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AN EXPERIMENTAL STUDY ON A CONSTRAINED MULTI-HOLE EXTRUSION PROCESS

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ABSTRACT

A constrained multi-hole extrusion process is developed for controlling the length and the bending of the extruded products. In this process, the extruded products are guided in the blind-holes instead of allowing them to come out freely from the holes in die. The process is compared with conventional unconstrained (free) extrusion process by conducting a number of experiments. It is observed that the constrained multi-hole extrusion process provides equal lengths for all the extruded products and the products are not having any curvature. The stress-strain behavior and micro-hardness of the products coming out from the free and constrained processes are studied. The products from the constrained extrusion process are having higher ultimate tensile strength and hardness. Thus, constrained multi-hole extrusion process not only provides better dimensional control, but also provides stronger products. The only drawback of constrained multi-hole extrusion process is that in this process, extrusion load is considerably greater (about 4 times) compared to corresponding free multi-hole extrusion process. However, with respect to a single-hole extrusion process, the increase in the extrusion load is less than 50%.

Keywords: Multi-hole extrusion; Mechanical properties; Bending of extrudates; Extrusion load

1. INTRODUCTION

Demand for extruded products having high accuracy and quality has increased considerably in the recent past. Among various extrusion processes, multi-hole extrusion process has been found highly suitable for manufacturing smaller components with high production rate. Multi-hole extrusion process is the process in which a die with more than one hole is used. Production of straight, finished extruded parts with desirable mechanical properties from a multi-hole die is an important area of research.

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A number of researchers have carried out both experimental and theoretical investigations on multi-hole extrusion process. An early work was carried out by Johnson et al. (1958) who presented empirical expressions for calculating the ram force with the help of a slip-line field solution. Ulysse and Johnson (1998) carried out an upper bound analysis to study the effect of process variables in unsymmetrical single-hole and multi-hole extrusion processes and obtained simple expressions to estimate the extrusion pressure, the exit angles and velocities of the emerging products. Peng and Sheppard (2004) simulated the multi-hole die extrusion process to study the influence of the number and distribution of die holes on extrusion parameters. Using commercial finite element method (FEM) software FORGE3®, they investigated three aspects of multi-hole extrusion viz., the peak load, the flow pattern and the metallurgical structure.

In the last decade, the focus of the extrusion studies has shifted from the extrusion load to product quality. One important quality attribute is maintaining the straightness or the desired curvature of the extrudates. Several researchers have studied the process of bending of the extrudates with a motivation to have a control on the curvature of the extrudates. Shiraishi et al. (2003) proposed an extrusion process in which a billet is extruded through a die aperture whose normal makes some acute angle with the central axis of the container. This angle is called the inclination angle and is provided in order to obtain desired bending on the extrudates. Rectangular and H type bars and tubes of different dimensions were produced. It was observed that the curvature of the extruded bar increases with increasing inclination angle of the die regardless of the cross-sectional shape and dimension and decreases as the height and width of the die aperture increase. The curvature of the extruded tube increases exponentially by increasing the inclination angle of the die, and decreases linearly with increasing wall thickness of the tube regardless of the cross-sectional shape of the tube. This study throws some light on controlling the curvature of the extrudates. Onuh et al. (2003) carried out experimental study on cold extrusion of aluminum and lead alloys. They studied the effect of reduction, die angle and extrusion speed on the quality of the extruded products. The radii of curvature for both lead and aluminum alloy were found to increase with increase in reduction and extrusion speed. The average hardness value of the extrudate was also found to increase with increase in reduction and extrusion speed. Muller (2006) carried out finite element method (FEM) simulation along with experimental investigation to study the production of curved products by extrusion. Based on his study, the author has provided some guidelines for efficient extrusion of curved products. Li et al. (2010) investigated the regularity of die aperture offset in the extrusion process with experiments and finite element analysis. The complexity in metal flow in the plastic region increases with the increase in die aperture offset. The uniform velocity of metal flow caused by the proper die aperture offset can effectively control the bending of the extruded products.

