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Procedia Engineering 69 (2014) 72 – 80

Procedia Engineering

www.elsevier.com/locate/procedia

24th DAAAM International Symposium on Intelligent Manufacturing and Automation, 2013

Contact Pressure Profiles in Axisymmetric Compression Considering Friction and Geometrical Factors

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Abstract

Contact pressures in open die forging of axisymmetric parts are mainly influenced by friction and billet geometry through the shape factor. In this work, a FE model has been developed for analyzing the compression of axisymmetric billets, assuming different friction conditions and shape factors of the workpiece in order to evaluate the contact pressures behaviour under compression and to determine general trends. A constant friction factor law is assumed, *m*, and the shape factor is determined as the ratio between the height of the workpiece and its diameter, *H/D*. Additionally, results are compared with those obtained by the SM method to validate the numerical model. The results presented in this paper demonstrate that the area of highest wear is located in different positions depending on the original geometry of the workpiece, so this information could be considered as a useful guidance when designing dies in more complex compression processes as well as in other recent related processes such as multi-material forming.

Selection and peer-review under responsibility of DAAAM International Vienna

Keywords: forging; upsetting; axisymmetric; friction factor; shape factor; contact pressure; Finite Element Method

1. Introduction

Metal forming industry is well known by an efficient material utilization, excellent final material properties and high production rates. In the last decades, investigations have been focused in the development of new processes

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Selection and peer-review under responsibility of DAAAM International Vienna
doi:10.1016/j.proeng.2014.02.205

which can overcome some of the limitations and/or disadvantages of conventional ones. In fact, some of them are developed by combining some of these conventional techniques. Some recent examples are localized Incremental Forging (LIF) processes [1], which are based in the application of incremental forces in order to globally form the workpiece; there is also a growing interest in covering the gap of knowledge mainly concerning design criteria of multi material forming processes and its simulation [2]. Thus, to improve the knowledge in these new processes, it is advisable to get detailed information about the conventional ones through analysis tools. Different analytical techniques have been developed in order to study metal forming processes. Early methods are based on simple theoretical foundations, where only geometrical considerations and stress distributions are considered. Some examples are the Slab Method (SM), also called Sachs' Method [3], and the Upper Bound Theorem (UBT) [4]. Nowadays, analytical methods such as SM and UBT are commonly used to validate FEM results. Since decades, the Finite Element Method (FEM) has been established as an indispensable tool for metal forming analysis [5]. This numerical method is a powerful technique that takes into account the three main contributions to the total energy required (homogeneous deformation, friction and distortion). By using FEM it is possible to study at the same time the influence of several technological factors; although the effect of friction in metal forming processes has been analyzed since years [6-8], lastly some focus on the friction influence is being observed [9-12]. In compression of solid billets between parallel flat dies, the complexity of non-uniform deformation is not only represented by barrelling phenomenon due to friction [13] but also by the fact that a part of the initially free surface comes into contact with the platen during compression, phenomenon called folding [14]. The mode of deformation is also influenced by the billet geometry, measured by the shape factor [15]. The main aim of this work is to evaluate these phenomena for a best knowledge of the die-workpiece interface behaviour by means of contact pressure profiles. The influence of friction and shape factors on contact pressures is analyzed, which is important to investigate or understand in order to identify general trends of contact pressures under compressive conditions. This knowledge is directly related to some recent developments based on forming by compression, such as multi-material forming and can be also of guidance when more complex geometries has to be form, as in the case of impression-die forging. The knowledge of maximum contact pressures location can be helpful in order to predict die wear and subsequent die failure.

2. Methodology

2.1. Definition of cases

Contact pressure distributions for different geometries are going to be obtained under different friction conditions, defined by the so called friction factor. The different cases that are submitted to finite element analysis are shown in Table 1. The case codes denote how each FE model is named for an easy identification.

Table 1. Technological factors and case codes.

