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Rheological characterization and finite element modeling of an extrusion process of a WC–Co compound

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ABSTRACT

The use of hard metals, in particular for cutting tools, is becoming wider. Their manufacturing cost, higher than traditional steel, is compensated by an increased lifetime. This work involves the rheological characterization of a WC–Co compound, in order to evaluate its viscosity for different values of strain rate. Following this characterization, the data are implemented in a FEM code, in order to simulate the extrusion processes of such compounds to manufacture hard metal bars. This study highlights the importance of an accurate viscosity evaluation of these mixtures and the correct setting of FEM parameters in order to predict successfully extrusion processes. As an example, an analysis is presented for the case of cutting tools with helical holes for the passing of fluid coolant.

1. Introduction

The Widia (Wie Diamant — as diamond, from the German), also known as cemented carbide or hard metal, is a material consisting of hard particles of carbide embedded in a metallic matrix. It is produced through the sintering process, that is fine powders of the components are mixed, pressed and then heated [1–3] to form a single piece. These materials are not metals, but carbides (80–95%) bound to a metal. The carbides frequently used are based on tungsten (WC), titanium (TiC) and tantalum (TaC), whereas the metallic matrix is often cobalt.

The use of hard metal tools [4] has increased greatly in recent years. Today, most turnings, drillings and millings [5] are carried out with this tool type, characterized by high hardness [6]. Their development is driven by the evolution of machine tools, which allow and require tools more and more wear resistant [7–11], more tenacious [12] and which allow cutting speeds much higher than tools made of HSS. According to Ceratizit [13], a leader in hard metal manufacturing, 60% of metalworking tools are steel and the remaining 40% are hard metal tools [14]. The price of hard metal tools is up to 30% higher than that of steel tools, but their life is greater. Hard metal tools are able to work up to 15 million units before requiring sharpening. Normally, the sharpening can be performed from 8 to 10 times, while the steel tools allow a maximum of 1 million manufactured pieces.

The first phase of this work evaluates the viscosity of WC–Co pastes. The experiments conducted by Bouvard [15] show that the viscosity of these mixtures exponentially increases with the density under isothermal conditions, but it dramatically decreases during the conventional sintering cycle. The need to evaluate this parameter is critical to characterize the mixture in the extrusion process. In fact, in order to allow the mixture to maintain a high viscosity and a plasticity degree suitable for the forming step, it is necessary to add reduced binder (Co) amounts [16] in the WC–Co compound. The viscosity evaluation is carried out for different values of shear rate, by means of a testing fixture designed and manufactured for these experiments.

Subsequently, finite element analyses with LS-DYNA code are carried out, starting from the rheological characterization, for the simulation of an extrusion process of hard metal pastes. These analyses highlight the importance of a correct rheological characterization of the WC–Co paste and validate the design of the extrusion die. Based on these results, a die is manufactured and is used in the extrusion process to validate the results from the process simulation using the finite element method (FEM).

2. Viscosity measurement

This section presents the viscosity measurement of a paste of a hard metal mixture, whose main constituents are: tungsten carbide (WC), cobalt (Co) and paraffin wax. Evaluation of the viscosity is performed with an extruder rheometer, which is a measuring instrument for characterizing the rheological behavior of biphasic systems with high solid concentrations (near the maximum packing fraction), such as cement pastes or carbide mixtures. An extruder rheometer consists essentially of a cylinder

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and a capillary tube, inside of which the mixture flows in order to be characterized. Fig. 1 highlights the features of a rheometer: R and L are the inner radius and the length of the capillary, whereas V_p and r_p are the feed rate and the radius of the piston that moves the mixture.