The effect of process parameters on mechanical properties and microstructure of the extrudates has been studied by a few authors. Solomon and Solomon (2010) studied the influence of flat die on material flow, microstructure and mechanical properties during the direct single-hole extrusion process. The authors observed from simulations and experiments that the homogeneity and mechanical properties in the cross-section of the extruded products can be controlled by using a die with fillet radius in the bearing surface. This is because the friction during deformation process has major influence on the defects in the extruded products. Luri et al. (2011) studied the influence of die geometry on the damage of the processed parts produced by equal channel angular extrusion. In their study, FEM simulations and experiments were carried out. It was observed that fillet radii of the intersection of both the channel have much influence on the damage of the extruded products. The optimum intersection angle of 90º between the entrance and the exit channels gives minimum damage value. It is concluded that the geometry of the die has to be selected properly in order to deform the material with homogeneity along the cross-section of the extruded parts without damage. Sinha *et al*. (2009) studied the mechanical properties and variation in length of the extruded products by conducting a number of experiments on multi-hole extrusion.

Recently, several researchers investigated the bending of extrudates in multi-hole extrusion. Chen et al. (2008) studied the bending of aluminum alloy tubes in multi-hole extrusion process by using finite element analysis. Fang et al. (2009) carried out a comparative study of experiments and FEM simulation of extrusion through two-hole multi-step pocket dies. The authors focused on the metal flow, extrusion speed and peak extrusion pressure. Peng and Sheppard (2005) observed that the proper design of die pockets can significantly reduce the bending of the extruded products. Donati et al. (2009) experimentally studied the effect of pocket shapes on the flow of material inside a multi-hole extrusion die. They observed that the different pocket geometries and wall thicknesses result in different profile exit velocities at low and high speed conditions. You-feng et al. [2010] carried out FEM simulation on the extrusion process with two different multi-hole portholes die with and without pockets to investigate the metal flow, temperature at the die bearing exit and the extrusion load. From the simulation results, it was observed that pockets can be used to reduce extrusion load as well as to balance the metal flow.

Although the proper die design, particularly the die pocket design can help to control the bending of extrudates, it requires a thorough theoretical and/or experimental understanding of the process, which is not an easy task. Moreover, the design of pocket is highly sensitive to material and process conditions. Thus, there is a need for a robust method of producing straight products.

In this work, a constrained multi-hole extrusion process has been introduced for getting equal lengths of the extruded products. A number of experiments have been carried out to assess the suitability of the process. Mechanical properties such as micro-tensile strength and micro-hardness of the extruded products through constrained and free extrusion are also studied.

2. CONCEPT OF CONSTRAINED EXTRUSION

In the conventional direct extrusion, the material moves freely after exiting from the die. Such type of extrusion can be called free extrusion and is prone to produce bending of the extrudates. In order to avoid the bending, the material can be guided in a hole, which in effect is increasing the die land. However, in multi-hole extrusion, there is a need to guide the material in a blind hole instead of in a through hole to control the length of the extrudates. Guiding of the extrudates in the blind holes not only controls their lengths, but also improves their mechanical properties due to application of a forging type compressive load.

There are examples in the literature, where a combination of extrusion and forging has been used. For example, Altinbalik and Can (2006) studied the influence of number of teeth and billet diameter on the forming load and die filling in lateral extrusion of splines. Lateral extrusion is also called injection forging or radial forging. Here, a cylindrical billet contained in the chamber is compressed causing the radial metal flow through a fixed die cavity. Plancak et al. (2009) carried out backward extrusion by a shaped punch having involute gear profile and studied the total load, average punch pressure as well as the stress and strain distribution in the cross-section of the component. In this process also the material undergoes axial as well as radial compression.

In the above mentioned processes, plastic deformation is employed not only to obtain the precise shape but also to improve the mechanical properties. In fact, of late the severe plastic deformation is being used for obtaining ultrafine grained microstructure. For example, Talebanpour et al. (2009) carried out dual equal channel lateral extrusion of aluminum to study the microstructural and mechanical properties of the extrudates. The authors could obtain severe grain refinement and increased hardness after six passes of extrusion.