Case code	Diameter *D* (mm)	Height *H* (mm)	Friction factor *m*	Case code	Diameter *D* (mm)	Height *H* (mm)	Friction factor *m*
G1.0	10	3	0	G4.0	10	10	0.0
G1.1			0.1	G4.1			0.1
G1.2			0.2	G4.2			0.2
G1.3			0.5	G4.3			0.5
G2.0	10	5	0.0	G5.0	10	20	0.0
G2.1			0.1	G5.1			0.1
G2.2			0.2	G5.2			0.2
G2.3			0.5	G5.3			0.5
G3.0	10	7	0.0				
G3.1			0.1				
G3.2			0.2				
G3.3			0.5				

Workpieces are cylinders of 10 mm in diameter, *D*. The height of the workpiece, *H*, changes from the lowest one, where $H = 3$ mm, to the highest one, where $H = 20$, as it is indicated in Table 1.

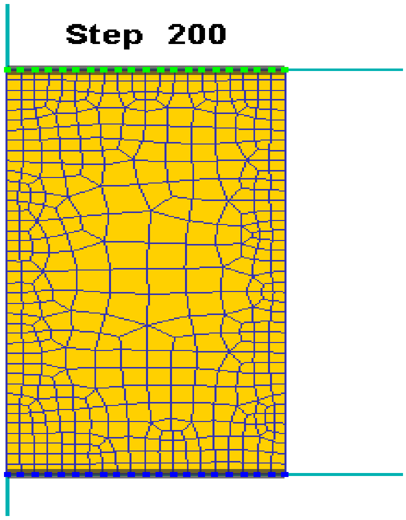

Fig. 1. Example of mesh and contact nodes in Finite Element Model by DEFORM F2™.

2.2. Finite element model

Finite element models have been developed in DEFORM F2™. It is a computer aided engineering software that enables designers to analyze metal forming processes.

An specific axisymmetrical model is simulated for each case of the ones defined in Table 1. Symmetry conditions are imposed, so only half of the model is analysed. Flat platens are modeled as rigid parts and workpiece as a deformable body. The workpiece in all models is meshed by solid (brick) elements as showed in Fig. 1. Regarding the material, the billet has been modeled with aluminium alloy AA 7075-O, whose main mechanical properties are shown in Table 2.

2.3. FEM validation

In order to validate the results obtained by FEM an analytical method is employed. The Slab Method in its axisymmetric form is simple to apply compared to FEM and provides a good first approach to the required load in forging problems. Concretely, the expression of the total pressure applied by the platens is defined in (1).

$$\frac{P}{Y} = 1 + \frac{mR}{2H\sqrt{3}} \tag{1}$$

Because of the assumptions adopted during the analytical development of the method, this provides good results when friction factors are low, but must be carefully used when high friction factors are involved.

Table 2. Mechanical properties.

E (GPa)	ν	*Y* (MPa)
200	0.3	457.8

Table 3. Shape factors of billet used in validation.

Diameter *D* (mm)	Height *H* (mm)	Shape factor *H/D*
10	3	0.3
10	5	0.5
10	7	0.7
10	10	1.0
10	20	2.0

The shape factors to be considered in the validation procedure are shown in Table 3. Results obtained after applying the Slab Method to these particular conditions are represented in Fig. 2. As expected, pressures provided by FEM are slightly higher than by the analytical method. This is due to the fact that FEM takes into account all the energy contributions as explained in [16] and Slab method only considers homogeneous deformation and friction components [3]. Considering that Slab method should be applied carefully with high friction factors, this can explain the behaviour observed for the higher friction factor (m = 0.5).