The areas of greatest interest for the purposes of the rheological characterization are represented by the junction between the cylinder and the capillary tube, in which occurs section of reduction (*die entry region*) and the capillary tube. In the case of extrusion of a plastic material, the material in the extrusion chamber is subjected only to compressive stresses and moves with the piston. The material can adhere to the extruder wall or slide without friction, thus generating either higher or lower compressive stresses. In the die entry region, the material is instead subjected to shear stresses. Around the die entry region a static area (*dead zone*) forms in which the material does not experience any deformation and is excluded from the flow. The extension of this zone should be limited because the material, which is continually under pressure, tends to dry out and its fragments may break off depositing in the extrudate. This process causes defects in the final product. To this purpose, conical nozzles are generally used to allow a gradual decrease of the section, which avoids the formation of a dead zone. Finally, in the capillary tube, away from the variation of section, the material moves according to the piston flow. The movement occurs on a liquid thin layer with low concentration in solid, in direct contact with the die wall, in which is concentrated the shear deformation.

In the die entry region the material is forced into the nozzle with smaller diameter than the cylindrical one. It causes an alteration of the velocity profiles because the material flow conditions are in transition state from the flow regime in the cylinder (low speed) to the flow regime in the nozzle (high speed). This transition involves a high pressure drop, which is recorded in the die entry. The capillary tube however, has the main function of regulating the flow, preventing the formation of surface defects that affect the extrusion quality. The compacted powder reacts to the pressure induced in the capillary as a viscous solid, the viscosity of which increases with decreasing porosity [17]. It is important to note that the total pressure drop in the extruder rheometer, nΔP_{tot}, is given by the sum of two terms: the pressure drop in the die entry, ΔP_e, and the pressure drop in the capillary tube, ΔP:

$$\Delta P_{\mathrm{tot}} = \Delta P_e + \Delta P = \Delta P_e + (\Delta P/L) \cdot L. \tag{1}$$

The viscosity measurement of a non-Newtonian fluid, as in the studied case, is obtainable by the following relationship [18]:

$$\eta = \tau_w/\dot{\gamma}_w = \tau_w/(C_{WR} \cdot \dot{\gamma}_{aw}). \tag{2}$$

where η is the viscosity, τ_w, $\dot{\gamma}_w$ and $\dot{\gamma}_{aw}$ are the shear stress, the shear rate and the apparent shear rate measured on the wall, and C_{WR} is the Weissenberg–Rabinowitsch correction [19]. The shear stress and apparent shear rate are:

$$\tau_w = R \cdot \Delta P/2L \tag{3}$$

$$\dot{\gamma}_{aw} = 4Q/\pi R^3 \tag{4}$$

where Q is the volumetric flow, that is so defined:

$$Q = \pi r_p^2 \cdot V_p. \tag{5}$$

The Weissenberg–Rabinowitsch correction is:

$$C_{WR} = \left[\frac{1}{4}\left(3 + \frac{d\ln\dot{\gamma}_{aw}}{d\ln\tau_w}\right)\right]. \tag{6}$$

In order to perform an adequate viscosity measurement, it is necessary to know the rheometer geometrical characteristics, the piston feed rate and carry out two corrections: Bagley and Weissenberg–Rabinowitsch corrections. The Bagley correction allows determination of the $\Delta P/L$ ratio from the slope of the Bagley straight lines, that is the straight lines describing the total pressure trend as a function of the capillary length. The Weissenberg–Rabinowitsch correction arises to take into account that for non-Newtonian fluids the velocity trend of the mixture does not present a parabolic profile, a valid assumption for Newtonian fluids.

2.1. Tests equipment

The rheometer used is composed of a piston with $r_p = 35$ mm, placed inside a cylinder, downstream of which is placed the die, that consists of a capillary with $R = 2.5$ mm. The Bagley straight lines are determined by two values of L/R ratio, that is 0 and 12 (in Fig. 2a representation of the two capillaries in section). In order to obtain a null L/R ratio is necessary to provide the capillary orifice of a conical hole, making sure that the extruding material interacts with the die face on which is present the smaller hole. This die provides the pressure drop for a null capillary length and then the intercepts of the Bagley straight lines. The die with L/R ratio equal to 12 (with $L = 15$ mm) is chosen since this represents a typical geometric condition of the dies used in the extrusion processes.

