Billet Cropping Numerical Modelling : an Approach Based on Inverse Analysis

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ABSTRACT: The paper presents the development of a numerical model of the slugs shearing process properly calibrated through experimental simulative tests. To this aim a mechanical cropping device was designed and set up; the numerical model of the process was developed considering the previous drawing step to take into account the process chain effect. Compression tests were carried out to determine the material rheological behaviour, while uniaxial tensile tests were devoted to gain workability data to be implemented in the fracture criterion. The accuracy of simulated results is discussed and possible causes of deviation from experimental data underlined and critically assessed.

Key words: cropping, numerical simulation, damage model

1 INTRODUCTION

The cropping operation is a key step in cold forging processes because the cropped billet directly affects the final cold forged component quality. Among others, sheared billets suffer of profile distortion, cross section deformation, lack of sheared surfaces flatness, cracks on the sheared surfaces; all of these features can be considered responsible of defects in the forged component.

Since 70's, many investigations have been carried out focusing on those parameters influencing the slugs quality [1-5]. Many authors focused their attention on material mechanical properties and grain flow, material strain hardening tendency and its effect on slugs hardness increase due to shearing. In particular, the plastic flow equilibrium, which is responsible for profile distortions, is affected by the strain hardening so the latter has to be minimised to reduce the plastic shearing deformations [6-9]. High speed cropping, cropping under axial compression load, rotating bending cropping, low impact stress cropping and cropping using torque and lateral compressive stress are shearing methods developed in order to get both better control on the shearing mechanisms and higher cropped billets quality [5,10-13]. Especially cropping with axial compression improves billet quality reducing shearing distortions and giving origin to smoother and flatter cropped surfaces. Nevertheless this type of cropping leads to higher strain hardening of the material nearest to the shearing area. This effect is due to the high equivalent plastic strain values reached in the shearing area because of the induced pure shearing mechanism [5, 8].

In recent years, the use of FEM codes to analyse and optimize manufacturing processes took an important role. There are some papers dealing with the cropping numerical modelling: they are focused on both the capability to simulate the process by commercially available FEM codes and on how process key parameters affect both the cropped billet geometry and stress-strain distribution. Some papers deal also with axial compression force effect on the cropped billet [14-15]. This paper presents the development and the calibration of the numerical model of the cropping operation both without axial compression and under hydrostatic pressure. The model is set-up to take into account the initial radial strain hardening gradient due to the previous drawing step.

Compression tests were carried out to determine the material rheological behaviour, while uniaxial tensile tests were devoted to gain workability data to be implemented in the fracture criterion. A dedicated cropping device was developed and set-up to compare numerical and experimental results. The accuracy of simulated results is discussed and possible causes of deviation from experimental data underlined and critically assessed.

2 CROPPING EXPERIMENTS

The developed cropping device is able to perform both single or double cropping on round bars up to 10mm diameter. The radial clearance between the bar and the closed moving blade is 0.1mm, and it is 0.05mm between the bar and the bar clamping blocks. The clearance between moving blade and stationary blade can be fixed in a range from 0 to 0.5 mm, that is the interesting range related to bar diameter for cold forging in typical industrial applications. The moving blade is made of tungsten carbide, while the stationary ones are made of hardened hot working tool steel X37CrMoV 5-1 KU. Cropping tests using axial compression load are made possible thanks to a pre-loading screw moving in the specimen axial direction; the screw is M22 threaded making the maximum axial force available up to 3 tons, corresponding to a compression stress up to 390MPa on 10mm diameter bars. This value is half the yield stress for a medium carbon steel (AISI 1035). For ductile materials an axial load of half the material yield stress is usually high enough to activate the pure shearing mechanism. A load cell is positioned between the screw and the bar end to instantly measure the superimposed axial force. Figure 1 shows a schematic illustration and a picture of the device. This device is used on a tool holder that can be installed on several machine typologies to reproduce the most suitable blade kinematics. The tool holder is equipped with load cells in order to measure the vertical shearing force.

