A TWO-STEP INVERSE ANALYSIS APPROACH USED TO IDENTIFY THE MECHANICAL PROPERTIES OF METALLIC MATERIALS SUBJECTED TO LARGE PLASTIC STRAINS. APPLICATIONS TO LOCAL INVESTIGATIONS OF SURFACE LAYER'S BEHAVIOUR

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ABSTRACT

The aim of this research work is to improve the experimental and numerical analysis of the local mechanical properties corresponding to metallic alloys used by bulk forming processes. A non-conventional upsetting test and an optimal direct extrusion device designed by the authors are used in order to identify the constitutive rheological equations and the friction models, starting directly from measured load-stroke curves. A two-step inverse analysis strategy is thus proposed starting from a complete Finite Element Model of the experimental tests and using a strong numerical coupling of the FEM with an optimization platform in charge with the automatic parameters identification. The obtained results are correlated with experimental investigations based on X-Ray, EBSD and hardness measurements concerning the microstructure and the local mechanical properties of the surface layer obtained from a conical extrusion process.

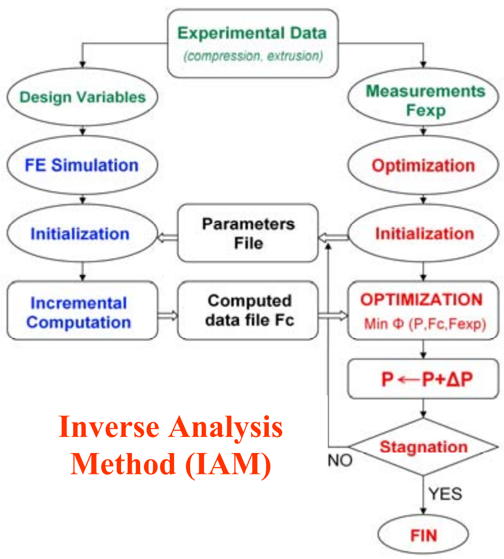
KEYWORDS: inverse analysis, rheology & tribology, cold metal forming, surface layer properties

1. Introduction

Today many manufacturing processes require improving the knowledge of the mechanical behaviour of material's surface layer, especially conditioned by the strong interaction between the global material rheology and the local tribological phenomena which occur at the tool-piece interfaces. The present work is then focused on the experimental and numerical analysis of the local mechanical properties corresponding to aluminium alloys used frequently by different bulk forming processes [1]. A non-conventional upsetting test [2] and an optimal direct extrusion device [3] have been developed in order to identify the constitutive rheological equations and the friction laws, starting directly from measured load-stroke curves. A two-step inverse analysis strategy is proposed starting from a complete Finite Element Model (FEM) of the experimental tests and using a strong numerical coupling of this FEM with an optimization platform in charge with the automatic parameters identification [4, 5]. All the mechanical complexity of the experimental friction test caused essentially by the non-linearity of the large plastic deformations and of the local contact evolution, characterizing the tool-specimen interfaces, is taken into account by the numerical model [6]. The obtained macroscopic rheological and tribological behaviour is then used to analyse local microstructure and mechanical properties of the surface layer generated by a conical extrusion deformation [7].

2. Mechanical properties identification using a Two-Step Inverse Analysis approach applied to an extrusion process

At a macroscopic and mesoscopic scale, to identify the rheological and the tribological properties of a material used during a bulk forming process requires to reproduce the same plastic deformation conditions via specific mechanical tests. During the forming process, the formation of new contact surfaces between the piece and the tool requires similar mechanical history able to describe the material behaviour corresponding to large plastic strains and for loadings close to the real ones. Recently the authors have been proposed an optimal forward extrusion test [3, 7] with a geometric design defined by an input cylindrical zone (with a diameter Di = 20 mm and a length Li = 40 mm), an output cylindrical zone (with a diameter Do = 17 mm and a length Lo = 7 mm) and a conical die (with an angle equal to 5°).