The piston–cylinder system leans on a columnar structure which allows a visual inspection of the extruded paste at the die exit. In the cylinder, by means of a GAS thread, a pressure transducer is inserted that is connected to a data acquisition scanner for static and dynamic measurements. Since a suitable extrusion temperature is needed to perform the tests, the system is equipped with an oil heater with adjustable power

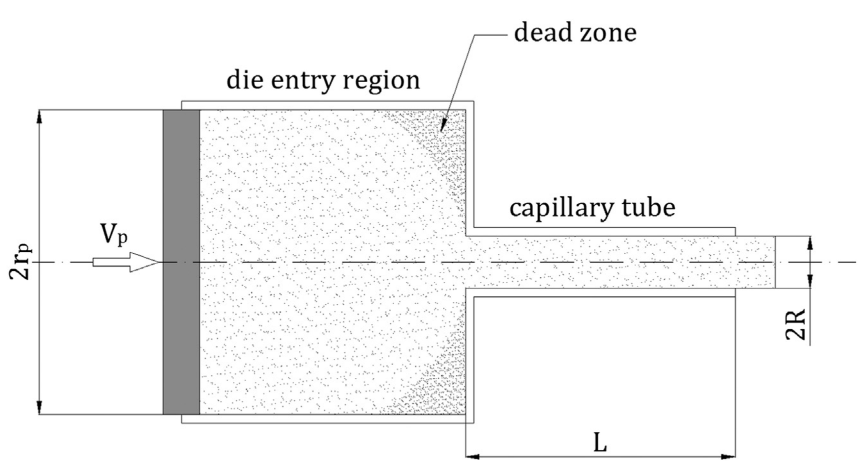

Fig. 1. Schematization of an extruder rheometer.

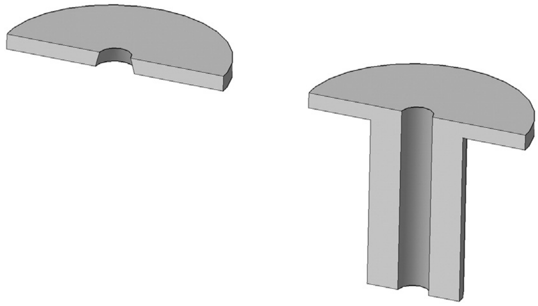

Fig. 2. Representation of the two capillaries.

(500–2000 W). The heated oil evolves into copper pipes which lead to two coils wound around the extrusion chamber and the die. The oil temperature is controlled with a thermometer. The extruder rheometer and its supporting structure are positioned between the plates of a universal testing machine. Through the movement of the upper crosspieces the testing machine performs the piston translation inside the extruder cylinder with a set speed and therefore set mixture compression.

The filling of the cylinder with the mixture to be extruded is manually done taking care to eliminate the trapped air in the paste, in order to ensure the compactness and homogeneity of the extruded product.

The tests are performed at a paste temperature of about 40 °C, where the product is perfectly compact and homogeneous and then ready for extrusion. Another important parameter is the piston speed which affects the material compression (feed rate). The speed sets for test execution are equal to 5, 7.5, 10, 12.5 and 15 mm/min, which correspond to apparent shear rate values of about 209, 313, 418, 522 and 627 s^{-1}. Fig. 3 represents the equipment during a test, whereas in Fig. 4 it is possible to note that the extrusion process is continuous and the obtained green form is shiny and compact.

2.2. Viscosity values

The following results allow the determination of the viscosity values at different shear rates. The Bagley straight lines provide both the losses at the inlet and the losses distributed along the capillary. From the peak values of the measured pressures five straight lines can be constructed related to the five considered extrusion speeds (Fig. 5).