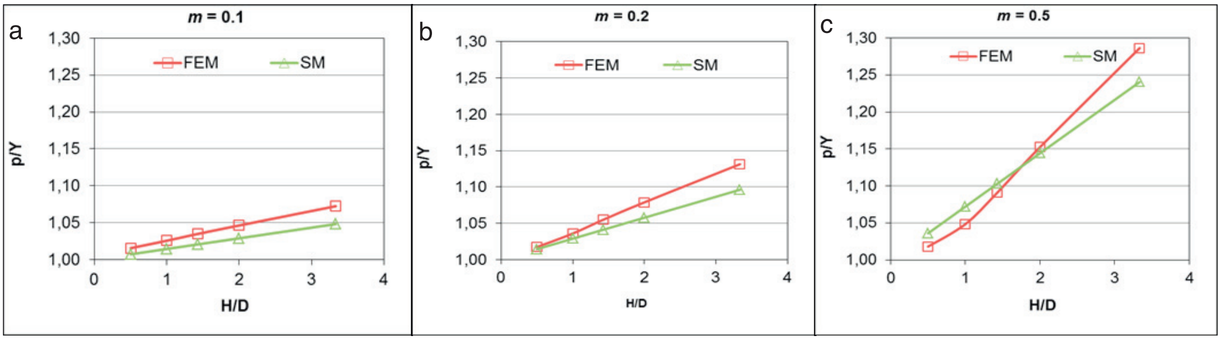

Fig. 2. Validation of FE models with Slab method for different friction conditions (a) m=0.1; (b) m=0.2; (c) m=0.5.

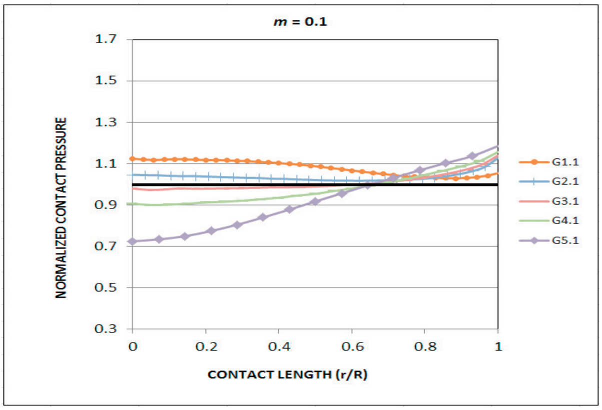

Fig. 3. Adimensional contact pressures versus contact length for all shape factors and m=0.1.

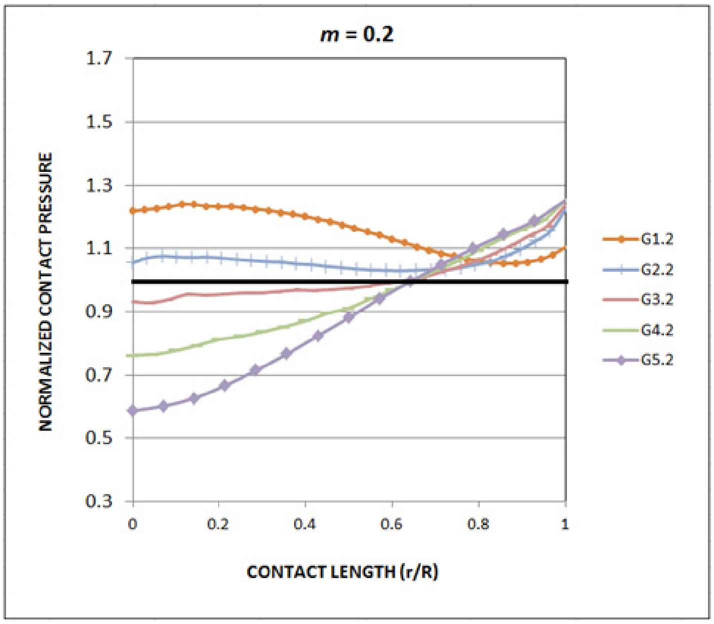

Fig. 4. Adimensional contact pressures versus contact length for all shape factors and *m*=0.2.

