metal flow, and flaws in the final product. Experiments with cold extrusion were carried out on three solid profiles with various levels of complexity. Halak *et al.* [4] studied the microstructure evolution of 7075AAaluminum alloy in the friction extrusion process under theinfluence of different extrusion forces and different die angles. The researchers used Finite Element (FE) software to analyze two strips of an aluminum alloy using low extrusion force and high forming angles on the first strip and high extrusion force and low extrusion angles on the second strip. The researchers concluded that the first type leads to a constant extrusion rate. In contrast, the second type leads to the complete recrystallization of the microstructure, which leads to an increase in the extrusion rate. Nilesh [5] used the direct cold extrusion method for aluminum alloys in extrusion dies with varied angles (30°, 45°, and 60°) to perform an experimental study on the impact of die angles on the quality of the extruded product, such as surface finish and product hardness. The researcher used

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aluminum alloy type AA6351 in the first experiment without any lubricant, then aluminum alloy type AA1100 in the second experiment with cherry fatand Vaseline as lubricants. The study came to the conclusion that 45° is the ideal angle to employ since it reduces the load placed on the die. He also concludedthat changing the angles of the die has no effect on the surface finish and that the highest values of hardnesswere obtained when using the angles (60°) and (30°). It was noted that the hardness values increased when Vaseline was used as a lubricant. Saeed *et al.* [6] used the REFORM-3D simulation program to study the effect of some basic variables of the extrusion process, such as die shape, material, and extrusion type. The researchers used three different metal materials to make the inner mould (brass, brass, steel), in addition to using two different shapes of the extruded metal exit area (square, circular) and two types of cold extrusion processes (front and back). Wang *et al.* [7] The capacity of the back extrusion procedure to create round and square bars with less effort made the researchers believe that it is superior to the frontextrusion process. The researchers also found that extruding circular bars requires less pressure than extruding square bars, regardless of the type of extrusion process. Shukur, J. J., & Jaber [8] studied some basic variables related to cold extrusion technology in a practical and theoretical way using the finite element method using the ANSYS 16 program. The researchers used three different moulding angles (45°, 30°, and 15°) and three moulding speeds (3, 2, and 1) mm/min. The researchers analysed and compared all the practical and theoretical results with each other. Bhavani *et al.* [9] studied the extrusion variations using the Finite Element Method (FEM) to simulate the extrusion process by using the DEFORM-3D program to simulate the hole in aluminium alloy type 6061AA with the aim of reducing defects, improving the extrusion process comprehensively and covering it, and increasingproductivity. Bressan and Marcelo [10] stated that it is possible to model metal flow mathematically due to the constant volume and variable viscosity in the metal forming process. The researchers used mathematical equations for the extrusion forming process by applying the finite volume method to determine the pressure and velocity values in the front extrusion process. Direct hot melting of aluminium alloys. Samaras and Haidemenopoulos [11] studied the development of the microstructure of aluminium alloys before and after extrusion forming processes by presenting a study on heat treatments of aluminium alloys, emphasising the formation of a microstructure that increases the extrusion ability of the alloy. Sun and Mueller [12] used a numerical method to simulate hot extrusion processes while modelling the microstructure of the aluminium alloy. The researchers used AA6005A aluminium circular bars to investigate the front and back extrusion process with different extrusion ratios, different temperatures for the workpieces, different extrusion speeds, and different cooling conditions for the extruded parts. Ambati *et al.* [13] conducted an experimental examination to see how the die angle affects the properties of the extruded product, such as hardness and surface finish. The results of the cold extrusion procedure for 6060 aluminum alloys were compared with those of Nano-SEC-enhanced cold-extruded aluminum alloys. Nowotynska and Kut [14] conducted a study to compare the effect of changing die angles on applied load and wear within the die during simultaneous extrusion. Rafid [15] studied the effect of the die angle on the stress distribution in the direct cold extrusion process of Al-1100 aluminum alloy. The researcher used the Deform3D program to simulate the direct extrusion process to find the best extrusion angle. Rahim *et al.* [16] used the Deform 3D simulation program to try to estimate the extrusion speed and temperature during the hot extrusion process of 6061 aluminum foil. The researchers focused their study on enhancing comprehension of the behavior and distribution of forming mechanics to predict the optimal parameters for the hot extrusion process using 3D forming with lubrication in weather forecasting. Martins and Button [17] used different methods (Finite Volume Method (FVM) using Mac Cormack software, Finite Element Method (FEM) using Forge software, Euler formulation and SIMPLE method) to analyse the direct hot extrusion process of aluminum alloy type Al-6060, Al-6351. Tahmasbi and Mahmoodi [18] produced wire-shaped specimens from AA7022 aluminum alloy using Friction Stir Extrusion (FSE), which uses heat generated by friction between the die and workpiece and extrusion pressure at different rotational speeds and extrusion forces. The researchers also studied the mechanical properties of the samples. After performing several tests on the samples, including hardness, compression and dislocation density tests. The researchers examined the microscopic structural properties of the materials using optical microscopy and Scanning Electron Microscopy (SEM). Rajesh and Anupama [19] studied the effect of lubricants and die angle on the cold front extrusion process of aluminium alloy type AA6063 by using the Taguchi-based grey relationship analysis method in analysing the extrusion process. The researchers used lubricating oil (Grease), engine oil, and castor oil in the same quantity as test lubricants, in addition to using die angles (50°, 60°, 0°, and 30°). After conducting the experiments, they measured the load, surface roughness, and hardness of theproduct, and with the aid of graphs, they concluded the researchers say that engine oil and a block angle of 50°were the two optimum choices.