The slope of the straight line ($\Delta P/L$) identifies the distributed losses per unit length of the capillary. These values are used for the calculation

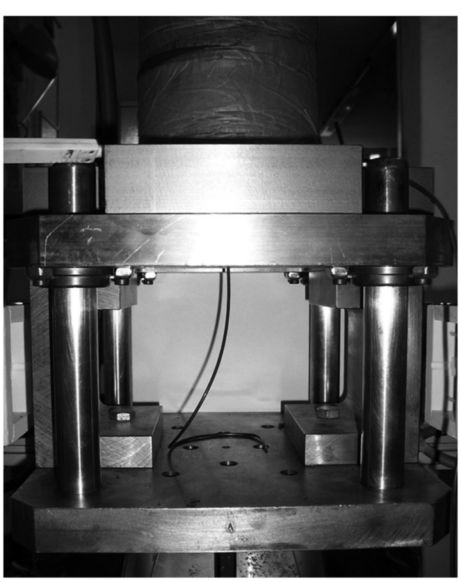

Fig. 3. The equipment for the tests.

Fig. 4. Extruded product.

of the shear stress on the wall (τ_w) for the different speeds by Eq. (3). The Weissenberg–Rabinowitsch correction, equal to 1.33, is calculated by evaluating the slope of the $\dot{\gamma}_{aw}-\tau_w$ curve in double logarithmic scale and substituting the value in the Eq. (6). Downstream of the two corrections, it is therefore possible to determine the paste viscosity with the relationship expressed by Eq. (2) for the piston speeds. Figs. 6 and 7 show respectively the shear stress and the viscosity trends as a function of shear rate. The material presents a pseudo plastic behavior, with decreasing values of the viscosity with increasing strain rate. A complete summary of the different parameters considered is shown in Table 1.

3. FEM analysis of an extrusion process

The purpose of this section is to highlight the importance of a correct setting in a FEM code and the utility of the same to simulate the extrusion process of a mixture made of tungsten carbide. More precisely, the analyses do not concern all the steps of the process, but only the flow of the WC–Co mixture inside an extrusion die. In the specific case, FEM analyses are intended to verify if the die imposes a correct rotation to the mixture under actual process conditions. For this aim, FEM analyses are carried out by LS-DYNA 971 software. This computational code is widely used for analyses involving materials with nonlinear behavior.

The extrusion die, the object of this study, is a special tool, placed downstream of an extruder, which forms rods with inner helical holes evolving along the longitudinal axis of the extruded material. To develop a mechanism for the production of these rods, with adequate process repeatability, information is gathered from patent literature [20–22]. After an investigation on the characteristics of the material to be

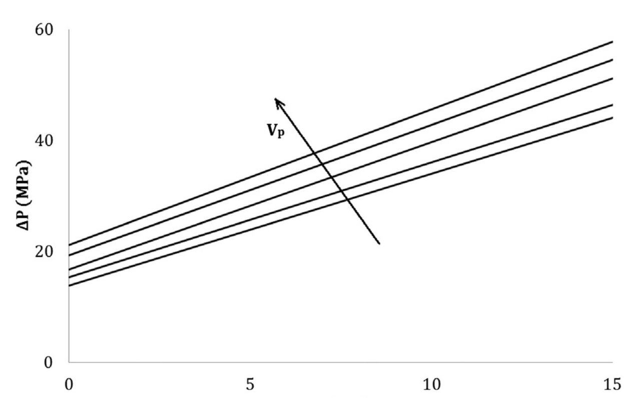

Fig. 5. Bagley straight lines.

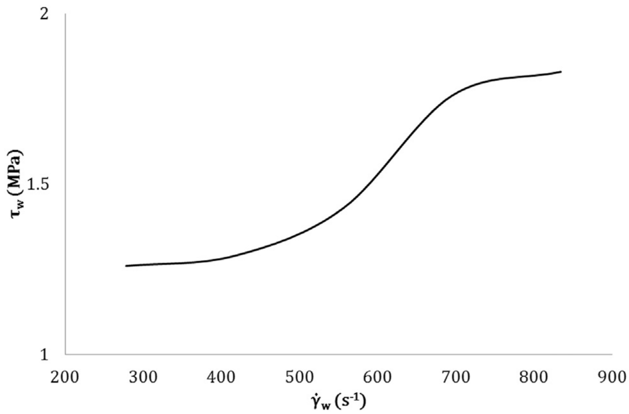

Fig. 6. Shear stress–shear rate trend.

