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Comparative Analysis of Extrusion Processes by Finite Element Analysis

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Abstract

Extrusion processes are quite extended in the manufacturing of long products for a wide range of industrial applications. There are different approaches of extrusion processes, depending on either the final shape of the product to obtain or the maximum loading capacity of the equipment to be used. This work presents a comparative study of extrusion processes (solid and cup extrusion), considering both direct and indirect forming conditions and showing the most interesting differences between them. The comparison is realized by Finite Element simulation of the processes, using the code DEFORM F2. The material is a low carbon steel (AISI-1010) and the same extrusion ratio and ram displacement are considered in all cases. By comparing the required forces it can be concluded that required loads are higher in cup extrusion processes than in solid extrusion ones. Regarding the friction load, the maximum contribution due to the die-billet contact in cup extrusion is much higher than in the case of solid extrusion. On the contrary, the maximum friction load contribution due to the container wall is much higher in the case of solid extrusion than in cup extrusion.

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Keywords: extrusion; friction; direct; indirect; FEM

1. Introduction

Extrusion processes are one of most extended processes used in the manufacturing of long products for a wide range of industrial applications. There are different approaches of extrusion processes, depending on factors such as the final shape of the product to obtain or the maximum loading capacity of the equipment to be used [1].

Extrusion processes can also be divided into direct/forward and indirect/backward/reverse ones; in direct

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extrusion, the directions of work piece and tool movement are identical, whereas in indirect extrusion, both movements are opposite to each other so the metal is forced to flow through the extrusion die in a direction opposite to the motion of the ram [2]. Friction is one of the most significant parameters to be considered in direct extrusion, as the workpiece surface is moving along the container, so the contribution to the required energy can be extremely high; however, recently some studies are also focused on friction influence in inverse extrusion [3] and extrusion of non-rounded products [4]. Friction reduction in metal forming processes such as extrusion ones contributes to a more efficient performance of manufacturing processes [5].

In the last decades, different tests to determine friction coefficients under cold forming conditions have been developed on the basis of extrusion processes [6-8]; especially when other methods, such as the ring compression test [9, 10], are not suitable for metal forming processes where the surface expansion is high. Some examples are the double-cup extrusion test [11], the boss and rib test [12] or the combined forward rod-backward extrusion [13], among others. For quasi-stationary conditions at extrusion processes, required forces can be calculated as the sum of ideal forming force, friction force at the container, friction force at the die wall and shear force. Most of these studies have been implemented considering the Finite Element Method (FEM), as one of the most widespread computation tools in manufacturing engineering [14] and specifically in metal forming [15, 16]. By Finite Element Analysis (FEA) attention can also be paid to the improvement of die design [17]. In some other studies such as the one from Gouveia et al. [18], specific guidelines for FE simulation of cold forward extrusion are given.

This work presents a comparative study of solid and cup extrusions of low carbon steel (AISI-1010), considering both direct and indirect forming conditions, showing in detail the most interesting differences between them. The comparison is realized by FE simulation of the processes, using the code DEFORM F2.

Nomenclature

A_0	initial transverse section of the billet
A_f	final transverse section of the billet
D_0	initial diameter of the billet
F_c	extrusion load due to friction at the container-billet interface
F_{die}	extrusion load due to friction at the die-billet interface
F_{dh}	extrusion load due to homogeneous deformation
F_{ex}	total extrusion load
F_f	extrusion load due to friction
F_s	extrusion load due to shear
L	remaining billet length
a	Johnson model empirical constant
b	Johnson model empirical constant
r_x	extrusion ratio
ε_x	extrusion deformation
$\bar{\sigma}_f$	average flow stress

2. Methodology

This work analyses four different extrusion processes using a numerical simulation tool, concretely the code DEFORM F2. FEA is very useful in the study of manufacturing processes based on plastic deformation of materials such as metal forming processes. DEFORM F2 is a code especially developed to perform two dimensional analysis of metal forming processes. It is a simulation software that shares the FEM solver with DEFORM-2D. The program is especially effective in cases where a symmetry axis can be defined, because it is able to reduce the computational resources needed for simulation. As typical FE codes, DEFORM-F2 analysis are divided into three stages: pre-processing, simulation and post-processing.