Ayer *et al.* [20] used an extrusion die simulation of AA6063 aluminum alloy. Simulation using the program (Hyper Extrude Inspire Extrude Metal 2019) in the extrusion process at a temperature of 450 °C and an arm speed of 5 mm/s. Sheng *et al.* [21] studied the direct hot extrusion process of aluminum alloy type 7055AA and conducted a spray deposition process for this alloy before performing heat treatments to explore the effect of this process on the homogeneity of the microstructure. Paula *et al.* [22] studied the development of high-durability aluminum alloy wires (AL-CU-Li) for the purpose of using them as a raw material. The two researchers proposed two methods of using metal powders to produce wires. The first way consists of mixing powders, uniaxial pressure, and hot extrusion. To obtain the product, the two researchers used the Direct extrusions from Green Compacts (GC) method as a second meth. Odoh [23] and Charyulu *et al.* [24,] used the well-known SELLARS-TEGART model and developed constitutive equations to predict the hot flow stress behavior of these alloys. It was possible to study the effect of alloy composition on the flow stress behavior of AL, Mg, and Si alloys as well, such as the effect of extrusion conditions on the final mechanical properties. Solomon and Solomon [25] and Thanoon and Abdullah [26] conducted an experimental and numerical study of the process of extruding lead metal through a die consisting of 5 holes with a diameter of 5 mm to produce circular bars using Deform 3D as simulation program for metal formation. Koklu *et al.* [27] and Baysal *et al.* [28] conducted an experimental and numerical study of the effect of die shape on the metal flow pattern in the direct extrusion process and on the microstructure of the extruded product and its mechanical properties. The researchers used Forge2 software to simulate the extrusion process.

After reviewing the previous studies on this topic, it was clear that most of them used the Finite Element Technique (FEM) with different forming engineering software in order to obtain the optimal design of the extrusion die. It was also observed that cold forming was used in the majority of real-world experiments on extrusion processes with different parameters. The aim of the current study is to design and manufacture different metal dies to produce aluminum rods by a hot extrusion process, studying the effect of the shape of the dies on loads and on some mechanical properties practically.

III. Experimental Description and Extrusion Procedure

In this study, we designed insert dies with different angles (15°, 30°, and 60°) and three different diameters for each angle 16, 18, and 20 mm. The billets of initial diameter and height of 30 and 50 mm, respectively, had a chemical composition as presented in Table I.