Table 1
Features for the rheological characterization of the paste.

V_p (mm/min)	$\dot{\gamma}_{aw}$ (s^{-1})	$\dot{\gamma}_w$ (s^{-1})	$\Delta P/L$ (MPa/mm)	τ_w (MPa)	η (Pa·s)
5	209	278	2.02	1.26	4531
7.5	313	417	2.06	1.29	3093
10	418	556	2.29	1.43	2571
12.5	522	695	2.82	1.76	2532
15	627	834	2.93	1.83	2194

extruded, a virtual prototype of the instrument is designed by using a parametric CAD software, CATIA V5R19 (a CAD section of the extrusion die is represented in Fig. 8). The extrusion die is rigidly linked to the nozzle by a bolted coupling. Furthermore, two elastic threads, made of nylon, protrude through the inner part of the nozzle. The hole of the die, having a diameter equal to 10 mm, is characterized by the presence of ten helical grooves. This geometry induces the paste to take a cylindrical shape and, at the same time, imposes a twist around the longitudinal axis. This rotation is done by covering a defined angular amplitude which is the function of the mixture feed rate and the geometric parameters of the grooves.

As a result of this rotation the elastic threads generate a pair of internal helical holes. They, being characterized by a structural stiffness similar to that of the material in extrusion, are also twisted, and each of them generates a helical hole. The diameter of each hole is equal to the diameter of the single elastic thread, i.e. 0.4 mm and, in the same way, the distance of the threads, equal to 4 mm, defines the corresponding pitch of the formed holes. The grooves have a pitch and a height of 120 mm; since the useful length of the extrusion die is 30 mm, the helical grooves allow to the paste to rotate 90°. This ensures that the elastic threads, during the process of twisting, do not lock in the extrudate.

In order to gain the target, it is considered appropriate to model the paste and the inner surface of the extrusion die, i.e. the one in contact with the extrudate. Starting from the CAD modeling of the die and by the conversion of this into a compatible format with the preprocessing software LS-PrePost 4.1, surfaces deemed necessary for the simulation are selected to run. These are discretized with shell elements, prevalently quads, whose average size is 0.15 mm. The choice of this dimension is justified by the need to model the helical grooves, present in the die, which have a circumferential section having a radius of 0.4 mm.

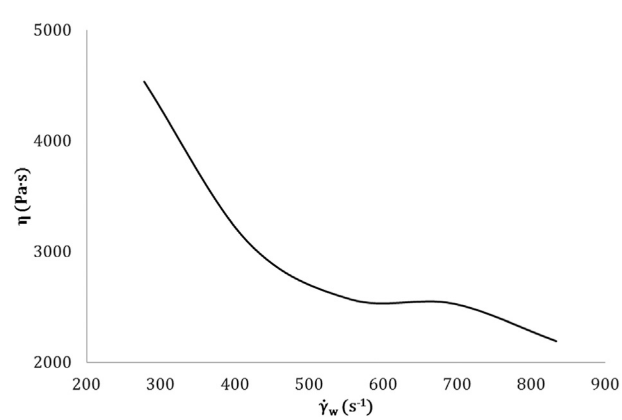

Fig. 7. Viscosity–shear rate trend.

Under the hypothesis that the die is characterized by almost zero deformation, a rigid material model is chosen for this component that needs the following data: Mass density, Young's modulus and Poisson's ratio. To the mixture is associated a solid mesh on a cylindrical volume having a defined height (4 mm), equal to one tenth of the entire die length. This choice is justified by significantly reduced the calculation time to obtain a solution. The model has the capacity to contemplate the dynamic viscosity of the material. Fig. 9 shows the assembly view of the FEM model, whereas the characteristics of the extrusion die material, typically steel, and of the WC–Co used in the FEM code are reported in Table 2.