As exposed before, four extrusion processes are considered, two direct and two indirect. For each one of these principal groups or types, two subtypes are considered, those related to the geometry of the final product obtained from the initial billet: solid and cup extrusion.

Figure 1 shows the two configurations considered for direct extrusion type. In Figure 2, the two extrusion processes for indirect extrusion are represented. Due to the symmetry of the processes only one half of the crosssection of each case is modelled. For all the cases the workpiece is cylindrical with an initial radius of 5 mm and 10 mm in height. The cross-sectional area of the final extrusion is also the same in all cases. Thus, for all the extrusion processes considered, the extrusion ratio is the same, defined as the ratio between the initial and the final cross-sectional area, as indicated in equation (1).

$$r_x = \frac{A_0}{A_f} \qquad (1)$$

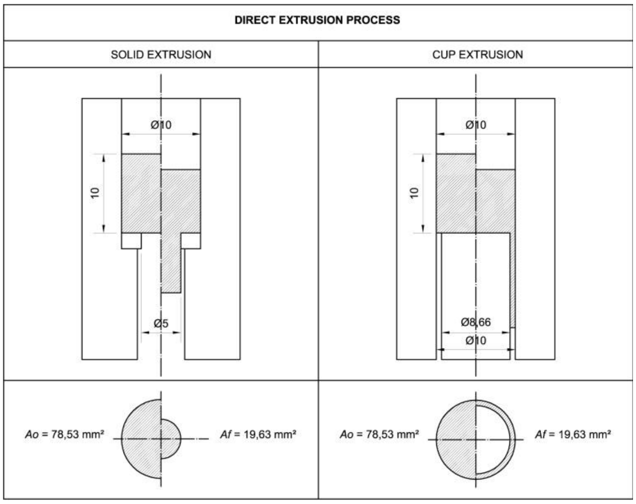


Fig. 1. Geometric sketches for direct extrusion.

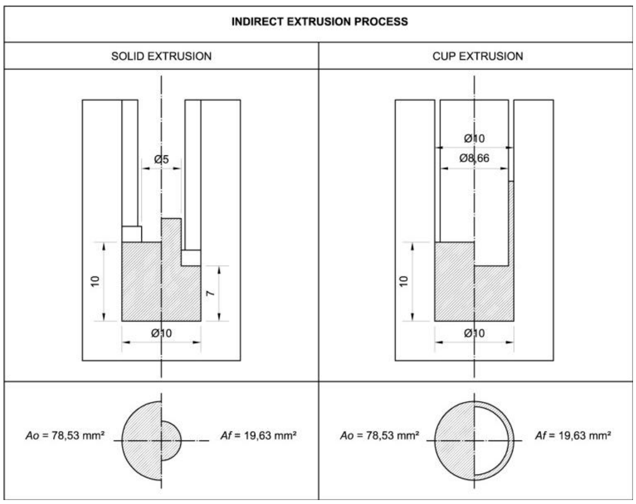


Fig. 2. Geometric sketches for indirect extrusion.

Once the geometrical conditions for all the cases have been defined, new parameters must be implemented into the software used. Thereby, all the simulated extrusions correspond with cold forming conditions and the material of the billets is a low carbon steel, concretely AISI 1010. This steel is widely used in extrusion processes as it presents good formability.

Not only the dimensions of the workpieces and extrusion tools are enough to define the extrusion process, but also additional information is required by the software. The shape complexity of the mesh that defines the geometry of the work piece must be specified. For all the analysis developed this parameter was considered as moderate. In the same way, the accuracy for the mesh was also defined as moderate.

On the other hand, other features for the extrusion process were addressed and introduced into the software. The extrusion semi-angle considered for the simulations of this work is always the same and equal to 90 degrees. A constant ram speed for the punch of 250 mm/s is selected, and in the same way, the total primary die travel is determined, with a value of 7 mm in all the simulations. The friction factor must be established too; Tresca friction law is used in this work, and three different values of the friction factor will be considered for each process in order to compare their influence in the different results. Thus, each one of the four extrusion processes considered run in three different friction conditions; low friction (m=0.08), maximum friction (m=1), and an intermediate situation between both previous values (m=0.5).