In the proposed constrained multi-hole extrusion, the extrusion load is expected to be considerably greater than the extrusion load for free extrusion, but compared to a single-hole free extrusion, the increased load may not be very high. On the other hand, the quality of extrudate in terms of its curvature and mechanical properties is much better compared to free single or multi-hole extrusion processes. As the extrudates are guided in blind holes, the length of the extrudate does not have any significant effect on the bending and mechanical properties.

3. EXPERIMENTAL PROCEDURE

Figure 1(a) shows the experimental setup. A 100 kN capacity universal testing machine (Make: Instron, Model: 8801) was used as an extrusion press. The container, die, punch and fixture were made of die steel (H13). Five-hole and nine-hole dies with hole diameter of 2 mm were used.

Figure 1(b) shows the front and top view of die and fixture assembly of the five-hole die. In the fixture the blind holes constrain the free flow of the extrudates from the die exit. Commercially available lead alloy was used to prepare billets of 20 mm height and 20 mm diameter. This material was chosen due to limitation of the load capacity of the available presses. The compression test of the specimen was carried out in a universal testing machine to find out stress-strain relationship. The following relation is fitted from the stress-strain data obtained:

$$\sigma_y = 53.46(\varepsilon_{eq})^{0.22} , \tag{1}$$

where σ_y is the flow stress in MPa and ε_{eq} is the equivalent strain. The Vickers micro-hardness test was carried out on the sample of billet material and the average hardness was found to be 10.2 VHN. The fixture with blind holes allowed the extruded materials to go into the blind holes in order to get the equal length of the product. Proper fastening was made to prevent misalignment of the die and fixture during extrusion. For each extrusion test, the container wall, die, punch and the specimen were first cleaned with ethanol and lubricant was then applied on the die, punch and container.

After each test, the entire set up was removed from the machine and the extruded products were cut carefully for measurement of length.

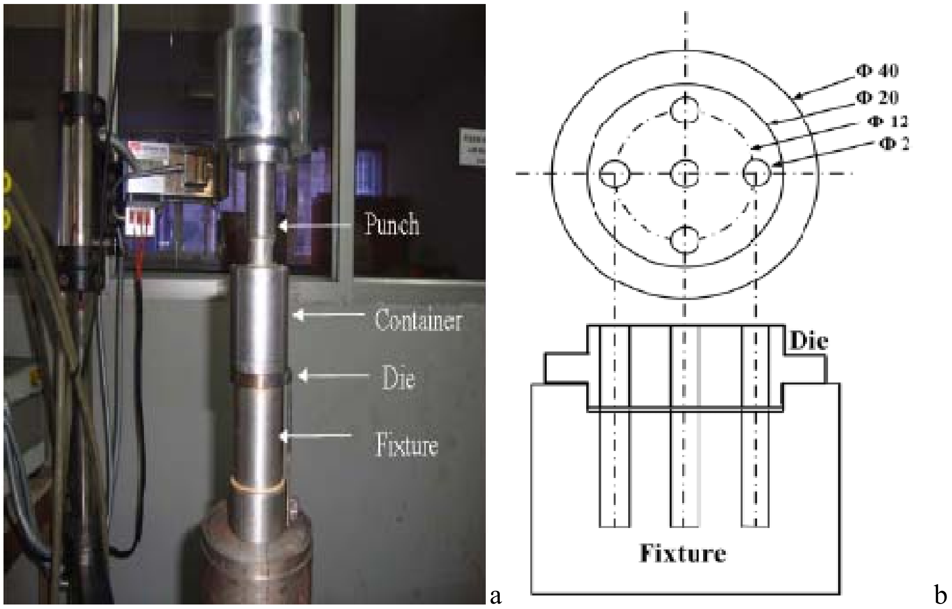


Figure 1. Experimental set up (a) photograph (b) drawing of die-fixture assembly.

Micro-hardness tests were carried out for extruded products through different holes on 5-hole and 9-hole dies. Three replicate experiments were conducted for each case and the average hardness of the product was recorded. Tensile tests were carried out for the extruded products on micro-tensile tester (Make: DEBEN, Model: MICROTEST, 5 kN capacity).

