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Comparative study of the damage attained with different specimens by FEM

J.P. Fuertes[a,]*, R. Luri[a], C.J. Luis[a], D. Salcedo[a], J. León[a], I. Puertas[a]

[a]*Mechanical, Energetics and Materials Engineering Department, Public University of Navarre, Campus de Arrosadia, s/n, 31006, Pamplona, Spain*

Abstract

This present research work deals with the analysis of the design of different specimen geometries so that by finite volume simulations, the appearance of cracks may be predicted in the case of forging processes. To this end, each of the geometries selected are studied by means of compression tests between plane shape dies in the same conditions (T = 25 ºC). On the one hand, a value for the critical damage value is obtained by applying the Cockroft-Latham's criterion and on the other hand, a damage distribution along all the specimen volume with the aim of defining a specimen which shows the most likely place for the crack to appear. This crack location may be also determined through visual inspection with the aim of being able to evaluate this experimentally in the near future.

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Keywords: Damage, Isothermal forging

1. Introduction

This study is focused on how to easily obtain the critical damage value by finite element simulations. In order to do this, different specimen geometries are employed. The aim is to find the most adequate design the specimen must have so that it is possible to analyse the damage effect on the forging of parts.

As is well-known, damage evaluation is an important issue in forging to avoid defects in manufacturing parts [1]. Moreover, failure criterion is related to the imparted damage in forging processes.

* Corresponding author. Tel.: +34-948-169-608; fax: +34-948-169-290.
E-mail address: juanpablo.fuertes@unavarra.es

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Material critical damage has to be determined before the design of the strokes in the forging process of a mechanical part. It has to be assured that the imparted damage in the forging process is below the critical damage of the material [2].

In these past few years, several attempts have been made in order to implement a useful fracture criterion that may be employed in the finite element simulations of parts forming [3-8]. Kobayashi and Lee [3] were the first to implement the Cockcroft-Latham's criterion [9] in a rigid-plastic material by finite element in order to study solid cylindrical parts and ring tests. Oh et al [4] combine the Cockcroft-Latham's criterion with that by McClintock [10] in order to determine the formability in extrusion and drawing of bars. This study achieved a good level of agreement between the experimental results and the theoretical analysis in the formation of cracks. Clift et al. [5] use the finite element methodology in the forging between plane shape dies and in the extrusion of an elastic-plastic material, among others. These authors apply different fracture criteria, that by Freudenthal [11] being the criterion which best estimates the start of fracture for all the studied processes. Zhu et al. [6] present a theoretical study which is based on other finite element formulation in the case of an elastic-plastic material. Basically, the authors analyse different criteria for predicting the fracture start which apply to the compression of solid cylinders. As a conclusion from this study, the authors state that most of the fracture criteria may predict the part zone where the beginning of fracture takes place. Toda and Miki [7] apply the ductile fracture criterion by Oyane's [12] so as to predict and avoid fracture during the forging of steel components. The critical fracture value of a specific criterion when a part is formed is not determined by compression tests between plane shape dies but it is assessed by regression equations which take the steel carbon percentage into account as a predominant variable. Nevertheless, when numerical predictions are implemented in the experimental tests, several difficulties appear at the time of determining the strain value from which fracture starts. Wifi et al. [8] proposed tests in order to compare different fracture criteria and it is concluded that it is necessary to advance in this field so as to be able to validate the different existing fracture criteria. Gouveia et al. [13] performed tests to different specimens with several stress and strain conditions in order to validate the most widely used four fracture criteria.

Given that generally, the material behaviour description found in the libraries of the fem software is not perfect (where the damage is one of the most complicated parameters to be modelled), it is necessary to carry out this study with the aim of finding a simple way to obtain a material critical damage value during a forming process. This existing lack of information provokes that in forming processes with high strain values, it is not possible to know in advance and accurately if the final part is going to present external or internal cracks [14].

There are different kinds of models for predicting the start and the location of a crack [1, 11, 15, 16] and they are only adequate for some processes but not for all of them. Nowadays, manufacturing processes include parts with stress and strain zones difficult to study.