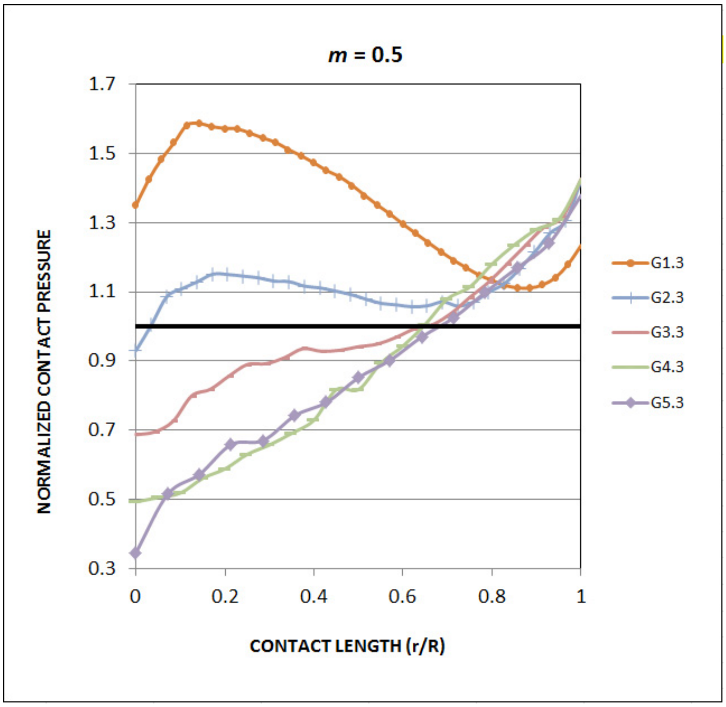

Fig. 5. Adimensional contact pressures versus contact length for all shape factors and *m*=0.5.

Taking into account mainly the results for the lowest friction factors (*m* = 0.1 and 0.2) it can be stated that FEM results are in good agreement with the analytical method.

3. Results and discussion

In order to represent the contact pressure distribution, a radial path of tracking points is defined from the centre to the border of the billets.

Contact pressures and the path coordinates are represented in an adimensional way for an easy comparison of results.