TABLE I. Chemical Composition of the Billet Materials

Element	Percentage	Element	%
Mg	2.07%	Ni	0.010%
AL	89.12%	Cu	0.634%
Si	1.94%	Zn	4.15%
Ti	0.030%	Zr	0.250%
Pb	0.030%	Mn	0.251%
Cr	0.031%	Fe	1.14%

The extrusion die was drawn using Auto-CAD, as indicated in Fig. 1, in accordance with the dimensionsof the billet that has to be extruded. It consists of a Container, punch, Insert Die, Billet and Base. Fig. 2 shows a diagram of the parts of an extrusion die. Steel CK45 was chosen to manufacture the die and parts.

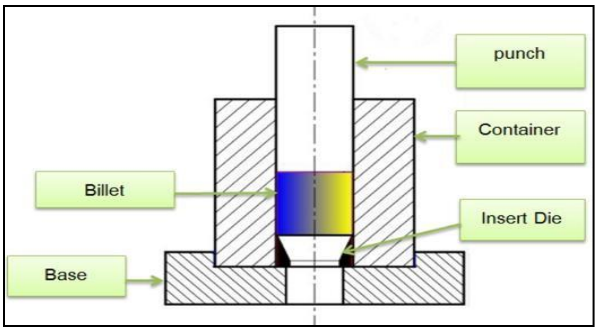


Fig. 1. Extrusion die assembly.

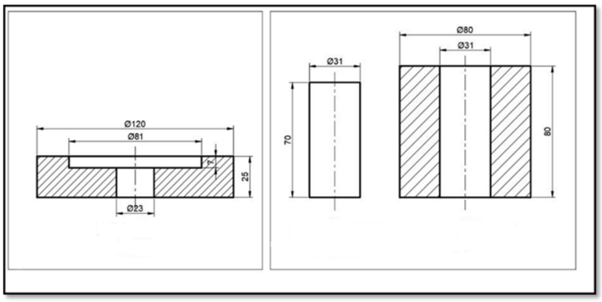


Fig. 2. Diagram of the parts of an extrusion die.

The SANS 100Ton hydraulic press equipment wasused to achieve the direct hot extrusion procedure. The die was heated with the billet inside it using an electric heater with a capacity of 2000 watts, as shown in Fig. 3. A laser thermometer was used to measure the temperature of the die and the billet. When the die reached the required temperature of 550 °C and the billet reached the temperature of 470 °C, the extrusion process was carried out. After finishing the extrusion process, the product was removed from the die. These steps were repeated according to the number of pieces required.

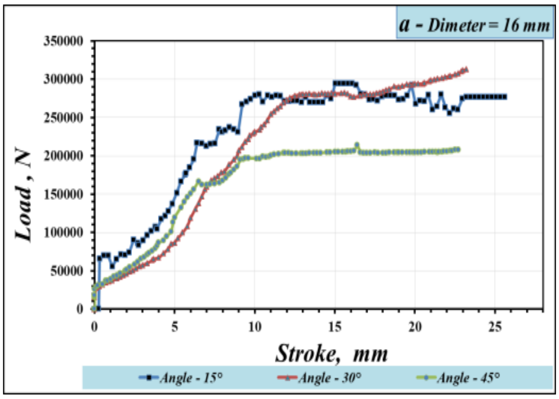
Fig. 3. The SANS 100Ton hydraulic press is used in the extrusion process, its accessories, and the method of heating the die.

IV. Result and Discussion

A. Extrusion Load

Fig. 4 shows the effect of different die angles (15°, 30°, and 45°) on the extrusion load of extruded metal with different diameters. From the figures,we notice that the highest load obtained was at an angle of 30° and load values ranging from (250,000–300,000) Newton for all diameters, while the load values were at an angle of 45°

for extruded products with diameters (16 mm, 18 mm) ranging from (200,000–170,000) Newton, where the more the higher die angle it lowers the load because the length of the shear line decreased, leading to a decrease in the dead metal zone. It was observed that the lowest forming load was at an angle of 15° for extruded products with a diameter of (20 mm) and load values ranging from (150,000–160,000) Newton. The large diameter of the die leads to the flow of the metal. Thus, we conclude that the best angle for extrusion dies in terms of shedding loads is 45° at a diameter of 18 mm for the extruded metal and an angle of 15° at a diameter of 20 mm for the extruded metal.