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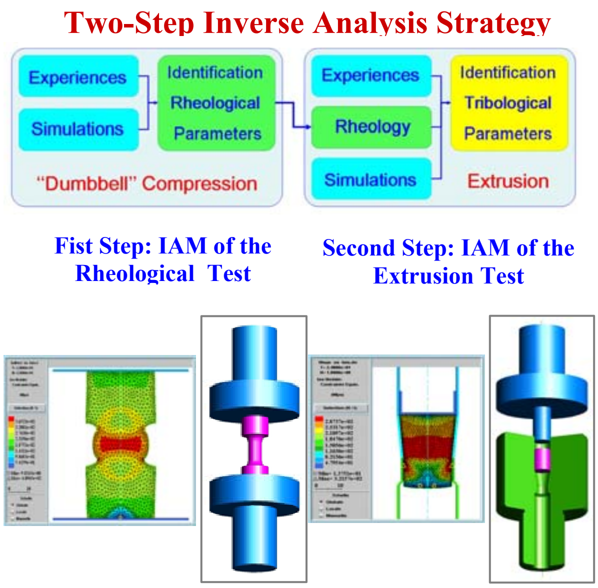


b)

***Fig. 1**. a) Principle of the Inverse Analysis Method (IAM) based on an optimal coupling between the Experiment and the Numerical Model, b) Two-Step Inverse Analysis Strategy applied to a sequential identification of the rheological and tribological properties*

During the extrusion process it has been shown that this geometry permits to maximize the influence of the friction phenomena and consequently allows for the identification of the tribological properties. Starting from the research results obtained by Diot et al. [2], a dumbbell specimen upsetting test can be used to identify an elasto-plastic rheological behaviour. In this case the friction has no effect on the material deformation and the measured load-stroke curve depends only on the constitutive rheological law.

The main problem is that in all these cases it is impossible to realize an analytical computation of the stress-strain variation and the use of an inverse analysis technique seems to be compulsory [4]. Figure 1a presents the principle of the Inverse Analysis Method and its application for the both proposed experimental tests.

It is based on a strong coupling between the experimental results, the numerical model used for the simulation of the experiment and an optimization modulus in charge to find the optimal set of the unknown parameters P that minimizes a cost function $\Phi\left(P, F^{\exp}, F^{c}\right)$ expressed in terms of the measured F^{exp} and computed F^{C} loads using a least square formulation.

The minimization algorithm can be based on a zero order or a first order optimization technique. In this study is used a Gauss-Newton iterative method detailed by Gavrus in [4].

In Figure 1b is pictured the scheme of the two-step Inverse Analysis strategy applied to a sequential identification of mechanical behavior. In a first stage, a compression test of a dumbbell specimen is performed to study and identify by inverse analysis the rheological behaviour of the material. In a second time, using the previous computed rheological data, the automatic identification method is applied to the direct extrusion process in order to obtain adequate formulations of friction models and to compute more precisely the corresponding coefficients [7].

The numerical models used to simulate the experimental tests were built from the commercial FE software FORGE2®

3. Application to AA 5083 aluminium alloy

3.1. Identification of rheological and tribological properties

For the AA 5083 aluminium alloy the rheological behaviour can be described by a Ludwik constitutive relationship:

$$\bar{\sigma} = \sigma_0 = \sigma_{00} + K\bar{\varepsilon}^{n} \qquad (1)$$

The inverse analysis using a FEM of the compression test leads to the plastic flow equation defined by:

$$\sigma_0 = 142 + 373.05\bar{\varepsilon}^{0.306} \qquad (2)$$

In the case of the extrusion process, the friction model defining the interface contact conditions must be defined by a Coulomb-Tresca criterion:

$$\tau_f = Min\left(\mu\sigma_n, \bar{m}\sigma_0/\sqrt{3}\right) \qquad (3)$$

Starting from the previous identified rheological law, a second inverse analysis applied to the extrusion test estimates the friction coefficients such as:

$$\begin{cases} \mu_{input}^{cyl} = \mu_{output}^{cyl} = 0.24, \mu_{conic}^{cyl} = \infty \\ \bar{m}_{input}^{cyl} = \bar{m}_{output}^{cyl} = 1, \bar{m}_{conic}^{cyl} = 0.37 \end{cases} \qquad (4)$$

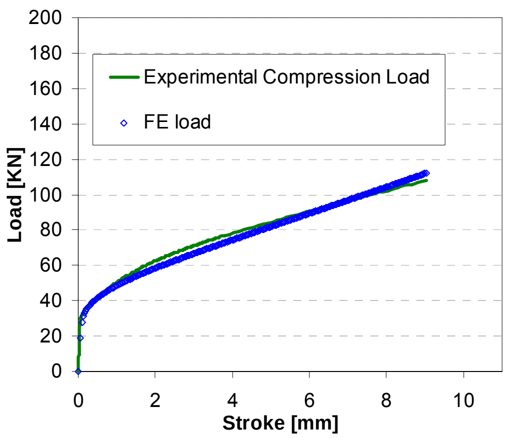
or

$$\begin{cases} \mu_{input}^{cyl} = 0.30, \mu_{conic}^{cyl} = \infty, \mu_{output}^{cyl} = 0.16 \\ \bar{m}_{input}^{cyl} = \bar{m}_{output}^{cyl} = 1, \bar{m}_{conic}^{cyl} = 0.36 \end{cases} \qquad (5)$$