Once the conditions and components involved in the extrusion process are defined, the simulation analysis based on the Finite Element Method starts. This stage corresponds to the second of the software; the simulation. After finishing the analysis the third stage begins; the post- processing. The software enables the visualization of the results in different ways and allows their exportation for comparative analysis in order to be able to draw conclusions that help the optimization of manufacturing processes.

3. FE model validation

Several models have been developed in order to quantify properly the actual true strain and ram forces involved in extrusion processes [19, 20]. With the aim of validating the FEM extrusion model, empirical models based in Johnson studies [21] are employed for estimating the extrusion force in direct and indirect solid extrusion processes. Johnson developed the following equation in order to estimate the extrusion deformation (2):

$$\varepsilon_x = a + b \cdot \ln r_x \tag{2}$$

The extrusion ratio, r_x, is obtained as indicated in (1). Empirical constants a and b use to take the typical values 0.8 and 1.2, respectively. In indirect solid extrusion processes, the extrusion load can be approached by (3) according to [2]:

$$F = A_0 \cdot \bar{\sigma}_f \cdot \varepsilon_x \tag{3}$$

For direct solid extrusion processes, where the friction at the container-workpiece interface has an important effect, the load can be estimated by (3):

$$F = A_0 \cdot \bar{\sigma}_f \cdot \left(\varepsilon_x + \frac{2L}{D_0}\right) \tag{4}$$

In Figure 3 a comparison of the ram forces obtained by FEM with those calculated by (3) and (4), for indirect and direct solid extrusion, respectively, is shown.

The figure shows that the empirical model for direct solid extrusion (4) provides an upper limit for the ram force, and it is very close to the force obtained by FEA and the maximum friction factor (m = 1); whereas the empirical model for indirect solid extrusion (3) gives a lower limit of the applied force. In both cases, but especially in the case of direct extrusion, results from FEA are in good agreement with the values calculated by both empirical methods; the relative difference is less than 9% for indirect extrusion, and less than 3% for direct extrusion, so the FE models can be considered validated.

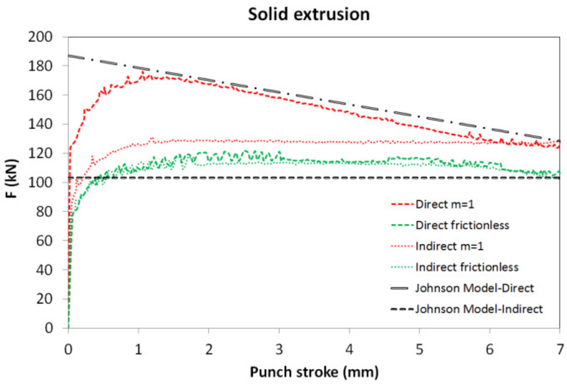


Fig. 3. FE models validation with empirical model developed by Johnson [21] (direct and indirect solid extrusion and limit friction conditions).

4. Results and discussion

Diagrams relating the extrusion force and the punch stroke are developed for each one of the cases of the study. Then, the different curves obtained are compared in a same diagram.

4.1. Solid extrusion

Figure 4 shows the results obtained for direct and indirect solid extrusion. Three curves are represented in each diagram, one for each friction factor considered in the simulations. The curves obtained from the values given by the code present oscillations. During the simulation process mesh nodes are constantly coming into contact or losing contact with the die/container surface, and this means a constant updating of the mesh system. Due to this, it is recommended the use of trend lines for the analysis of the results, being the polynomial type the most appropriate [18].