This present research work uses the Cockroft–Latham's damage model which is frequently used in order to predict the beginning of the crack [9]. As it is known, the criterion considers the relation between the maximum principal stress and the equivalent stress. It is calculated by Eq. [1], where σmax is the maximum principal stress and σ is the equivalent stress.

$$D = \int \frac{\sigma_{max}}{\bar{\sigma}} d\varepsilon \quad (1)$$

This criterion establishes that the critical value for fracture is dependent on the maximum principal stress value. As can be observed, the characteristics of the material do not have influence on the results obtained in this study for the Cockroft–Latham's damage parameter (D).

In order to carry out this piece of research work, different specimen geometries are proposed. Some of the geometries to be analysed correspond to those proposed by Gouveia et al. [13] in order to determine the critical damage by means of compression tests. Among the results obtained by these authors, it is worth mentioning that the best model in terms of agreement between experimental results and FEM simulations is that by Oyane [13].

From this, it may be stated that compression tests are more adequate than tensile tests so as to determine the damage as a forging parameter.

In this present research study, the influence of the specimen geometries proposed in [13] and others is to be analysed with the aim of determining the most adequate geometry in order to calculate the critical damage value.

2. Methodology

In this section, the methodology employed to carry out the simulations will be shown. 3D simulations of isothermal compression tests have been carried out for each proposed specimen, in order to obtain the damage evolution during the compression. The maximum imparted damage, the rate of damage and the location of the damage will also be studied.

2.1. Design of the specimens

As was previously-mentioned, this research work takes the specimens studied in [13] as a starting point. Moreover, two new designs of specimens are proposed with the aim of determining the zone with the highest damage value (Fig. 1 (a) to Fig.1 (d), geometries proposed by Gouveia et al. [13]; and Fig. 1(e) to Fig. 1(f), new geometries proposed).

As pointed-out, one of the two new designs is that shown in Fig. 1(e). The starting design is that from Fig. 1(d), which is shown in [13], although two modifications are applied. On the one hand, the height of the specimen is reduced and on the other hand, it is designed with a geometry which presents a higher level of barrelling. Furthermore, the edges are eliminated by fillet radii of 3 mm as these are zones where it is more likely to appear higher damage values. The aim of these changes is that when the specimen is compressed, the damage appears at the central zone of the specimen and at the outer surface. Thus, it is obtained that the specimen zone with the highest damage value is reduced and also, it is easy to observe and to delimit. Therefore, the appearance of the crack is easy to detect when the experimental tests are performed.

The second specimen proposed in this study (Fig. 1(f)) is a combination of specimen B (Fig. 1 (b)) and specimen E (Fig. 1 (e)). The highest length of the specimen is used and the intention is to focus the zone where the crack appears on the central zone.