Simulation parameters are selected to guarantee a strain rate of 400 s^{-1}. This value is in line with the extrusion process conducted at Nashira Hard Metals Company. For this value, the dynamic viscosity, considered for the material model information, is equal to 3220 Pa·s. The interaction between the die and the paste is treated by a contact model, named SURFACE_TO_SURFACE, for which it is recommended that the mesh defining any rigid body be as fine as that of a deformable

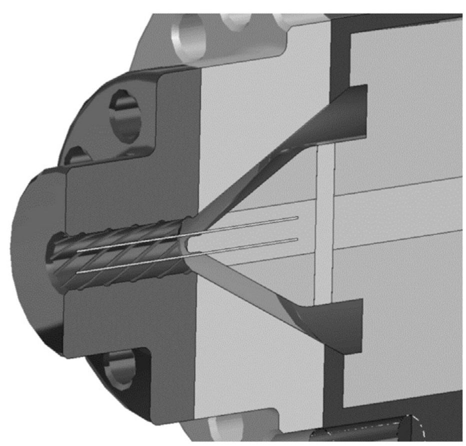

Fig. 8. CAD representation of the die section.

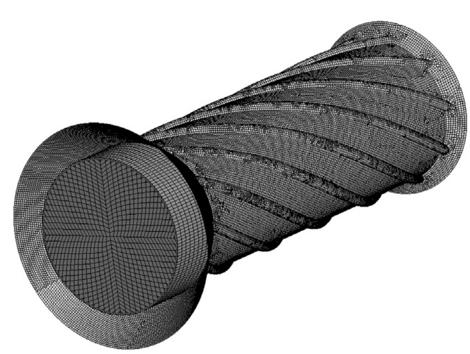

Fig. 9. FE model of the extrusion die and the portion of mixture.

Table 2
Characteristics of the materials used in FE code.

	Mass density (g/cm^3)	Young modulus (GPa)	Poisson ratio (MPa/mm)	Viscosity (Pa·s)
Steel extrusion die	7.85	210	0.3	–
WC–Co compound	14.00	60	0.3	3220

Table 3
FEM details of the extrusion process.

Steel extrusion die	
Material type	020_MAT_RIGID
Element type	4-Node shell element
Element formulation	Fully integrated shell element
Number of through shell thickness integration point	2
Number of elements	66,411
WC–Co compound	
Material type	060_MAT_ELASTIC_WITH_VISCOSITY
Element type	8-Node brick element
Element formulation	Fully integrated *S/R* solid intended
Number of elements	7360
Other settings	
Contact type	SURFACE_TO_SURFACE
Feed rate	0.2667 mm/s
Simulation end time	60 s
Time interval between outputs	1 s

body. In this contact type, the surface of the die is defined as the master side of the contact and the paste as the slave one; moreover, the shell elements are oriented towards the inside of the die. In order to eliminate the dynamic effects related to high frequencies, a viscous damping of 20% of the parameter VDC is used. To simulate the manner in which the paste twists under defined conditions, a motion on a set of 0.09pt?>nodes is imposed (BOUNDARY_PRESCRIBED_MOTION_SET). This set of nodes belongs to the external face of the mixture shown in Fig. 9. The assigned displacement–time curve allows the imposition of a constant feed rate of 0.2667 mm/s, along the axis of the die, on the nodes.

Finally, the duration of the simulation is assigned, setting a termination time of 60 s and a time interval between outputs of 1 s. Table 3 summarizes the FEM details of the process simulation.

The FEM analysis checks the mixture rotation around the feed axis of the paste itself. This is apparent from Fig. 10, in which are shown six simulation stages, one every 10 s. It is possible to analyze how the helical grooves, present in the die, drive the advancement of the paste, imposing a rotation combined with a linear feed. It is measured, in the FEM environment, the rotational angle that the mixture undergoes during the feeding in the die. In order to perform an adequate measurement, the nodes of the center line of the paste are considered (Fig. 10) and the rotation is compared to the meridian plane of the extrusion die. The measured angle is equal to 46°. This value shows a deviation of 4% with respect to the angle, analytically calculated, for the geometrical configuration of the extrusion die. In fact, since the pitch of a single helicoid in the die is 120 mm and the same die has an extension of 30 mm, the crossing of the paste in the die has to ensure a rotation of the paste equal to 90°. Considering the feed speed of 0.2677 mm/s, in the analysis time (60 s) the paste runs 16 mm and undergoes a twist angle of 48°.