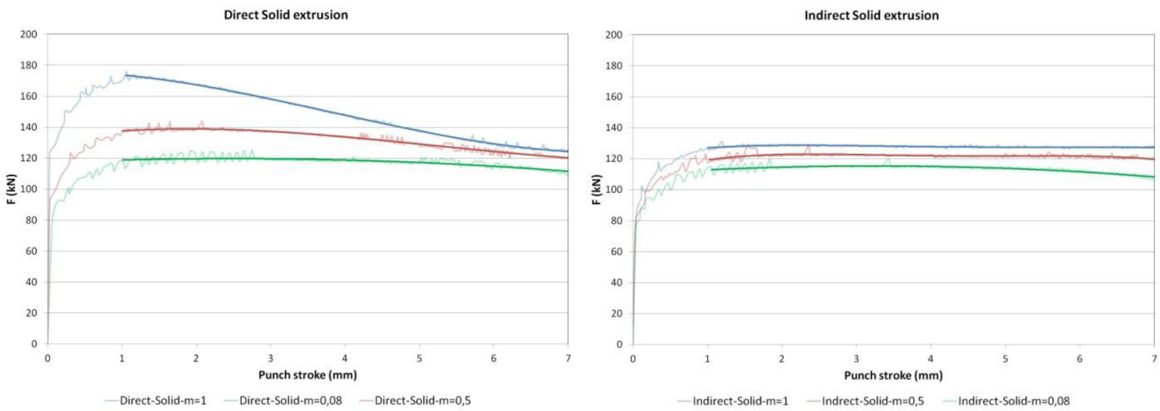


Fig. 4. Direct solid extrusion for different friction factors (left); Indirect solid extrusion for different friction factors (right).

In Figure 4 it is observed that in direct extrusion processes the required punch loads are higher than in indirect extrusion processes. The higher the friction factor, the higher the difference found. For the maximum coefficient of friction, the difference between punch loads in both processes, direct and indirect, is more pronounced. This is typical of direct extrusion processes, where friction at the container-billet interface makes the biggest difference in the required load. Thus, for m=1 (sticking conditions), one can see how the load-stroke curves have a clear descending trend, while this phenomenon is less important for lower values of the friction factor. The fact that the required load decreases with a constant slope is because the friction load against the billet movement decreases at constant speed when the extrusion is taking place, as the remaining billet length decreases.

In indirect extrusions, the workpiece displacement within the container does not occur, and therefore there is no friction between both, consequently, the loads required in the process are significantly lower.

However, there is a contribution to the friction load that has to be considered in both direct and indirect extrusion: this is the friction at the die-billet interface located at the end of the container. As a general trend, in both cases, the higher the friction factor, the higher the forces needed.

4.2. Cup extrusion

On the other hand, Figure 5 compares the ram forces needed in cup extrusion processes. Figure 5 (left) presents results for direct cup extrusion process and Figure 5 (right) presents the ones in indirect cup extrusion process. In both cases, again, three different friction values are considered (*m*=0.08, *m*=0.5 and *m*=1).

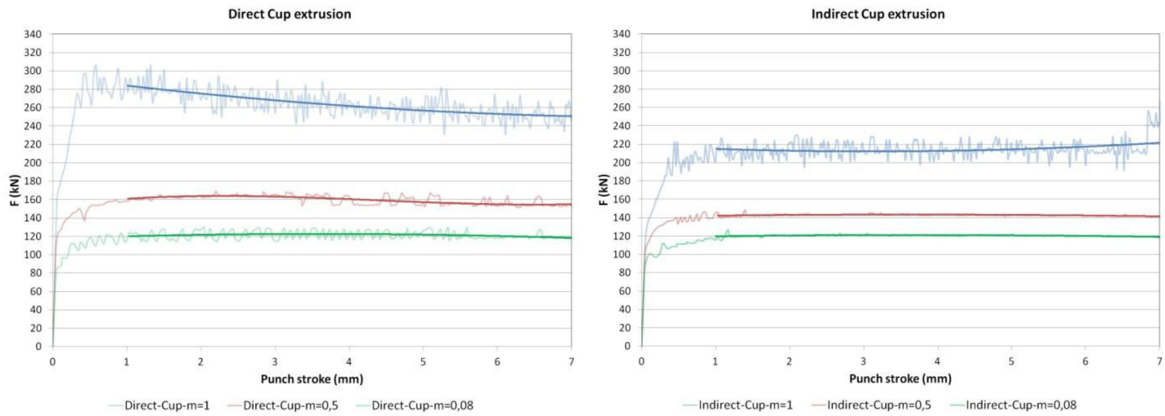


Fig. 5. Direct cup extrusion for different friction factors (left); Indirect cup extrusion for different friction factors (right).