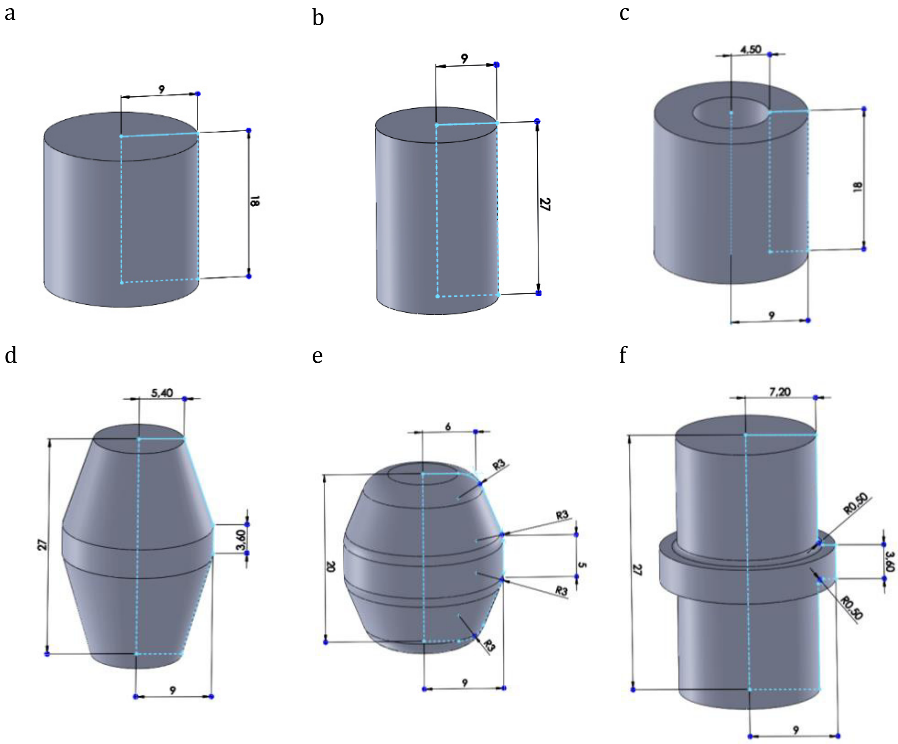

Fig. 1. Geometries for analysing the damage (a), (b), (c), and (d)correspond to those proposed by Gouveia et al. [13] and (e) and (f) correspond to the new geometries proposed in this present study.

2.2. Finite volume (FV) simulation

Once the different specimen geometries are designed, isothermal compression tests are performed for each of the specimens using plane shape dies.

Firstly, along with each damage specimen (which is defined as a deformable solid), the plane shape dies are generated (which are defined as rigid solids). The specimen material is an AA5754 aluminium alloy. On the other hand, as one of the aims of this research work is to select which specimen presents the simplest critical damage zone to analyse at a first glance with the same conditions, temperature is not taken into account as a design factor. Therefore, room temperature (25 ºC) is chosen as test temperature.

In addition, a hydraulic press with a velocity of 60 mm/min is selected in order to exert the required compression movement to the upper platform. This velocity value is the one at which experimental tests are carried out in order to validate the proposed geometries. In addition, a friction coefficient of Shear's type is selected with a value of m=0.3. Although the friction coefficient varies, from the authors' experience this value has been considered to be adequate in this case. On the other hand, as the intention is to compare different specimen geometries, it is assumed that this will not significantly affect the study. The press stroke is adjusted so that the final height of each specimen is 2 mm.

Finally, the specimen is meshed and a remeshing criterion is selected so that every specific number of cycles the geometry is meshed again and thus, there are no results with very distorted elements. The elements employed in this study are tetrahedral with an edge of 1 mm.

Fig. 2 shows the final step of the simulation of a compression between plane shape dies, taking into account the previously-mentioned parameters and employing the specimen shown in Fig. 1(e).

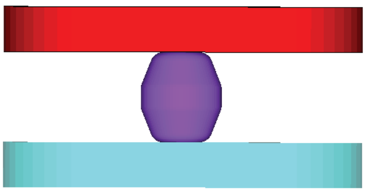

Fig. 2. FV model generation for the isothermal compression between plane shape dies.

3. Results and discussion

This section outlines the results obtained for each specimen in the FV modelling.

Fig. 3 shows the critical damage values for each specimen as a function of the press stroke during the compression. Approximately at half of the stroke, the value is practically similar for the six of them. Once exceeded 75 % of the stroke, it is observed that specimen B (Fig. 1(b)) is the one with the highest accumulated damage value whereas specimen E (Fig. 1(e)) is that one with the lowest. The differences appreciated at 75 % of the stroke increase until 100 % is reached, that is to say, at a final height of 2 mm. Specimen D (Fig. 1 (d)) is observed as an exception.

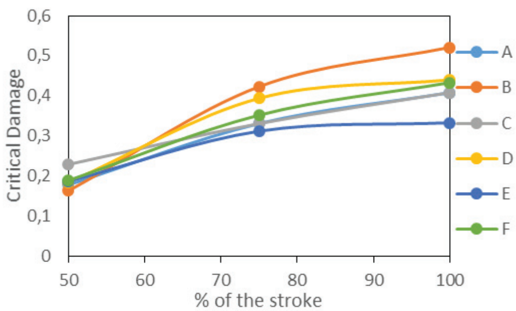

Fig. 3. Graph for the critical damage value as a function of the press stroke percentage in compression tests.

Fig. 4 shows the damage distribution for specimen D (Fig. 1 (d)) along the compression between plane shape dies. As the intention is to carry out experimental tests so as to detect the critical damage value in a near future research work, Fig. 5 (a) to Fig. 5 (f) show the damage distribution once the specimen is compressed down to a height of 2 mm, where this is the point that will be experimentally analysed.