The first friction model I.1 (Eq. (4)) assumes equal values for the Coulomb parameter in input and output cylindrical parts, where the mechanical contact is perfectly elastic, when for the conical die area, where important plastic deformations occur, a Tresca formulation is used. For the second model I.2 (Eq. (5)), different Coulomb coefficients are used to define the elastic contact in the cylindrical zones of the extrusion die.

In order to avoid the strong coupling existing between the friction parameter's influences on the input area, conical zone and the output one, a gap j equal to 0.15 mm has been chosen between the initial specimen and the extrusion die ($j = \left(D_i - D_s\right)/2$).

The comparisons between the experimental load-stroke curve and those obtained from a finite element simulation (using the previous identified rheological and tribological parameters) are plotted in Fig. 2.



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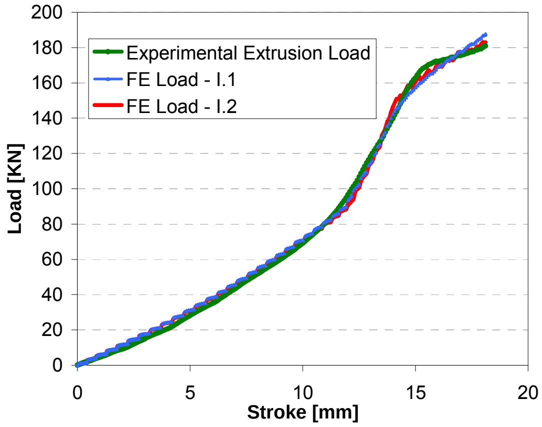


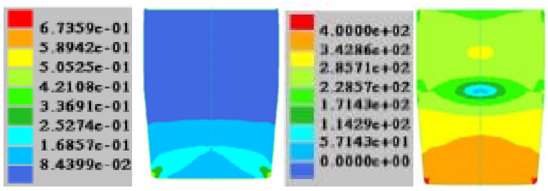
b)

***Fig. 2**. Comparison between the experimental load-stroke curves and the FE ones using the previous identification results [3]: a) for the compression test (the load is independent with respect to the interfaces friction), b) for the direct extrusion test (realized for dry friction conditions)*

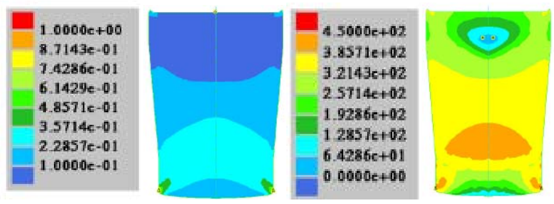
A very good agreement is obtained for the both mechanical tests, pointing out that the friction model I.2 reproduces correctly the extrusion curve describing the load-stroke variation.

3.2. Numerical analysis

Using the identified rheological and tribological data corresponding to the AA5083 aluminum alloy (constititive Eq. 2 and friction model I.2), a finite element simulation of the extrusion process has been analyzed in details. Figure 3 presents the distributions of the cumulated plastic strain and of the Von Mises stress corresponding to two different stages of the extrusion process.



a) punch displacement equal to 11.79 mm



b) punch displacement equal to 18.11 mm

***Fig. 3**. Iso-values of the plastic strain (left pictures) and of the Von-Mises stress (right pictures) for two extrusion stages*

These numerical results permit to understand the complex path of the specimen deformation history, the non homogeneity of the strains or stresses and especially to quantify the most important mesoscopic mechanical variables which characterize the new specimen surface formed during the plastic contact of the extruded material with the conical die.

4. Analyses concerning the layer surface properties of an extruded AA5083 specimen

More numerical and experimental correlations can be obtained using data based on the investigations of the material by microstructure observations, by local hardness tests and by estimation of macroscopic shear stress variations on the layer surface [3]. A lot of samples have been prepared from the initial AA5083 specimen (D_S=19.7 mm, L=25 mm and Ra=0.8 µm) and especially from the extruded ones according to Fig. 4.