The result of the above described analysis highlights the good choice of the contact type and of the elements dimensions. In order to completely validate the FEM model, additional simulations are performed, considering different viscosity values. Therefore two FEM models are considered, having both a higher and lower viscosity value than the one measured experimentally. Specifically, the simulations are performed with the values of 322 and 32,200 Pa·s, which respectively represent a reduction and an amplification equal to one order of magnitude with respect to the value measured by experiments. This choice allows to investigate the sensitivity of the material model to the viscosity variation. In the first case, LS-DYNA software does not complete the analysis because, after an initial motion of the paste, it computes a negative volume for some of the solid elements; this is due to the inconsistency of the material caused by the low value of viscosity. This parameter indeed quantifies the resistance of fluids to flow, and then it is an index of the internal cohesion of the fluid. In the analysis performed with the value of viscosity of 32,200 Pa·s, it denotes the advancement of the paste in the extrusion die, but the mixture does not undergo twisting in the process. In this case, the material is characterized by a high internal strength of cohesion due to the high viscosity,

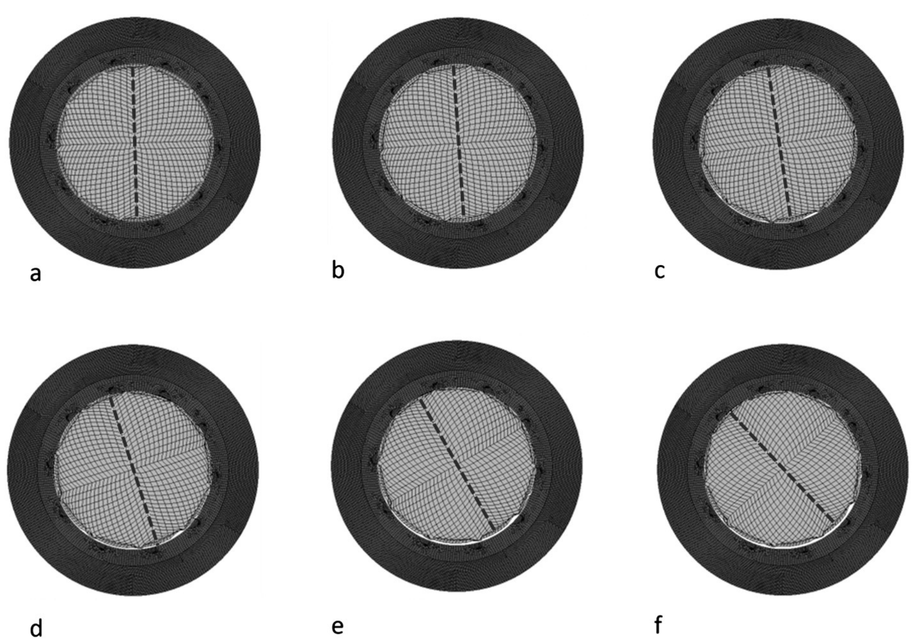

Fig. 10. Simulation time a) 10 s; b) 20 s; c) 30 s; d) 40 s; e) 50 s; f) 60 s.