As in solid extrusion, friction has a great influence in the value of the necessary loads. The higher the value of the friction factor, the higher the force required. This situation can be seen in both variants, direct and indirect extrusion processes. As in solid extrusion, for the highest values of friction, a descendent trend of the curve associated with the direct extrusion processes can be identified; while in the indirect extrusion cases, the curves are more horizontal, the loads remain more constant throughout the process at stationary conditions.

It is observed that the necessary loads for the simulated direct extrusion processes are greater than the required for indirect extrusion under the same friction conditions. This is as well due to the contact of the forming material with the container before being extruded through the extrusion die. In direct extrusion, the material is displaced by the punch and it is affected by the friction with the container walls. In the indirect extrusion this does not occur, as it can be observed in Figure 2; therefore, in comparison with direct extrusion, this component of the friction load does not exist so the necessary force to run the process is lower.

As a final comment, it is observed that forces required in cup extrusion are significantly higher than in solid extrusion for the same extrusion ratio.

4.3. Friction load contributions

Due to the relevance of friction in these processes, the contribution to the friction load is analyzed in more detail. Total load required in every extrusion process can be expressed as indicated in (5).

$$F_{ex} = F_{hd} + F_f + F_s \quad (5)$$

In direct extrusion processes, the component F_f can be divided as well as follows (6):

$$F_f = F_c + F_{die} \quad (5)$$

To quantify these contributions to the friction load, limit situations are considered: the highest friction value m=1 (corresponding to sticking conditions) and the ideal situation of a frictionless process m=0. As the software does not allow introducing the value of zero for the coefficient of friction, a value of 0.00001 is introduced as the closest value to the desired theoretical conditions. Thus, comparing the necessary forces required in both limit situations, the contributions to the friction load can be obtained and discussed. In Figures 6 and 7, the contributions to the friction load are represented by calculating the difference between the required load under sticking conditions and perfectly sliding conditions, for direct and indirect solid extrusion.

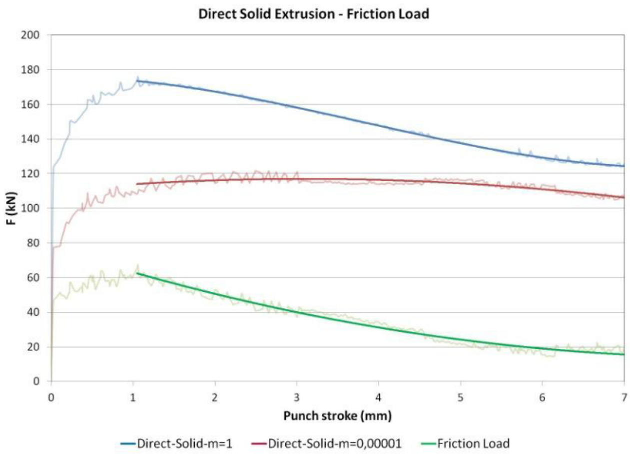


Fig. 6. Friction load for direct solid extrusion.

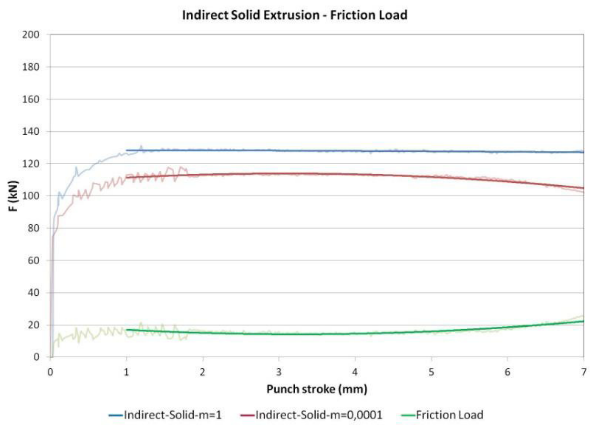


Fig. 7. Friction load for indirect solid extrusion.