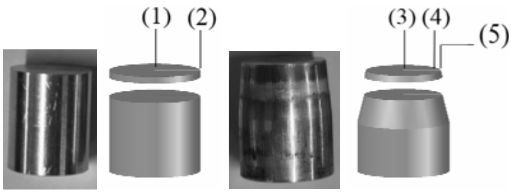


***Fig. 4**. Specimens and radial or axial cut samples (1, 3 – middle area, 2, 4, 5 – edge area) used for X-ray , EBSD measurements and hardness estimation for a) initial state, b) extruded state*

This study proposes to analyse an extruded sample obtained from a punch displacement of 11.79 mm, having a final diameter D_{extr} equal to 17.6 mm (Fig. 4b). So it is possible to investigate the influence of the local plastic shear friction on the surface layer properties before the complete filling of the conical die.

4.1. Experimental X-Ray analysis

From the X-Ray measurements of overall texture, it is possible to remark that for a plastic strain variation between 17% and 33%, the grain shape is not affected by the material deformation and the grains size is already uniform. The grains shape obtained after a deformation by extrusion is similar to that which was before deformation and the global texture of material obtained from X-Ray diffraction is similar after or before the extrusion process. Furthermore, near the edge of the extruded section, the grain shape is similar to the centre ones. Concerning the grain size, this one is therefore not sensitive to the friction at the tool-specimen interface. The distribution of the grain size in the sample sections, before and after extrusion, is presented in Table 1.

***Table 1.** Grains size distributions in the cut specimen sections, before and after extrusion*

Grain Size	Middle area		Edge area	
	Before	After	Before	After
$[2.5\,\mu m,\ 9.5\,\mu m]$	-	-	58.8%	52.8%
$>10\,\mu m$	56.6%	66.2%	-	-

Firstly it is observed that for the centre area of cutting samples, most grains have a size larger than 10 µm; for the edge area the majority of grains have a size between 2.5 µm and 9.5 µm. On the other hand it can be seen that the change in grain size before and after extrusion is not important. In the centre of the initial sample, 56.6% of the grains have a size greater than 10 µm and this value is 66.2% after deformation by extrusion. At the edge of the section, under the simultaneous effect of friction and plastic deformation, the grain size distribution varies only by 6% (from 52.8% to 58.8%). This variation is considered very low if are taken into account the measurement uncertainty and the non-homogeneity of the samples. Finally it is possible to conclude that during an extrusion process characterized by an average plastic deformation of 25% (defined by $\bar{\varepsilon} \approx 2\ln(D_i / D_{extr})$), the influence of the friction on the grain size is rather negligible.

4.2. Experimental EBSD analysis

To obtain information concerning the grain orientation, an EBSD measuring system (Fig. 5) has been used.

***Fig. 5**. System EBSD - Microscope JSM-6400*

The Figure 6 and Figure 7 show the obtained pole figures corresponding to the extruded specimen in the central both area (zone 3) and the edge one (Zone 5).

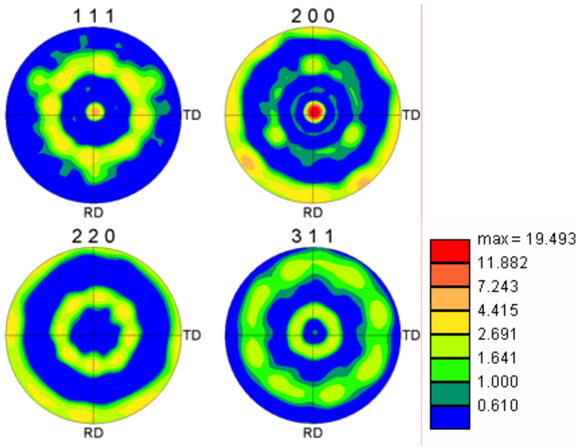


Fig. 6*. Pole figures corresponding to the central area (zone 3) of the extruded specimen (EBSD measurements)*

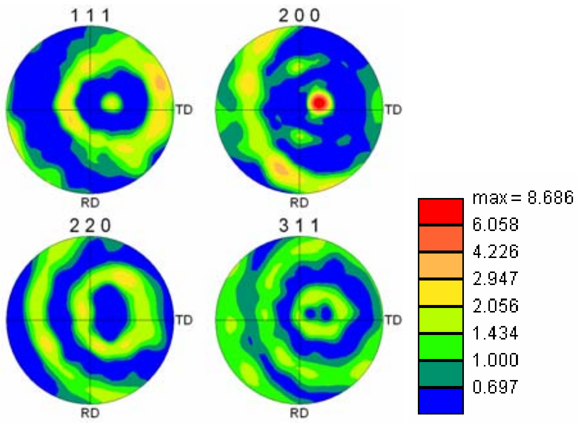


Fig. 7*. Pole figures corresponding to the edge area (zone 5) of the extruded specimen (EBSD measurements)*

Comparing zone 3 (central area of the specimen) and zone 5 (positioned at 100 μm from the outside surface), the intensity distribution is generally asymmetric relative to the centre of the pole figures, but near the sample edge, the asymmetry is more pronounced.

