Advanced Engineering Forum *Online: 2013-06-27*
ISSN: 2234-991X, Vols. 8-9, pp 269-276
doi:10.4028/www.scientific.net/AEF.8-9.269

Numerical simulation and experimental investigation on thixo-backward extrusion of 7075 aluminium alloy

Adriana Neag[1, a], Veronique FAVIER[2,b] , Liviu Nistor[1,c], Regis BIGOT[3d]

[1] Technical University 103-105 Bwd.Muncii, 400641 Cluj-Napoca, Romania

[2] Arts et Métiers ParisTech, PIMM UMR CNRS 8006, 151 Bd.de l'Hopital, 75013 Paris, France

[3]Arts et Métiers ParisTech, LCFC, EA 4495, 57078 Metz Cedex 3, France

[a]adriana.neag@ipm.utcluj.ro, [b]veronique.favier@ensam.eu, [c]liviu.nistor@ipm.utcluj.ro, [d]regis.bigot@ensam.eu

Keywords: Semi-solid, 7075 aluminium alloy, thixoextrusion, numerical simulation.

Abstract. The thixoextrusion process could become an important technique to extend the complexity of extruded profiles. However, the complex thixotropic flow behavior of semi-solid, during thixoextrusion is still partly characterized. The study described in this paper investigates thixoextrusion for 7075 aluminium alloy at different temperature conditions. A complete die filling and a good surface state of parts was obtained at high solid fraction (f_S = 0.70), in heated dies, for an extrusion ram speed of 416 mm/s. The thixoextrusion process is simulated using the finite element code Forge2009©. The constitutive equation used for these simulations is based on a micro-macro model for the semi-solid evolution. The tendency of the experimental curves evolution, preserving the same parameters of the micro-macro constitutive model, for each values of solid fraction, was reproduced, except the last step of the ram displacement.

Introduction

Thixo-extrusion is one branch of semi-solid processing which gained interest among researchers for forming alloys to near net shaped components [1]. This process required for forming alloys in semi-solid state, a non-dendritic microstructure consisting of solid spheroids surrounded by a liquid matrix in order to obtain thixotropic flow behavior [2]. Several methods can be used to produce this target microstructure. Rheological behavior of the materials in semi-solid state, the impact of raw material characteristics and the forming process parameters have to be attentively controlled.

The present study investigates thixo-extrusion using dies at temperatures much lower than the slug temperature, which means that the forming process is considered as non-isothermal. In the thixo-extrusion experiments realized at high ram speed, some critical forming parameters were studied in order to obtain an adequate semi-solid material flow and a good part quality: the initial slug temperature, the die temperature. The load–displacement curves obtained experimentally or numerically are discussed in relation to the impact of slug temperature and flow. The micro–macro constitutive model was used to follow the evolution of the initial slug temperature and of the solid fraction during the thixo-extrusion process

Experimental procedures

Material selection

The criterion of alloy selection for the semi-solid forming test by thixo-extrusion was the solidification temperature range. The solidification temperature range is defined as the temperature range between the liquidus and the solidus of an alloy. For the semi-solid applications it is commonly suggested by the researchers that the solidification range (ΔT) should be from 20 to 130 °C [3].

The material used for this study was a commercially 7075 aluminium alloy. The composition of the 7075 aluminium alloy given by the supplier is shown in Table 1.

Table 1 Chemical composition (%wt) of the 7075 alloy used.

Element	Zn	Mg	Cu	Cr	Fe	Si	Ti	Al
wt.%	5.1-6.1	2.1-2.9	1.2-2	0.18-0.28	max0.5	max0.4	max0.2	bulk

For the given alloy, the solid fraction (f_S) evolution versus temperature was identified by differential scanning calorimetry (DSC), as the literature specify [2, 4-6] and by the well-known Scheil equation (Eq. 1) [7].

$$f_S = 1 - \left(\frac{T_F - T}{T_F - T_L}\right)^{\frac{1}{k-1}} \tag{1}$$

In equation (1), T_F is the melting temperature of the pure metal, T_L is the liquidus temperature of the used alloy and k is the partition ratio.