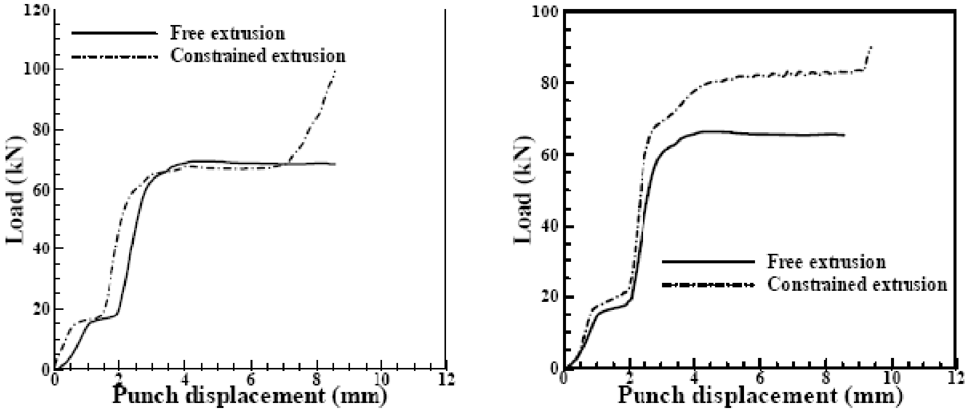
4. RESULTS AND DISCUSSION

In this section, the results of a comparative study of free and constrained extrusion are reported. Load-displacement curve, extruded lengths, bending of the extrudates, tensile strength of the extrudates and micro-hardness of the extrudates are the aspects that were studied.

4.1. Load–Displacement Curves

The load-displacement curve for free and constrained extrusion with five-hole and nine-hole dies is shown in Figures 2 (a) and (b) respectively (In the constrained extrusion cases, the load-displacement curve could not be plotted up to full load due to limitation of the equipment.). Initially there is a continuous increase in load till the material reaches plastic stage, where after the load remains almost constant till the outer surface of the billet touches the inner wall of the container.

After this load keeps on increasing till the material does not come out of the holes of the die. In free extrusion, once the extrusion starts, load keeps on reducing slightly due to reduction in the friction between the billet and container. The constrained extrusion process could be completed in a hydraulic press (Make: Lawrence and Mayo, 2000 kN capacity).



(a)

(b)

Figure 2. Load-displacement curves for free and constrained extrusion for (a) five-hole (b) nine-hole dies.

In constrained extrusion, once the extrusion through a hole is complete, the load further increases. This is due to the increased effective extrusion ratio. The maximum load for nine-hole die extrusion was found to be 240 kN, which is about four times more than the load required for free extrusion at similar process condition. For five-hole die constrained extrusion, maximum load of 180 kN was observed, which is about three times more than the load required for free extrusion. The higher load is the only drawback of constrained multi-hole extrusion process. For comparison, corresponding single-hole extrusion was carried out. The extrusion load was 135 kN, about 44% less than the maximum load of 240 kN obtained in the constrained extrusion with nine-hole die. The five-hole die constrained extrusion required only about 33% higher maximum load compared to single-hole extrusion. The benefits in the form of improved geometric and mechanical properties offset the disadvantage of some increase in the load. While carrying out the multi-hole extrusion, it is better to make an estimate of the load and set the pressure relief valve setting in the hydraulic press accordingly for the safety of the die, ram and machine.

4.2. Length of the Extrudates

In the constrained multi-hole extrusion, there is no variation in the length of the extrudates. In case of free multi-hole extrusion, the variation in the length of the extrudates is observed. The length of the extrudates obtained from different holes located at same pitch diameter and also from the same hole with replicate experiments for five-hole and nine-hole dies are shown in Tables 1 and 2. The coefficient of variation for length of the extrudates is calculated using the following formula:

$$\text{Coefficient of variation} = \frac{s}{\bar{x}} \times 100\%, \tag{2}$$

where s is standard deviation and $\bar{x}$ is average value .