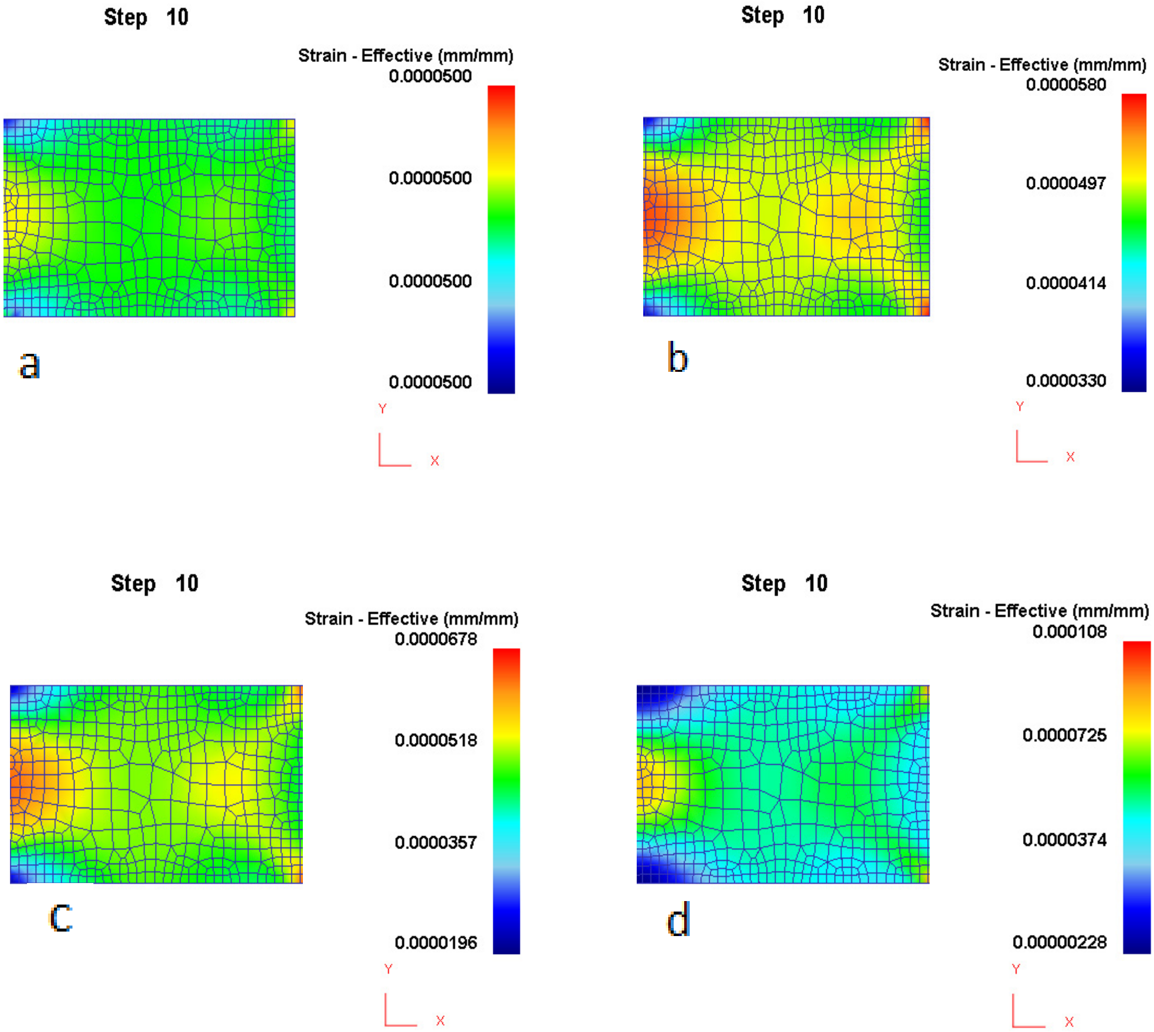

Fig. 6. Equivalent plastics strain diagrams for shape factor *H/D*=0.3 and different friction factors (a) *m*=0; (b) *m*=0.1; (c) *m*=0.2; (d) *m*=0.5.