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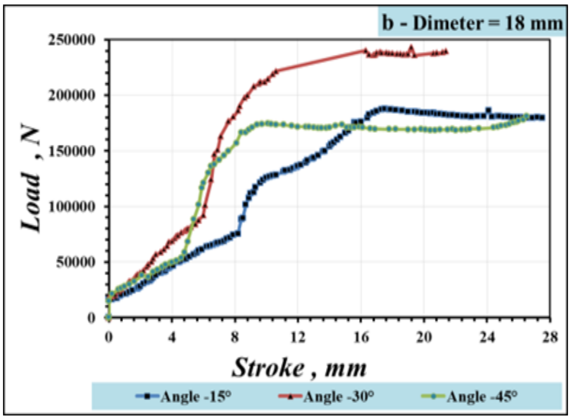

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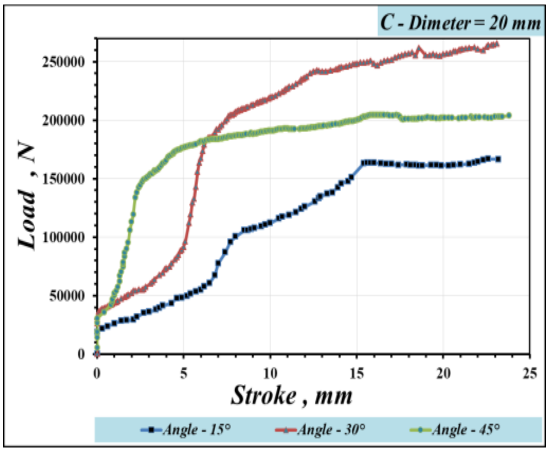

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Fig. 4. (a) 16 mm, (b) 18 mm, (c) 20 mm; Relationship between extrusion load and hole displacement for different die angles when the extruded metal diameter is constant.

B. Hardness Test

After cutting the extruded products into the required dimension, the samples were prepared for hardnesstest. In order to identify the distribution of hardness values on the surface of the samples after extrusion, the surface was divided into three locations from the centerarea to the edge of the sample (sample circumference). Because the sample is symmetrical, the hardness valueswere measured on one side, as shown in Fig. 5.

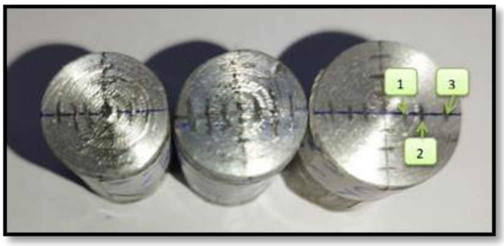
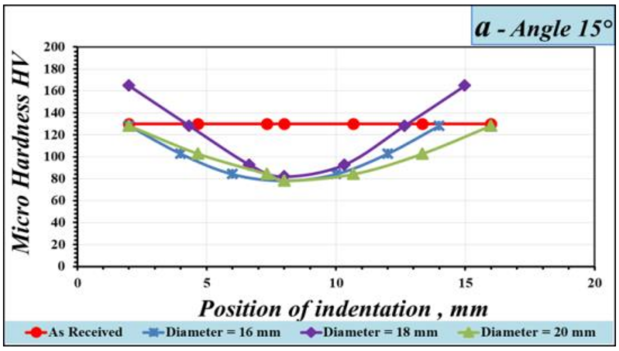


Fig. 5. Hardness measurement positions.

Fig. 6. shows the results of hardness measurement of extruded products at different angles and diameters of extrusion dies. The highest hardness of the extruded products for all extrusion diameters was at the points close to the surface that were affected by the formation because the excess frictional deformations are located toward the extruded surface. It was noted that the highest hardness at an angle of 15°, 30° was at a diameter of 18 mm. The hardness increases as the angle decreases due to the strain hardening caused by the high load necessary to resist the frictional force.

It was noted that the highest hardness angle of 45° was at 20 mm diameter.