Table 1. Length of the extruded products in free extrusion with five-hole die

Sl. No.	Length of extruded products (mm)					Coefficient of variation
	Centre hole	Peripheral holes				
		1	2	3	4	
1	65	73	60	88	77	14.98 %
2	74	80	73	96	80	11.42 %

Table 2. Length of the extruded products in free extrusion with nine-hole die

Sl. No.	Length of extruded products (mm)									Coefficient of variation
	Centre hole	Peripheral holes								
		1	2	3	4	5	6	7	8	
1	27	47	49	45	50	36	50	45	44	17.35 %
2	25	43	45	41	43	37	45	42	44	15.58 %

The unbalanced material flow causes variations in length of the extruded products. In replicates, the differences in length of the extruded products from the same hole are more for five-hole die as compared to nine-hole die. More number of holes on same pitch circle of the die provides lesser variation in length of the products as material flows easily through the holes with fewer gaps in between. A similar trend is observed in the results of Sinha et al. (2009).

4.3. Bending of the Extruded Products

The different radii of curvature were observed with the extruded products coming out from different holes in free extrusion. Moreover, the repeatability in bending pattern is poor with replicate experiments. Thus, it is difficult to get straight product with free extrusion. Though it has been reported earlier by a few researchers that the parameters like die pockets, eccentricity and die land length help in reducing the bending of the products, but the proper process and die design is a difficult task. The typical bent products obtained from free extrusion and straight products from constrained extrusion with a five-hole die are shown in Figures 3 (a) and (b) respectively.

Figure 4 shows the details of radii of curvature for the extruded products emerging from different holes. It is observed from Figures 4 (a) and (b) that significant bending occurs in free multi-hole extrusion process. The proposed constrained multi-hole extrusion eliminates the bending of extruded products without any need of optimizing the process parameters.

4.4. Tensile Strength of Extruded Products

Tensile tests are carried out for the extruded products obtained from both free and constrained extrusion with five-hole and nine-hole die and the maximum and minimum engineering stresses (among 3 replicates) are shown in Figures 5 and 6 respectively.

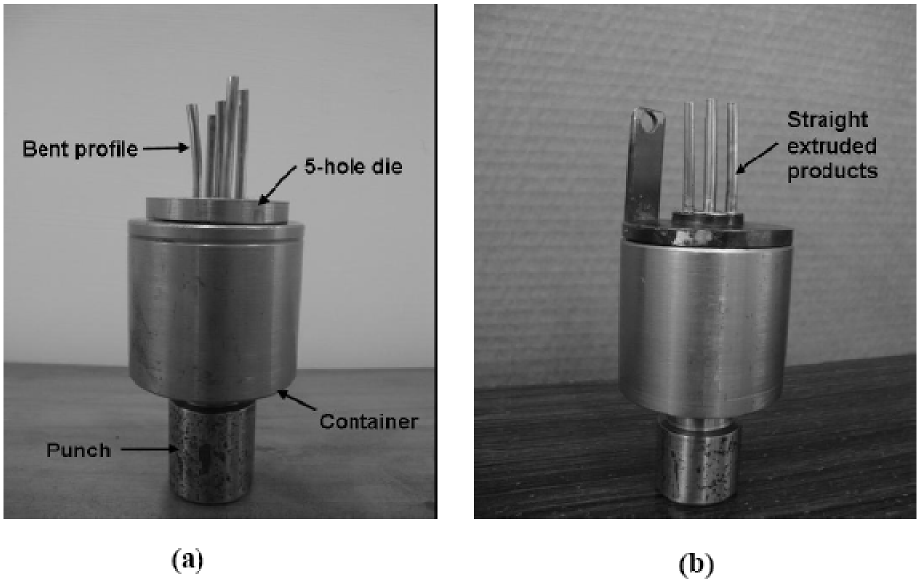


Figure 3. Extruded products from five-hole die (a) free extrusion (b) constrained extrusion.