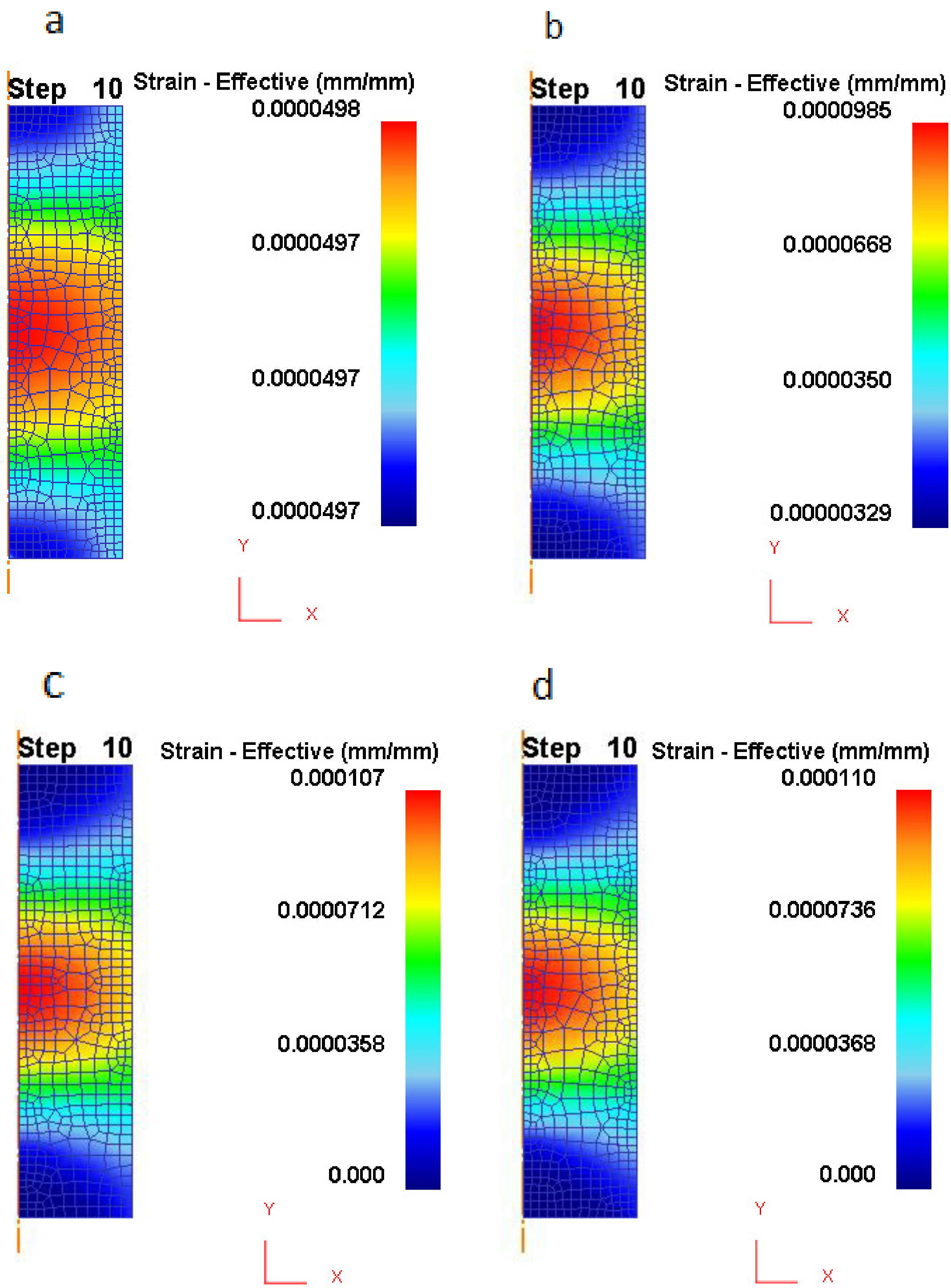

Fig. 7. Equivalent plastics strain diagrams for shape factor *H/D*=2 and different friction factors (a) *m*=0; (b) *m*=0.1; (c) *m*=0.2; (d) *m*=0.5.

Contact pressures are divided by the flow stress, Y, whereas the contact length defined by the radial position in the path, r, is divided by the radius of the billet, R.

Fig. 3 to 5 show contact pressure profiles for all shape factors defined in Table 2 and different friction factors (m = 0.1, 0.2 and 0.5).

For each friction factor, the contact pressure profile trend changes with the shape factor. For small shape factors, the peak of maximum contact pressure is located at the centre of the die, following the shape of the so called "friction-hill" previously studied by other authors such as [17]: when friction is present, the outward movement of the material in contact with the platens is restricted, hence the cylinder bulges. The friction force opposes the outward flow of the material, meaning that a higher stress must be generated near the centre of the contact zone to move the material outwards.

However, as the shape factor increases, the maximum changes at the end of the contact edge with the workpiece, whereas the minimum contact pressures are placed at the centre of the die. This would affect directly to the area of highest die wear, which will be located in different positions depending on the original geometry of the workpiece.

Moreover, this change in contact pressure profiles is more extreme as the friction increases, being the differences between maximum and minimum values more emphasized.

In all figures, one horizontal black line is drawn at the normalize contact pressure of value 1.0; this line represents the flow stress, so the areas where flow stress is exceeded can be easily identified in every case.

This can be also identified through equivalent plastic strain diagrams represented in Fig. 6 and 7; for the group of smaller shape factors (G1), equivalent plastic strains are not null because the flow stress is overcome close to the contact surface. However, for the group of higher shape factors (G5), equivalent plastic strains are registered only at the end of the contact surface, away from the axis.

4. Conclusion

In this work, a FE model has been developed for analysing the compression of axisymmetrical billets, assuming different friction conditions and shape factors of the workpiece in order to evaluate the contact pressures behaviour under compression.

The FE analysis shows that for small shape factors, the peak of maximum contact pressure is located at the centre of the die, following the shape of the so called friction-hill. However, as the shape factor increases, the profiles of pressure distribution obtained by FEM indicate that a simple friction-hill does not occur; instead, the maximum changes at the end of the contact edge with the workpiece, whereas the minimum contact pressures are placed at the centre of the die.

Also, the areas at the workpiece surface where flow stress is exceeded are also identified in every case by means of equivalent strain diagrams.

The results presented in this paper demonstrate that the area of highest wear is located in different positions depending on the original geometry of the workpiece, so this information could be considered as a useful guidance when designing dies in compression processes. These results could be of interest not only when the workpiece is a cylindrical billet, but also when more complicated shapes are plastically formed.

Future research plans include the evaluation of friction and shape factors on contact pressures in more complex compressive processes (such as impression die forging), in order to check if the trend observed in this paper can be generalized; the evaluation of friction conditions on other aspects such as surface roughness and surface microstructure of the workpiece; and the analysis of die wear in compressive forming processes under different lubricants and forming conditions and its relation to contact pressures analysis.

Acknowledgements

This work has been financially supported by the Ministry of Economy and Competitiveness of Spain (Project DPI2009-07300) and the funds provided through the Annual Grant Call of the E.T.S.I.I. of UNED (ref. 2013-ICF02).

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