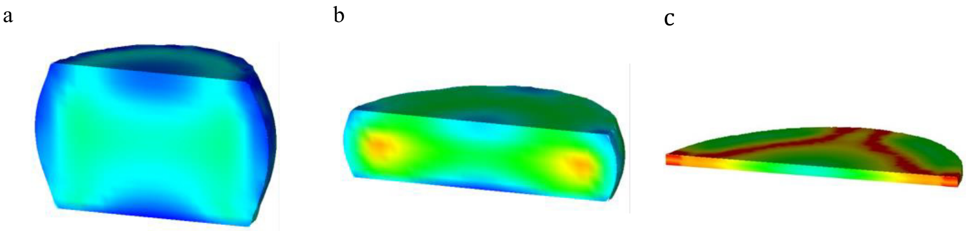

Fig. 4. Damage evolution for specimen D as a function of the stroke. (a) 50 %stroke (b) 75 % stroke (c) 100 % stroke.

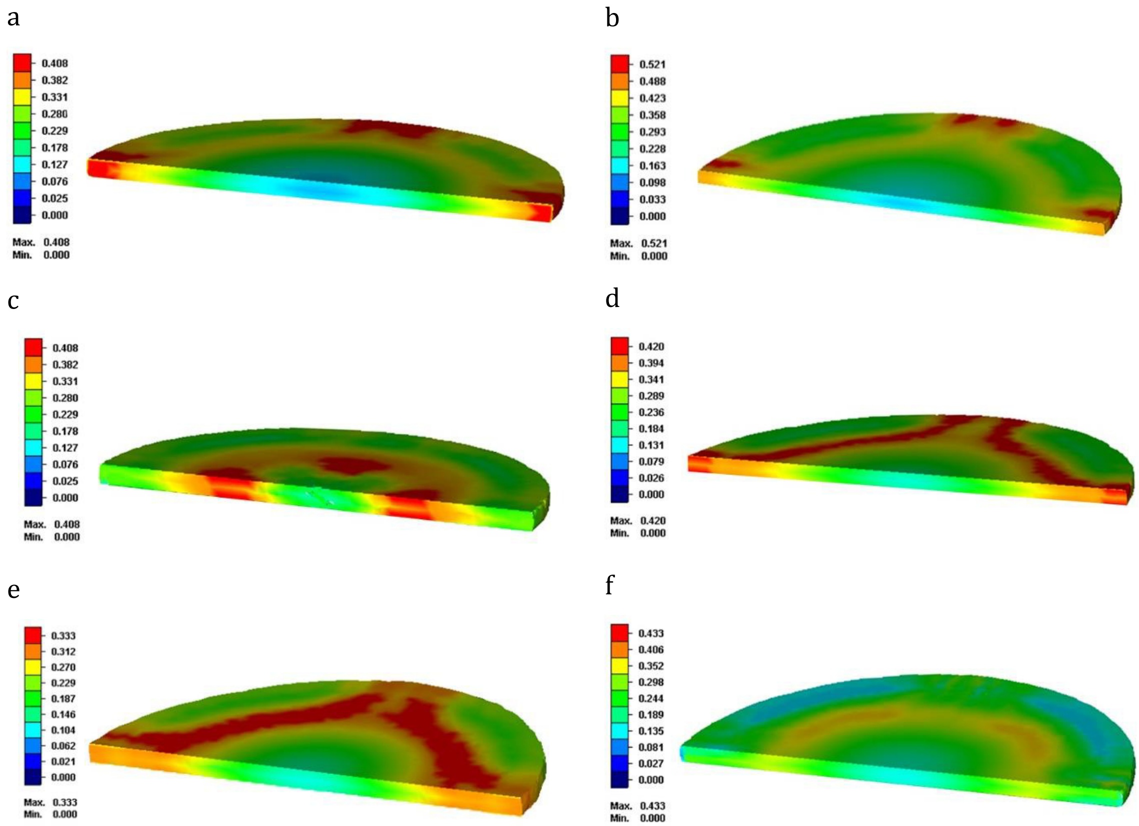

Fig. 5. Damage distribution in the specimens once the final height of 2 mm is reached.