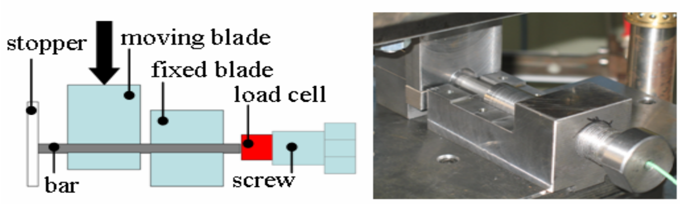

Figure 1. Cropping device: schematic illustration (left) and real setup (right)

Two different kinds of single cropping tests were carried out: cropping without any axial compression and cropping using axial pressure.

Table 1 Cropping test parameters

Blade Speed	250 mm/s
Blade clearance	0 mm
Radial clearance (bar-blade)	0.05 to 0.1 mm
Axial Pressure	0; 330 MPa

3 NUMERICAL MODEL

All the 3D simulations were performed using the commercial FE code FORGE2005™.

3.1 *Drawing Model*

The simulation of the previous drawing step was performed in order to get the actual radial strain distribution on the bar to be cropped. Table 2 reports the parameters set for the model.

Table 2 Drawing simulation parameters

Initial diameter	6.52 mm
Final diameter	6.20 mm
Reduction	~10.5 %
Drawing die half angle	7°
Drawing speed	1000 mm/s
Friction factor m	0.1

3.2 *Cropping Model*

Table 3 reports the parameters utilised for the two cropping models, with and without axial compression. FE simulations mesh and settings were kept equal for both cases (table 3). All the tools were considered as rigid.

Table 3 Cropping simulation parameters

	No axial compr.	With axial compr.
Blade speed	250mm/s	250mm/s
No. of nodes	~16000	~16000
Friction factor m	0.1	0.1
Radial bar clearance	0.05–0.1 mm	0.05–0.1 mm
Blade clearance	0 mm	0 mm
Fracture criterion	Oyane	Oyane

3.3 *Material characterization and modelling*

The used material is an annealed AISI 1010. The Hollomon law was used to describe the material rheological behaviour. The material parameters were identified through compression tests of cylindrical specimens. The tests were carried out on an

hydraulic press and test data were compensated for the machine stiffness.
Molibdenum bi-sulfate based lubricant was used in order to reduce barrelling effect due to friction between flat specimen ends and machine punches.
Material workability was investigated by uniaxial tensile tests in order to evaluate the equivalent strain at fracture. The Oyane fracture damage model was used as fracture criterion in order to take into account the sensitivity to triaxiality stress state. The Oyane critical damage parameter was calculated from the material equivalent strain at fracture. All material parameters are reported in Table 4.

Table 4 Material parameters

Material type	Annealed AISI 1010
Strength coefficent K [MPa]	743.6
Strain hardening coefficient n	0.25
Eq. strain at fracture ε_{eqf}	0.6
Oyane critical value C	1.2

4 RESULTS AND DISCUSSION

4.1 Cropping without axial compression

Figure 3 shows load displacement curves comparison between experimental and numerical data.

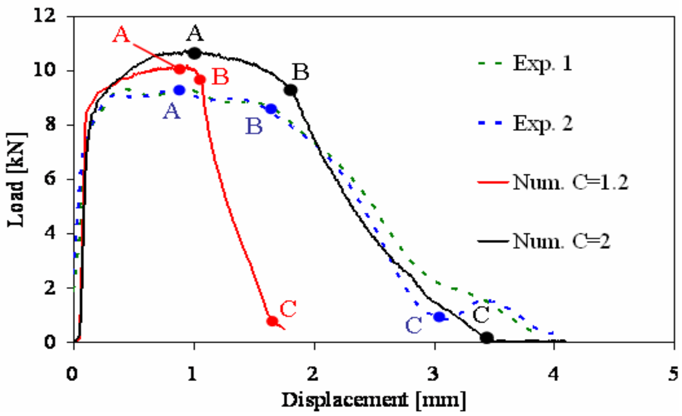

Figure 3. Load-displacement curves comparison for cropping experiments without axial compression

Experimentally determined load-displacement curves (Exp.1 and Exp.2 in Figure 3) are characterized by good repeatability. The usual load - displacement curve is characterised by 4 different parts: plastic deformation and maximum load value (0A), plastic shearing extension (AB), crack starting point (B) and crack evolution (BC). If the Oyane critical damage parameter calculated from uniaxial tensile tests is applied, the numerical curve (the red one in Figure 3) underestimates the fracture starting point of about 50%. This may be due to the very different stress state in the uniaxial tensile test and its effect on voids growth and coalescence when compared to the same ones in the cropping process. When a Oyane critical damage parameter equal to 2 (calculated by inverse analysis) is applied, a good agreement between experimental and numerical curves can be found, especially as concerns the plastic shearing extension (AB) and crack evolution (BC). The crack starting points (C) are comparable in terms of stroke but the corresponding loads differ of about 10%. A difference of about 16% can be seen at the maximum load value (0A). This differences may be due to the power law rheology that is not able to take temperature effect on flow stress into account. From numerical simulations, the temperature increase is, in fact, quite evident, as shown in the qualitative temperature distribution of Figure 5a.