When the initial billet is displaced along the container in direct extrusion processes, the final friction load is related to two different friction phenomena as explained above ($F_c + F_{die}$). In indirect extrusion processes this does not happen. In both cases, direct and indirect, there is a friction load contribution consequence of the contact between the material and the die, F_{die}. Only in direct extrusion the friction load at the container walls (F_c) will appear, so the maximum contribution of the component F_{die}, that is common to both kinds of processes, can be directly obtained from the friction load contribution in indirect extrusion process (green curve in Figure 7), and can be estimated around 20 kN. Figures 8 and 9 present the friction contribution to the load for the cup extrusion both in direct and indirect processes. As in the previous case, both graphs can be compared to evaluate the force associated to each type of friction condition, thanks to the different situations that take place in direct and indirect extrusion processes.

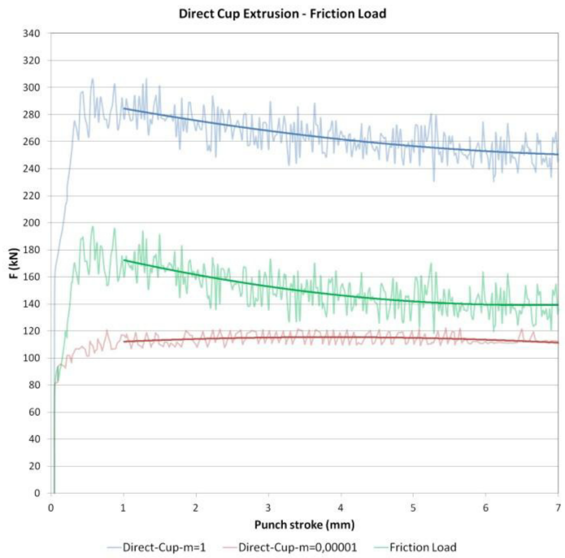


Fig.8. Friction load for direct cup extrusion.

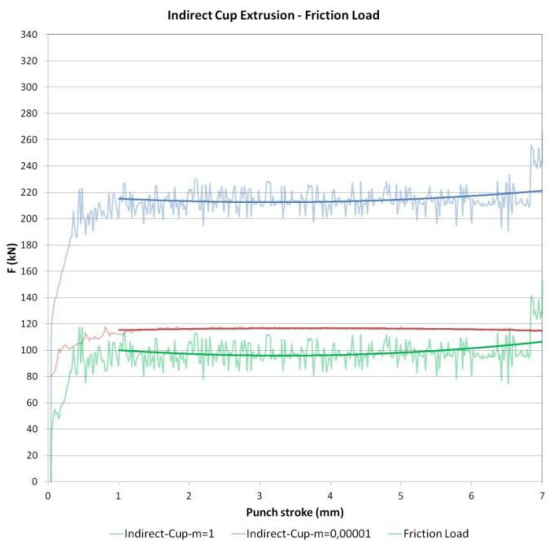
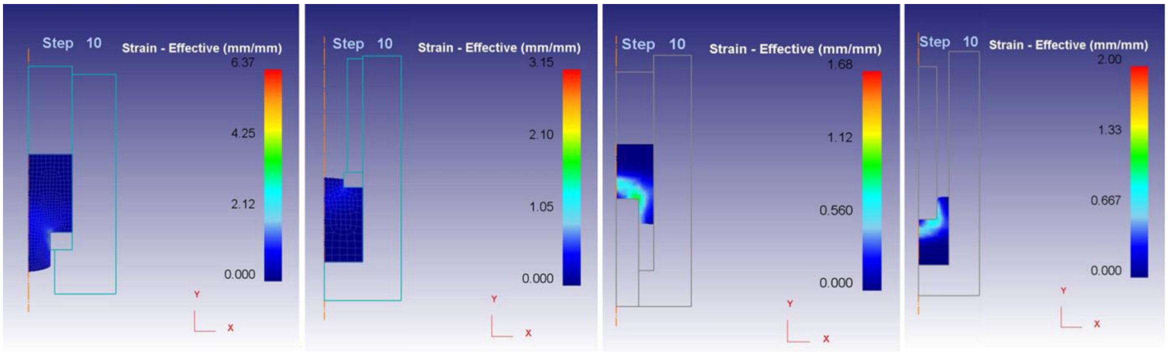


Fig. 9. Friction load for indirect cup extrusion.