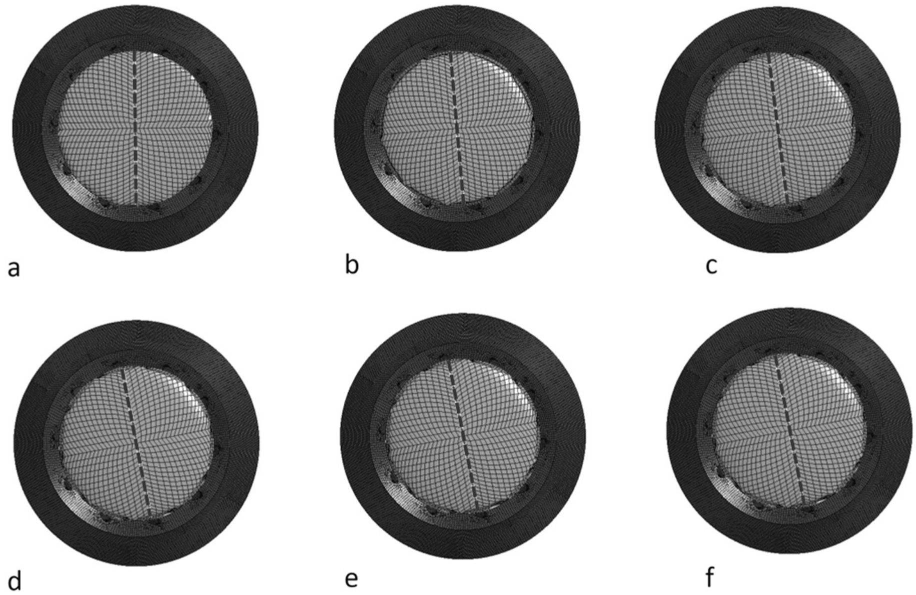

Fig. 11. Simulation time at 32,200 Pa·s a) 10 s; b) 20 s; c) 30 s; d) 40 s; e) 50 s; f) 60 s.

which denotes an increase in the threshold of shear stress relative to the plastic regime. The paste, after a slight twist registered in the nozzle of extrusion die, cannot follow the helical grooves in the die. Fig. 11 shows how, for the same feed rate of the paste, the extruding material is more resistant to twisting. In this case the rotational angle that the WC-Co mixture undergoes in the extrusion die during the FEM simulation (Fig. 11) is 12°.

Downstream of the FE simulation, the extrusion die is manufactured as well as designed. Then extrusion tests are conducted using the same conditions used in the numerical analysis. Fig. 12 shows a section of manufactured rod; the cross-sections show the trace of helical holes along the body of the extruded rod. Successively, measures of the pitch length, carried out by a caliper, highlight the good performance of the die in the working conditions and, then, the validity of FE analyses; indeed, the measured values satisfy the requirements to obtain rods that will be, after sintering, machined in order to get drilling tools with helical holes.

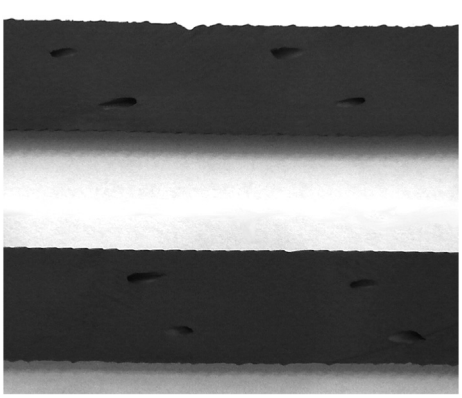

Fig. 12. Sections of extruded bar.

4. Conclusions

A rheological characterization of hard metal mixtures, using experimental equipment, produces viscosity values according to the shear rate necessary to design an extrusion die for carbide rods with inner helical holes. Furthermore, FE simulations are carried out by using LS-DYNA code, in order to predict the evolution of the material in the extrusion process. To correctly-simulate of the process, it is important to choose properly the various parameters, especially geometric ones, and to enter the data related to the rheological characterization of the mixtures. The simulations show the correct design of the extrusion die, because it reaches the appointed purpose: to assign a proper twist to the paste in the extrusion process. Additional FEM analyses are performed in order to validate the correct rheological parameters used in FE model. This operation is fundamental in order to realize the helical holes in the extruded product. In the final phase of the study, the die is manufactured and extrusion tests are conducted. These tests confirm the result predicted from FEM analysis.

Acknowledgments

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