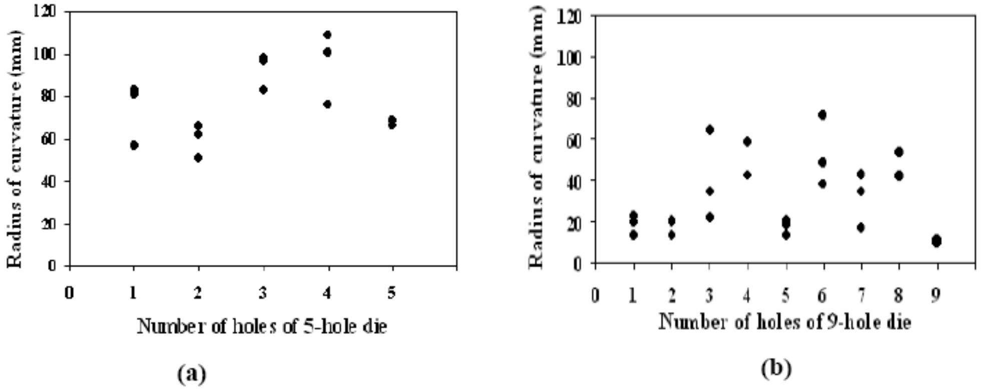
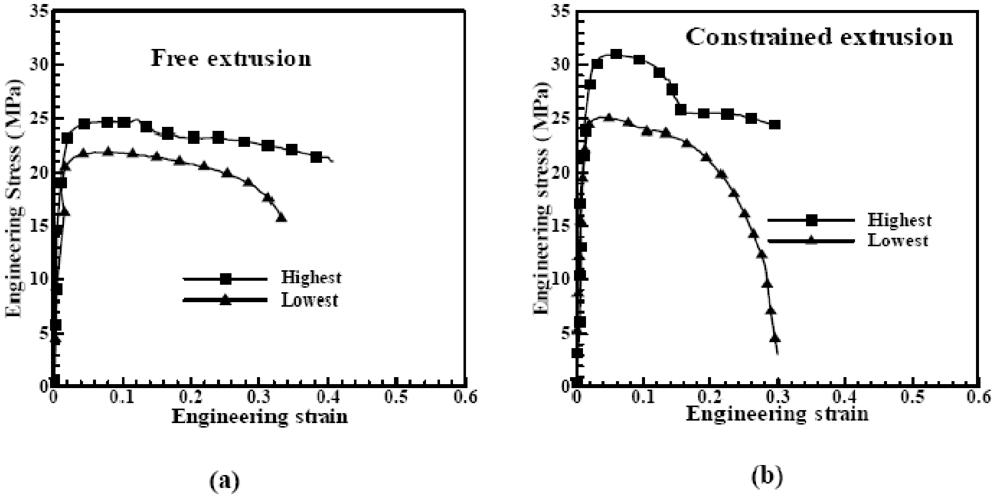


Figure 4. Radius of curvature of extruded products from (a) five-hole and (b) nine-hole die.

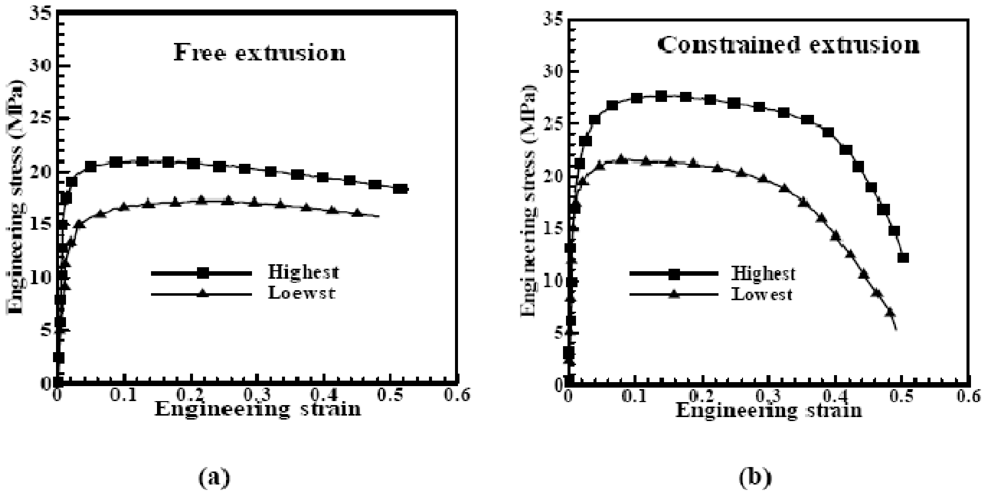
For both five-hole and nine-hole extrusion, higher tensile strength is observed for the products from constrained extrusion. The ultimate tensile strengths of the extruded products from free extrusion are shown in Tables 3 and 4. Due to non-uniform material flow, the extruded products form different holes of the same die get work hardened by different amounts.