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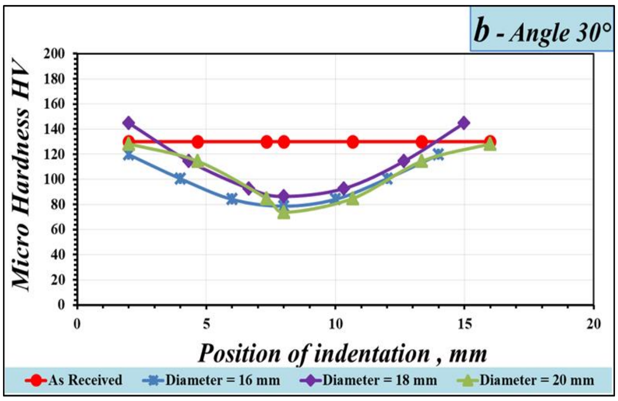

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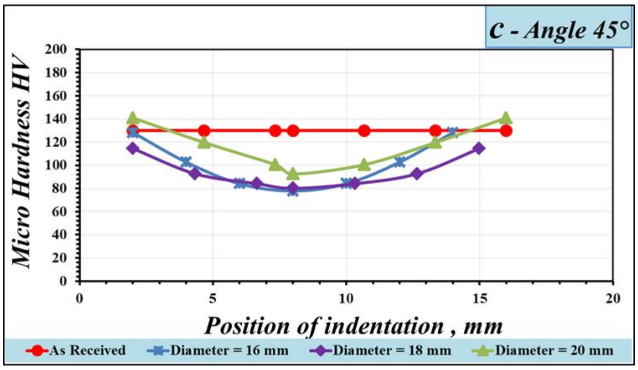

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Fig. 6. (a) 15°, (b) 30°, (c) 45°; Relationship between the hardness values and the test site for extruded products of different diameters.

C. Compression Test

Samples were prepared for inspection in order to evaluate theeffect of changing the shape of the extrusion die on thecompression test of the extruded metal. In this area, the sample surfaces were polished and levelled before the pressing procedure was carried out using a press. After being pressed, the sample configurations are depicted in Fig. 7.

Fig. 7. Samples after pressing.

The load-displacement relationship of the aluminum alloy before extrusion is depicted in Fig. 8.

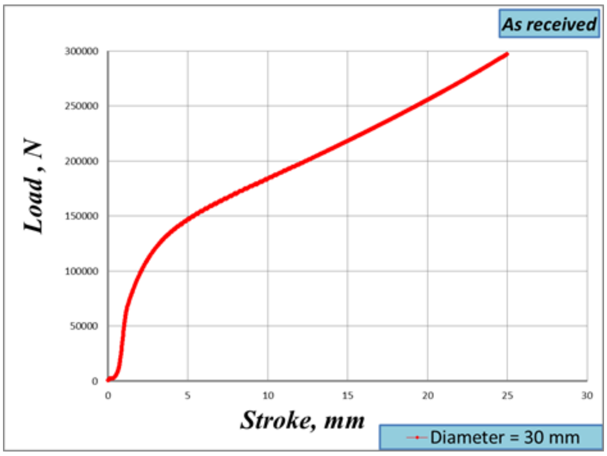
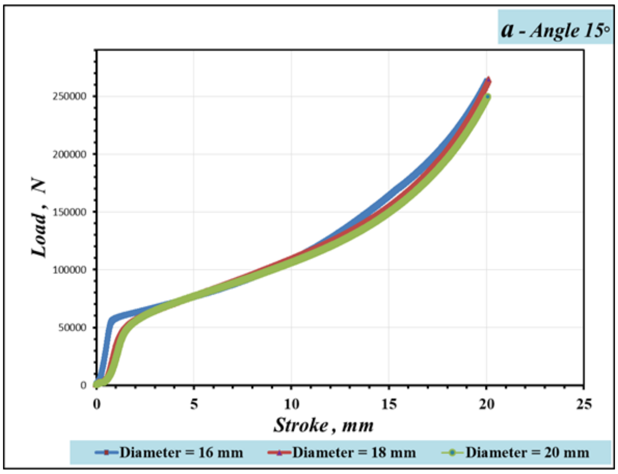


Fig. 8. The relationship between load and displacementbefore extrusion.