4.2 Cropping with axial compression

In case of cropping with axial compression, the load displacement curve can be divided in 3 different parts (Figure 4): plastic deformation up to the maximum load (0A), plastic shearing beginning (AB), and plastic shearing evolution (BC). It is interesting to observe that when Oyane damage model is used, the effect of the value critical damage parameter on the load-displacements numerical curves is negligible.

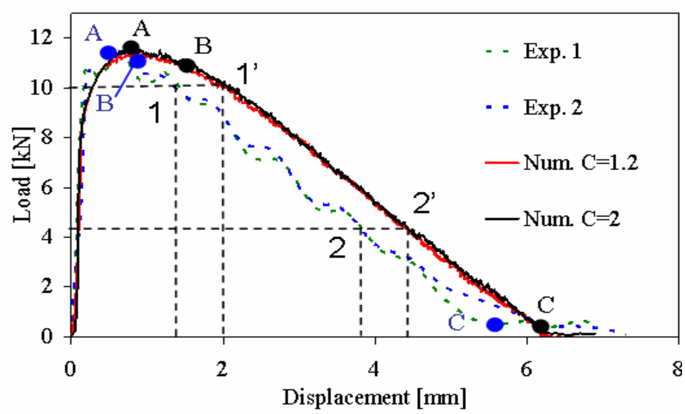

Figure 4. Load-displacement curves comparison for cropping experiments with axial compression

The comparison between experimental and numerical curves for C=2 shows a good agreement up to the maximum load value (0A) whereas the beginning of plastic shearing, for the numerical model, is more extended than the experimental one

(AB). Thus this difference affects the last part of the curve leading to a higher stroke between corresponding load values (1-1' and 2-2'). It can be seen that both experimental and numerical curves are characterized by the same slope (C): this means that the numerical model is able to simulate the plastic shearing mechanism which depends on the stress-strain field evolution.

Cropping under axial compression leads to an equivalent plastic strain higher than that developed in the former case [5,8]. From a qualitative point of view, it is strictly connected to the necessary amount of energy to shear the bar and the developed average temperature is therefore higher (Figure 5b).

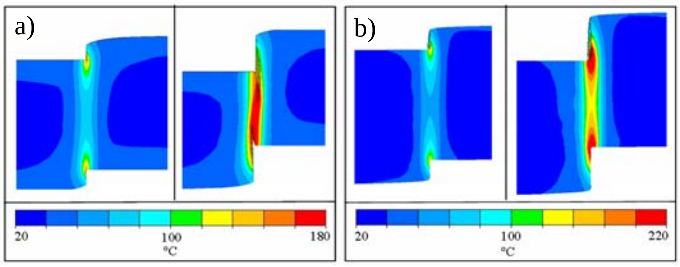

Figure 5. Temperature distribution a) without and b) with axial compression (C=2 in both cases)

5 CONCLUSIONS

In the case of cropping without axial compression:

1. the material workability, assessed by simple tensile tests, leads to an underestimation of about 50% of the crack starting point;
2. increasing Oyane critical damage parameter from C=1.2 (by tensile test) to C=2 (by inverse analysis) a better matching is obtained between experimental and numerical data;
3. the maximum load value is overestimated of about 16%, probably due to the use of the Hollomon rheology law which is not suitable to take into account the temperature increase effect on the material flow stress.

In the case of cropping with axial compression:

1. the Oyane critical parameter value does not affect the numerical load-displacement curve;
2. load-stroke curves comparison shows that Hollomon rheology law leads to an overestimation of the extension of the plastic shearing beginning;
3. plastic shearing mechanism leads to higher equivalent plastic strain increasing the average temperature over shearing area to more than 200°C.

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