Comparing the results for cup extrusion processes, and following the same methodology, the friction load at the die, F_{die}, can be directly obtained from the indirect cup extrusion process (green curve, Figure 9). In this case, the maximum friction load contribution due to the die-billet contact is around 100 kN, that is much higher than in the case of solid extrusion. On the contrary, the maximum friction load contribution due to the container wall is much higher in the case of solid extrusion than in cup extrusion.

As one example of the FE simulations, strain effective diagrams are shown in Figure 10 for a friction factor of m=0.08 and the same punch stroke during the deformation process.



(a) (b) (c) (d)

Fig. 10. Effective strain diagrams for $m = 0.08$. (a) solid direct ex., (b) solid indirect ex., (c) cup direct ex.; (d) cup indirect ex.

Conclusion

In this work, solid direct and indirect extrusion processes as well as cup direct and indirect extrusion processes of low carbon steel (AISI-1010) have been compared. DEFORM F2 has been used to simulate different extrusion processes in order to analyze the friction load contributions to the final load required in this kind of processes.

As expected, it is observed that the necessary loads for the simulated direct extrusion processes are greater than the ones required for indirect extrusion under the same friction conditions. This is due to the contact of the billet with the container before being extruded through the extrusion die. In direct extrusion, the material is displaced by the punch along the container and it is affected by the friction with the container walls. In indirect extrusion this does not occur, as it can be observed in Figure 2; therefore, in comparison with direct extrusion, friction at the container walls, F_c, is negligible and the necessary force to run the process is lower.

By comparing the load results of direct and indirect processes, it can also be identified the contribution of friction at the die, F_{die}, to the friction load. The maximum friction load contribution due to the die-billet contact in cup extrusion is much higher than in the case of solid extrusion. On the contrary, the maximum friction load contribution due to the container wall is much higher in the case of solid extrusion than in cup extrusion. Required loads for the same extrusion ratio are higher in cup extrusion processes than in solid extrusion ones. Thus, the analysis performed allows the estimation of the maximum effect of friction in the four extrusion processes, and to clearly identify the contributions of friction at the container walls and the extrusion die.

In future works this analysis will be extended to more complex geometries of the extrudates and to the extrusion of advanced materials such as high strength steels whose formability is poor compared to other metallic alloys. This will lead to broaden the application field of extrusion processes and to investigate their limitations in order to improve their performance in future industrial scenarios.

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References

[1] G.W. Rowe, Principles of Industrial-Metalworking Processes, Edward Arnold, London, 1977.

[2] M.P. Groover, Fundamentals of modern manufacturing , fourth ed., John Wiley & Sons, Hoboken, New Jersey, 2010.

[3] L. Butnar, N. Pop, H. Cioban (2009). Researches Concerning Friction Influence on Material Flow in Inverse Extrusion of Toothed Gears, Annals of DAAAM for 2009 & Proceedings of the 20th International DAAAM Symposium, 25-28th November 2009, Vienna, Austria, ISSN 1726-9679, ISBN 978-3-901509-70-4, Katalinic, B. (Ed.), pp. 0797-0798, Published by DAAAM International Vienna, Vienna.

[4] N. Ghiban, G. Chelu, N. Serban, B. Ghiban (2008). Extrusion Process Modelling of the Non-Rounded Products: a 2-D Approach, Annals of DAAAM for 2008 & Proceedings of the 19th International DAAAM Symposium, 22-25th October 2008, Trnava, Slovakia, ISSN 1726-9679, ISBN 978-3-901509-68-1, Katalinic, B. (Ed.), pp. 0517-0518, Published by DAAAM International Vienna, Vienna.