As a result of this tensile strength are found to be different. In case of nine-hole extrusion, the ultimate tensile strength of the extruded products is less as compared to that of five-hole extrusion. The constrained multi-hole extrusion produces high strength products. This can be observed from Tables 5 and 6. For both five-hole and nine-hole die extrusion, higher strength products are obtained in constrained extrusion compared to free extrusion. This is due to more work hardening in constrained extrusion.



(a) (b)

Figure 5. Engineering stress-strain curves of the extruded products through five-hole die (a) free extrusion (b) constrained extrusion.



(a) (b)

Figure 6. Engineering stress-strain curves of the extruded products through nine-hole die (a) free extrusion (b) constrained extrusion.

Table 3. Ultimate tensile strength of extruded products in free extrusion from five-hole die

Sl. No.	Ultimate tensile strength of extruded products (MPa)					Coefficient of variation (%)
	Centre hole	Peripheral holes				
		1	2	3	4	
1	23.65	25.99	25.11	20.17	21.89	10.12
2	23.4	25.69	25.39	20.71	22.21	9.00

Table 4. Ultimate tensile strength of extruded products in free extrusion from nine-hole die

Sl. No.	Ultimate tensile strength of extruded products (MPa)									Coefficient of variation (%)
	Centre hole	Peripheral holes								
		1	2	3	4	5	6	7	8	
1	19.46	16.20	17.01	17.88	20.15	19.31	20.15	20.97	18.93	8.32
2	19.95	16.61	16.43	17.84	20.08	19.94	20.16	20.85	18.09	8.80

Table 5. Ultimate tensile strength of extruded products in constrained extrusion from five-hole die

Sl. No.	Ultimate tensile strength of extruded products (MPa)					Coefficient of variation (%)
	Centre hole	Peripheral holes				
		1	2	3	4	
1	28.29	25.50	25.11	30.03	25.11	8.35
2	27.58	25.70	25.64	29.14	25.61	5.88

Table 6. Ultimate tensile strength of extruded products in constrained extrusion from nine-hole die

Sl. No.	Ultimate tensile strength of extruded products (MPa)									Coefficient of variation (%)
	Centre hole	Peripheral holes								
		1	2	3	4	5	6	7	8	
1	23.75	27.5	20.34	22.15	24.65	21.62	21.90	22.77	22.51	9.27
2	24.49	27.1	20.08	22.93	24.42	22.15	22.08	21.98	22.12	8.81

Comparing Tables 3 and 5, it is observed that on an average ultimate tensile strength of extrudates from constrained extrusion is about 14% greater than the ultimate tensile strength from free extrusion. Also, there is a lesser variation in the ultimate tensile strengths of extrudates in constrained extrusion compared to extrudates in free extrusion. Comparing Tables 4 and 6, it is observed that on an average ultimate tensile strength of extrudates from constrained extrusion is about 22% greater than the ultimate tensile strength from free extrusion. However, in this case, the constrained extrusion is providing slightly more variation in the ultimate tensile strengths of the extrudates in comparison to ultimate tensile strengths of the extrudates in free extrusion. This is due to different amount of straining experienced by the extrudates. The extrudates that fill up the blind holes earlier undergo the compression at the later stage and harden more. The variation in the mechanical properties among extrudates may not matter much in many situations as long as the mechanical properties are better than a threshold limit. It is also possible to reduce the variation in the mechanical properties by applying the higher extrusion load, which will ensure proper compaction of all extrudates. Altinbalik and Can (2006) also noted that in lateral extrusion of splines a higher forming load attains better die filling.

An interesting observation is that multi-hole extrusion from five-hole die provides higher average ultimate tensile strength of the extrudates compared to multi-hole extrusion from nine-hole die, in free as well as constrained extrusion. This can be observed by comparing Tables 3 with Table 4 and Table 5 with Table 6. This is due to the fact that effective extrusion ratio in five-hole die in greater than the effective extrusion ratio in nine-hole die. Consequently, extrudates from a five-hole die are strain hardened more than the extrudates from a nine-hole die.