Fig. 9 shows the relationship between load and displacement in extruded samples used to study the effects of loads applied to extruded samples when using extrusion dies at angles of 15°, 30°, and 45° through the curves. With respect to 15°, it is noted that the sample with a diameter of 18 mm had the highest load, and the sample with a diameter of 20 mm had the lowest load. The sample with the 20 mm diameter had the maximum load for samples extruded at a 30° angle, whereas the sample with the 16 mm diameter had the lowest load. The same applies to the samples that were extruded at a 45° angle, as shown by the fact that the sample with the highest load had a diameter of 20 mm and the sample with the lowest load had a diameter of 16 mm.



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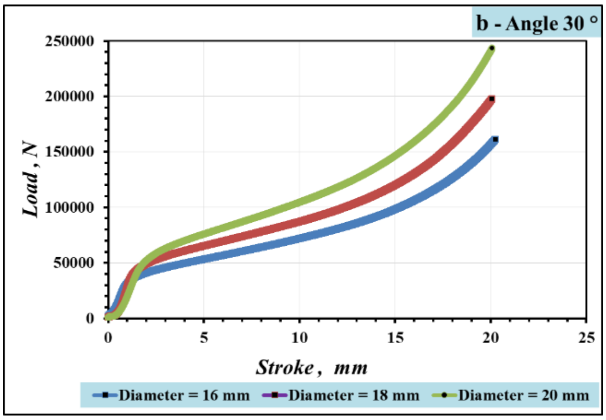

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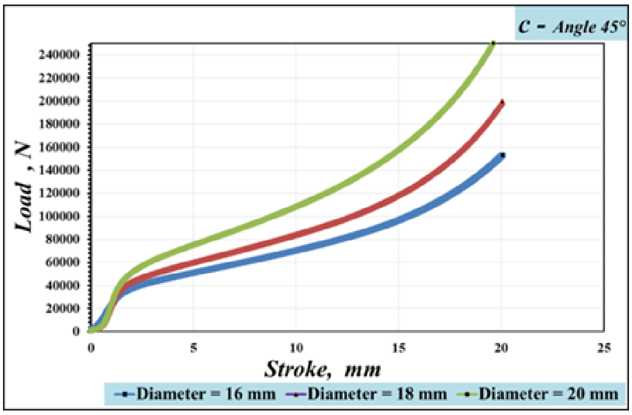

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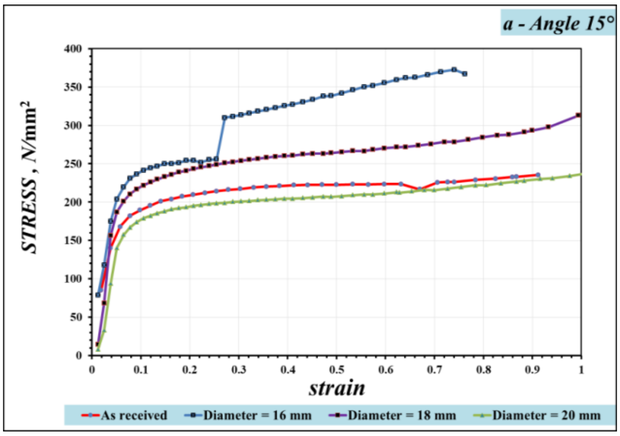
Fig. 9. (a) 15°, (b) 30°, (c) 45°; The relationship between load and displacement of extruded products of different diameters.

D. Stress-strain Diagram

After conducting a compressive test of the aluminum alloy before and after extrusion of the extruded samples, it is possible to study the change in the shape of the extrusion dies for the extruded samples according to the stress-strain curve, and it is good with the stress-strain curve of the alloy before extrusion, as shown in Fig. 10. At an angle of 15°, there is an evident increase in stress for the diameters 16 and 18 mm before and after extrusion. As for 30°, we notice that there is little difference between the stress distribution before and after extrusion, whereas at diameters of 18 and 20 mm, we notice that the stress is relatively less after extrusion. As for the angle of 45°, we also notice that there is convergence between the stress before and after extrusion, noting that the stress is relatively low at a diameter of 18 mm.