[5] S. Takakuwa: A Perspective on Manufacturing and Environmental Management, Chapter 09 in DAAAM International Scientific Book 2013, pp. 213-234, B. Katalinic & Z. Tekic (Eds.), Published by DAAAM International, Vienna, Austria.
[6] A. Gavrus, H. Francillette, D.T. Pham, An optimal forward extrusion device proposed for numerical and experimental analysis of materials tribological properties corresponding to bulk forming processes, Tribology International 47 (2012) 105-121.
[7] M. Bakhshi-Jooybari, A theoretical and experimental study of friction in metal forming by the use of the forward extrusion process, Journal of Materials Processing Technology 125–126 (2002) 369-374.
[8] Q. Zang, M. Arentoft, S. Bruschi, L. Dubar, E. Felder, Measurement of friction in a cold extrusion operation: study by numerical simulation of four friction tests, Proceedings of the 11th ESAFORM 2008 conference on material forming, 23-25 April, 2008, Lyon, France.
[9] M. Kunogi, A New Method of Cold Extrusion. Journal of the Scientific Research Institute 50 (1956) 215–246.
[10] A.T. Male, M.G. Cockcroft, A Method for the Determination of the Coefficient of Friction of Metals under Condition of Bulk Plastic Deformation, Journal of the Institute of Metals 93 (1965) 38–46.
[11] T. Schrader, M. Shirgaokar, T. Altan, A critical evaluation of the double cup extrusion test for selection of cold forging lubricants, Journal of Materials Processing Technology 189 (2007) 36-44.
[12] S.-H. Kang, K.S. Lee, Y.-S. Lee, Evaluation of interfacial friction condition by boss and rib test based on backward extrusion, International Journal of Mechanical Sciences 53 (2011) 59-64.
[13] L. Wang, J. Zhou, J. Duszczyk, L. Katgerman, Friction in aluminium extrusion—Part 1: A review of friction testing techniques for aluminium extrusion, Tribology International 56 (2012) 89-98.
[14] W.J. Deng, Z.C. Xie, Q. Li, P. Lin, Finite Element Modelling and Simulation of Chip Breaking with Grooved Tool, International Journal of Simulation Modelling, 12-4 (2013) 264-275.
[15] S. Kobayashi, S.I. Oh, T. Altan, Metal forming and the finite-element method, Oxford University Press, New York, 1989.
[16] M. Veganzones, A.M. Camacho, J.C. García-Prada, M.A. Sebastián, Contact pressure profiles in axisymmetric compression considering friction and geometrical factors, in: 24th DAAAM International Symposium on Intelligent Manufacturing and Automation, 2013. Procedia Engineering 69 (2014) 72 – 80.
[17] B. Ghiban, F. - D. Dumitru, N. Ghiban, R. Saban, A. Semenescu, M. Marin (2010). Consideration Regarding Die Design for Equal Channel Angular Extrusion, Annals of DAAAM for 2010 & Proceedings of the 21st International DAAAM Symposium, 20-23rd October 2010, Zadar, Croatia, ISSN 1726-9679, ISBN 978-3-901509-73-5, Katalinic, B. (Ed.), pp. 0189-0190, Published by DAAAM International Vienna, Vienna.
[18] B.P.P.A. Gouveia, J.M.C. Rodrigues, N. Bay, P.A.F. Martins, Finite-element modelling of cold forward extrusion, Journal of Materials Processing Technology 94 (1999) 85-93.
[19] T. Altan, S.-I. Oh, H.L. Gegel, Metal forming: fundamentals and applications, ASM International, Ohio, 1983.
[20] B. Avitzur, Metal forming: processes and analysis, Robert E. Krieger Publishing Company, Huntington, New York, 1979.
[21] W. Johnson, The pressure for the cold extrusion of lubricated rod through square dies of moderate reduction at slow speeds, Journal of the Institute of Metals 85 (1956-1957) 403-408.