These results are principally due to the specific state of the stress near the surface where the interface friction has a significant influence on the changes of the grain orientations.

Figure 8 pictures the grain orientations of the initial and extruded specimens obtained by EBSD.

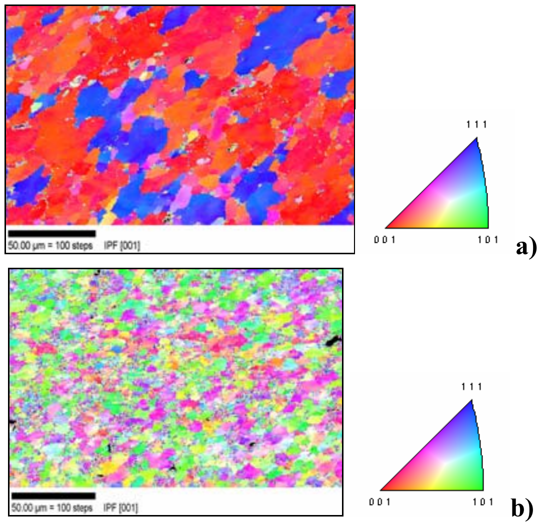


Fig. 8. *Maps of grain orientations obtained by microscopic EBSD measurements of the extruded specimen [3]: a) for the middle area (r/R= 0), b) for the outside surface (r/R ≃ 1)*

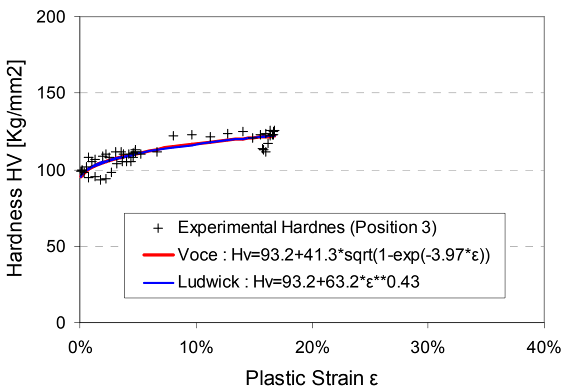
4.3. Experimental hardness analysis

Concerning the local mechanical properties of the layer surface, Vickers hardness measurements have been realized for the extruded specimen along a vertical section passing by a line through the point 3 (pictured in Fig. 4) and along the outside surface, named respectively measurement positions 3 and 5. Using the geometric coordinates of each measured point, the plastic strain values have been estimated from the numerical simulation of the extrusion process (Fig. 3a).

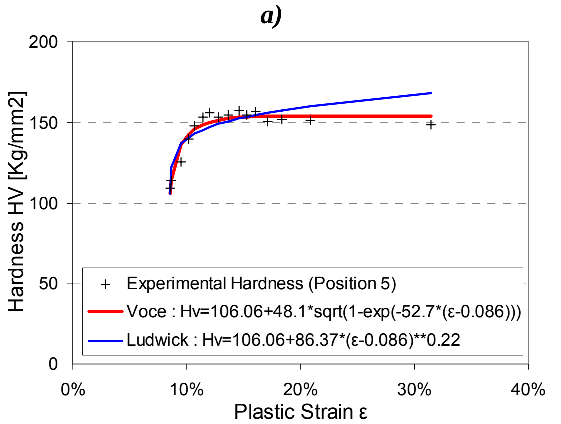
A non-linear regression permits to describe the variation of the hardness with the plastic strain using two relationships: a classical Ludwik formulation and a Voce one. Experimental variations and identifications results are plotted in Fig. 9.

It is possible to conclude that further the contact between the tool and the specimen, the hardness of the material occurs primarily as a result of plastic deformation and can be estimated by the following expression: $HV = HV_0 + f(\bar{\varepsilon})$. On the other side at the specimen interface the evolution of the hardness is strongly influenced by friction and consequently this one must be correlated with the entire history of both local plastic deformation process and local plastic contact phenomena.