4.5. Micro-Hardness of the Extruded Products

Micro hardness tests are carried out for the extruded products coming out from the free and constrained extrusion through five-hole and nine-hole dies. Tables 7 and 8 shows the micro hardness values measured for the extruded products coming out from five-hole dies in free and constrained condition. Extruded products from constrained extrusion are harder (about 6%) than products from free extrusion.

Table 7. Micro hardness of the extruded products in free extrusion through five-hole die

Sl. No.	Micro hardness of extruded products (VHN)					Coefficient of variation (%)
	Centre hole	Peripheral holes				
		1	2	3	4	
1	12.8	11.9	12.6	12.56	12.9	3.11
2	12.43	12.4	12.03	11.96	12.53	2.09

Table 8. Micro hardness of the extruded products in constrained extrusion through five-hole die

Sl. No.	Micro hardness of extruded products (VHN)					Coefficient of variation (%)
	Centre hole	Peripheral holes				
		1	2	3	4	
1	13.33	13.1	12.86	12.83	13.23	1.69
2	13.67	13.1	12.76	13.1	13.26	2.5

Table 9. Micro hardness of the extruded products in free extrusion through nine-hole die

Sl. No.	Micro hardness of extruded products (VHN)									Coefficient of variation (%)
	Centre hole	Peripheral holes								
		1	2	3	4	5	6	7	8	
1	12.16	12.8	12.23	12.1	11.93	12.06	12.63	12.43	11.93	2.5
2	12.43	12.56	12.16	11.96	12.33	12.33	12.67	12.26	12.2	1.73

Table 10. Micro hardness of the extruded products in constrained extrusion through nine-hole die

Sl. No.	Micro hardness of extruded products (VHN)									Coefficient of variation (%)
	Centre hole	Peripheral holes								
		1	2	3	4	5	6	7	8	
1	12.76	12.63	12.96	13.23	13.16	12.83	12.56	12.90	12.96	1.72
2	13.10	13.00	12.73	13.00	12.73	13.16	13.20	13.03	13.06	1.29

Average micro hardness and coefficient of variation, obtained for free and constrained extrusion with nine-hole die are shown in Tables 9 and 10. Here also extrudate products from constrained extrusion are harder (about 5%) than products from free extrusion.

Comparing Tables 9 and 10 with Tables 7 and 8, it is observed that lower hardness products are obtained from nine-hole die as compared to five-hole die, for free as well as constrained extrusion. This is expected as the effective extrusion ratio in a five-hole die is greater than the effective extrusion ratio in a nine-hole die. Onuh et al. (2003) also observed that the average hardness value of the extrudate increases with increase in reduction. Surprisingly, the coefficient of variation in hardness value is less for nine-hole die extrusion as compared to five-hole die. This is contrary to the observations in case of ultimate tensile strength. This indicates that there may not be a strong correlation between the increase in micro-hardness and increase in ultimate tensile strength. There is a scope to carry out further investigation on this aspect for different materials.

CONCLUSION

In the present work, a constrained multi-hole extrusion process is proposed and its performance is compared with the free multi-hole extrusion process. The process is somewhat similar to a combination of extrusion and closed-die forging. The constrained multi-hole extrusion process is found to produce straight and equal length extrudates. The extruded products have better mechanical properties in constrained extrusion than in free extrusion.

The micro-hardness and ultimate tensile strength of extrudates from nine-hole die are lesser than micro-hardness and ultimate tensile of extrudates from five-hole die. This is expected as the extrudates from five-hole die undergo more straining than the extrudates from nine-hole die.

The developed process is more suitable for small-length components. For the longer components, the fixture size will be more and creating a deep hole with very high length to diameter ratio poses problems. The major drawback of constrained extrusion process is that it consumes more power than the free extrusion process. However, when a multi-hole constrained extrusion process is compared with a single-hole free extrusion process, this fact gets undermined. At the same time, improvement in geometric accuracy and mechanical property of the extrudates makes a strong case for the use of this process, in spite of some increase in the extrusion load and power.

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