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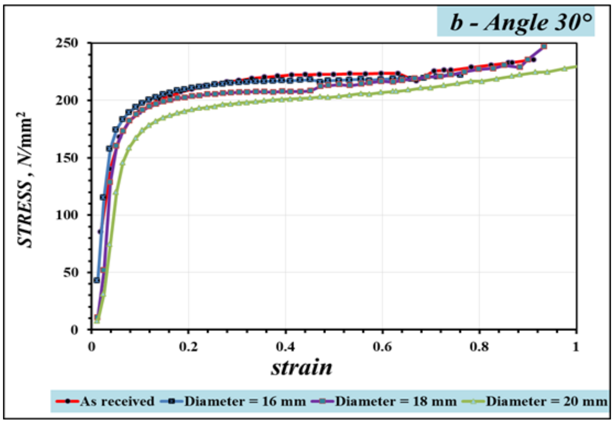

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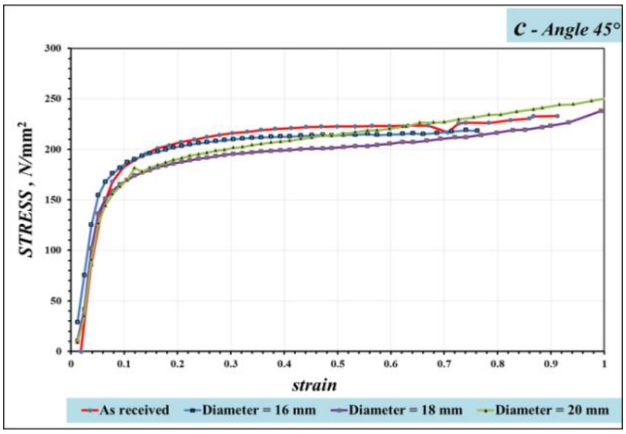

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Fig. 10. (a) 15°, (b) 30°, (c) 45°; Stress and strain diagram for the extruded products of different diameters with fixed die angles.

V. Conclusion

The summary of the results presented in this study shows that the precise design of the extrusion die offers a robust control of the applied loads and a reduction of stresses that could cause major defects in the structure of the extruded product. This results in a product of high quality, with good mechanical properties, and with the least amount of load, which leads to extending the life of the extrusion machine and dispensing less metal.

- Practically, the direct hot extrusion process was carried out for the selected AA7075 aluminum alloy in this study, and according to the desired parameters in the extrusion die, extruded products with different angles anddiameters were obtained.
- The practical results of studying the effect of changing the shape of the extrusion die on the forming loads proved that the highest load was obtained at an angle of 30° while the lowest load at an angle of 15° was at a diameter of (20 mm).
- By studying the effect of changing the shape of extrusion dies on the hardness of the extrudedmetal, it was found that the highest hardness of extruded products at an angle 15°, 30°, and 45°) and for all extrusion diameters was at points close to the outer diameter that was affected by the formation, while it was noted that the highest hardness was in the three positions at (18 mm) in diameter with respect to the two angles (15° and 30°). It was observed that the highest hardness in the three positions was (20mm) in diameter with respect to the angle (45°).
- The results of the effect of the applied loads on the extruded samples showed the difference between the loads of the samples before and after extrusion, as it was noticed that the highest load was for the sample whose diameter was (18 mm) and the lowest load was in the sample whose diameter was (20 mm) with respect to the angle 15°, it was noticed that the highest load was forthe samples extruded at an angle 30° and 45° was in the sample whose diameter was (20 mm) and the lowest load was in the sample whose diameter was (16 mm).
- At an angle of 15°, a difference was observed in the stress-strain curve before and after extrusion. As for the angle of 30°, it was noticed that there is a slight difference between the curves before and after extrusion. As for the angle of 45°, it was noticed that there is convergence between the curves before and after extrusion.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Zina Saad designed the model and the computational framework and analyzed the data. carried out the implementation. performed the calculations and Mohammed wrote the manuscript with input from all authors. Zina and Mohammed conceived the study and were in charge of overall direction and planning. All authors had approved the final version.

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