In a general way, starting from the theory of Tabor, for a material characterized by an elastoplastic hardening behaviour, the hardness value can be supposed to be proportional to the Von Mises stress.



a)



b)

Fig. 9*. Variation of the Vickers hardness with the plastic strain: a) cut sample from the extruded specimen (vertical cut in Position 3), b) outside surface of the extruded specimen (Position 5)*

Thus concerning the initial hardness value this one can be computed from the formulae $HV_0 = \gamma\sigma_0$ (both terms expressed in kg/mm^2), where γ is an empirical coefficient, generally equal to 3.0 for a large class of metallic materials, if the equivalent stress σ_0 is evaluated for a representative plastic strain value around 0.08 (8%). Thus, for the analysed AA 5083 aluminium alloy, using the rheological law identified from the dumbbell compression test, the initial value of the hardness must be approximately equal to 94.3 kg/mm^2. This value is close to those given at the beginning of the hardness curves (HV_0 $\in$ [90 kg/mm^2, 106 kg/mm^2]), values which permit to valid the experimental recordings and all the previous comments.

5. Discussions

The previous EBSD and hardness experiments have been shown, beside the shape and the grain size distribution, the important changes of the microstructure morphology and of the local mechanical properties around the layer surface corresponding to the conical die-piece interface. These changes can be explained by the important effect of plastic friction phenomenon at this interface.

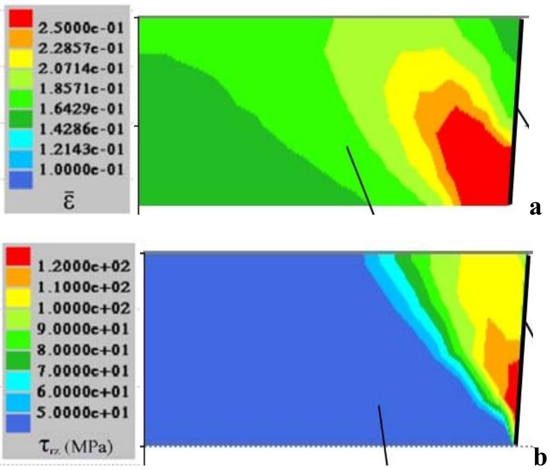


Fig. 10*. Finite Element simulation of the conical extrusion process (simulation using the friction model I.2 with $\mu_i = 0.3$, $\overline{m}_c = 0.36$ and $\mu_f = 0.16$) :*
a) Iso-Values of the equivalent plastic strain $\overline{\varepsilon}$,
b) Iso-Values of the shear stress τ_{rz}

Using finite element simulations obtained from the commercial software FORGE2®, numerical results concerning the maps of the equivalent plastic strain and of the shear stress in the extruded specimen, especially inside the conical part of the tool, are shown in Fig. 10.

When there is no friction between the specimen and the die it is found that the plastic deformation of the material is almost constant over the entire section of the specimen. However, when friction at the contact interface between the tool and the sample is important, increasing plastic deformation values are located rather close to the contact zone (zone 5).

The plastic deformation in this zone is about three times larger than that of the centre of the section (zone 3) and can have locally values up to 40%. Therefore the friction at the interface has a great influence on the evolution of the deformation in the layer near the outside surface of the test material. Concerning the shear stress a similar phenomenon is observed: the shear stress in the area near the edge surface is much larger than that at the centre of the specimen. So a rapid change of stress values can be observed in the contact area. This considerable shear gradient is consistent with the microstructure changes in this area especially for the grain orientations and also for the evolution of the hardness.

6. Conclusions

A new approach has been developed by the authors to investigate rheological and tribological properties of metallic materials undergoing large plastic deformations during a bulk forming process. The experimental and numerical investigations of a forward extrusion confirm that during the deformation the specimen is in contact with the outgoing part of the die by a new surface generated in the conical part by the material plastic flow. In this zone, the layer surface has different microscopic and local mechanical properties than the initial one. Furthermore the analysed results confirm also the difference of the Coulomb coefficients values defining the input zone (Di) and the output area (Do) corresponding to a perfect elastic contact. Numerical values of plastic strain and shear stress corresponding to the material layer surface have been correlated with the EBSD and hardness measurements. The results emphasize the need to develop multi-scale approaches in order to obtain quantitative predictions of observed microstructure evolutions, in particular for the grain morphology principally defined by the size and spatial orientations.

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