Analysing the results obtained, it may be observed that the specimens with geometries C (Fig. 5 (c)) and F (Fig. 5 (f)) are not the most adequate to determine the crack appearance as the highest critical damage values are reached at the specimen inner part and therefore, the crack may not be observed at a first glance. Moreover, when specimen C (Fig. 5 (c)) is compressed, a fold is formed in the inner part which is finally compressed and leads to a great internal crack (Fig. 6).

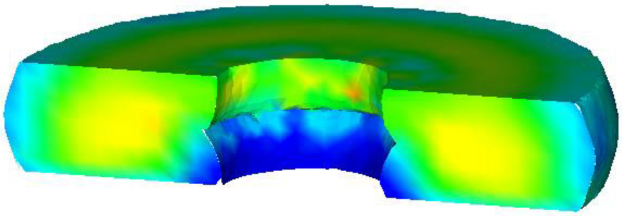

Fig. 6. Internal crack generation in specimen C during the compression test between plane shape dies.

Finally, specimens A (Fig. 5 (a)), B (Fig. 5 (b)), D (Fig. 5 (d)) and E (Fig. 5 (e)) are considered to be valid since the four of them present specific surface zones where the critical damage value appears, specimen E being that with the lowest damage value (25 % lower than specimens A and D).

Although specimens A (Fig. 5 (a)), B (Fig. 5 (b)), D (Fig. 5 (d)) and E (Fig. 5 (e)) are valid, specimen E is selected as the optimum since the highest damage values take place at the outer surface (see Fig. 7 (b)) due to its geometry and specifically, at the fillet radius zone, as can be observed in Fig. 7 (a). This facilitates the crack to be detected once the experimental damage tests are carried out in a future research work.

a b

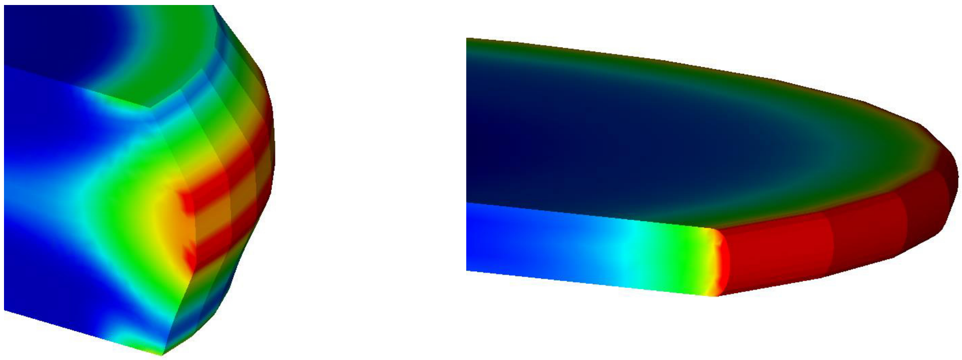

Fig. 7. Surface where the critical damage value appears in specimen E. (a) h = 4 mm (b) h = 2 mm.

Table 1. Critical damage obtained.

Specimen	Critical damage
A	0.408
B	0.521
C	0.408
D	0.420
E	0.333
F	0.433

It is observed that specimen B is that with the highest accumulated damage value, which is logical since its geometry is the one with the highest strain value after the compression. Anyway, numerical data are not enough to be able to evaluate the adequacy of the geometries designed and simulated. Therefore, it is necessary to obtain a mapping of the results in order to observe the damage distribution throughout the specimen, as was shown in Fig. 5 (a) to 5 (f).

4. Conclusions

Several designs for specimens have been analysed in order to obtain the critical damage values by means of finite volume simulations of an isothermal compression between plane shape dies. In order to carry out this, four existing specimens from a previous study [13] are used and in addition, two new geometries are proposed in this research work.

Thanks to finite volume simulations, the critical damage values are obtained for each of the specimens, where specimen B is that with the highest value and specimen E is that with the lowest value for the same height value.

If the damage distribution is analysed throughout the specimen volume, it is concluded that depending on where the zones with the highest damage values appear, specimens A, B, D and E are the most adequate in order to be able to observe the formation of cracks at a first glance. Nevertheless, because of its geometry, specimen E presents a better ease to detect the possible cracks as they appear in the outer surface and specifically, at the zones with the fillet radii.

Therefore, due to its low critical damage value and to its geometry, it is stated that the optimum specimen in order to detect the critical damage for a compression between plane shape dies is specimen E.

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