Fig. 1 shows the results of calculation of the solid fraction versus temperature curves for the 7075 alloy obtained by DSC analysis [8], and Scheil equation. It is important to note that DSC analysis is carried out at lower heating rates (15 °C min^{-1}) than induction heating rate applied in our case (350 °C min^{-1}). The DSC analysis was used even if the calibration conditions are never identical to the heating condition for thixo-extrusion test and the kinetics of solidification and fusion is not the same. The solid fraction approximation identified by this methods offer us several information concerning the real solid fraction evolution.

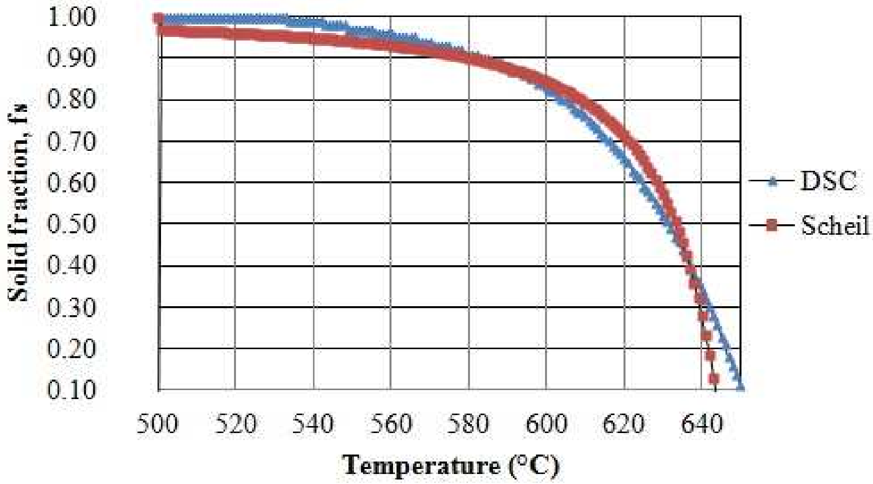


Fig. 1 Solid fraction vs. temperature curves of the 7075 alloy obtained by DSC analysis and Scheil equation.

In the temperature window, it can be observed that the temperature is less sensitive for temperature ranging from 500 °C to 610 °C and much more sensitive for temperature ranging from 610 °C to 640 °C. In this study, the working temperature window was chosen equal to [580-610 °C] in order to get a not to high solid fraction (ranging from 0.9 up to 0.7) required to get thixotropic behaviour but also a not to low solid fraction to get a reliable process, namely to avoid strong changes of solid fraction due to variation in temperature.

Slug

The slug was obtained from 7075 aluminium alloy bars extruded (with an extrusion ratio of 16:1) and T6 heat treated by the supplier.

The slugs used to thixoextrusion were obtained by cutting the extruded bars. The volume of the slug is chosen to fully fill the extrusion tool. For these tests the slug dimensions are 35 mm in diameter and 37 mm high, cut from an extruded bar of 35 mm. The height of the slug was chosen not too large in order to avoid its downfall under its own weight. This depends on the liquid fraction of the slug.

Semi-solid material preparation

Semisolid manufacturing requires heating the slug to the semisolid state with coexisting liquid and solid phases. The recristalisation and partial melting (RAP) process was used to recrystallize the 7075 aluminium alloy. In our work the slugs were re-heated into an induction furnace. In this case a

Fives Celes MP50 generator was used to re-heating the slug (Fig. 2a). The parameters of the slug heating are reached using the induction heating to a maximum power of 50 kW and a frequency between 20-100 kHz.

The heating efficiency and the temperature distribution inside the slug depend on the design and position of the induction coil. The slug are positioned in the axis of the inductor and stands on a special ceramic support which resist to thermal stresses, and is thermal insulated.

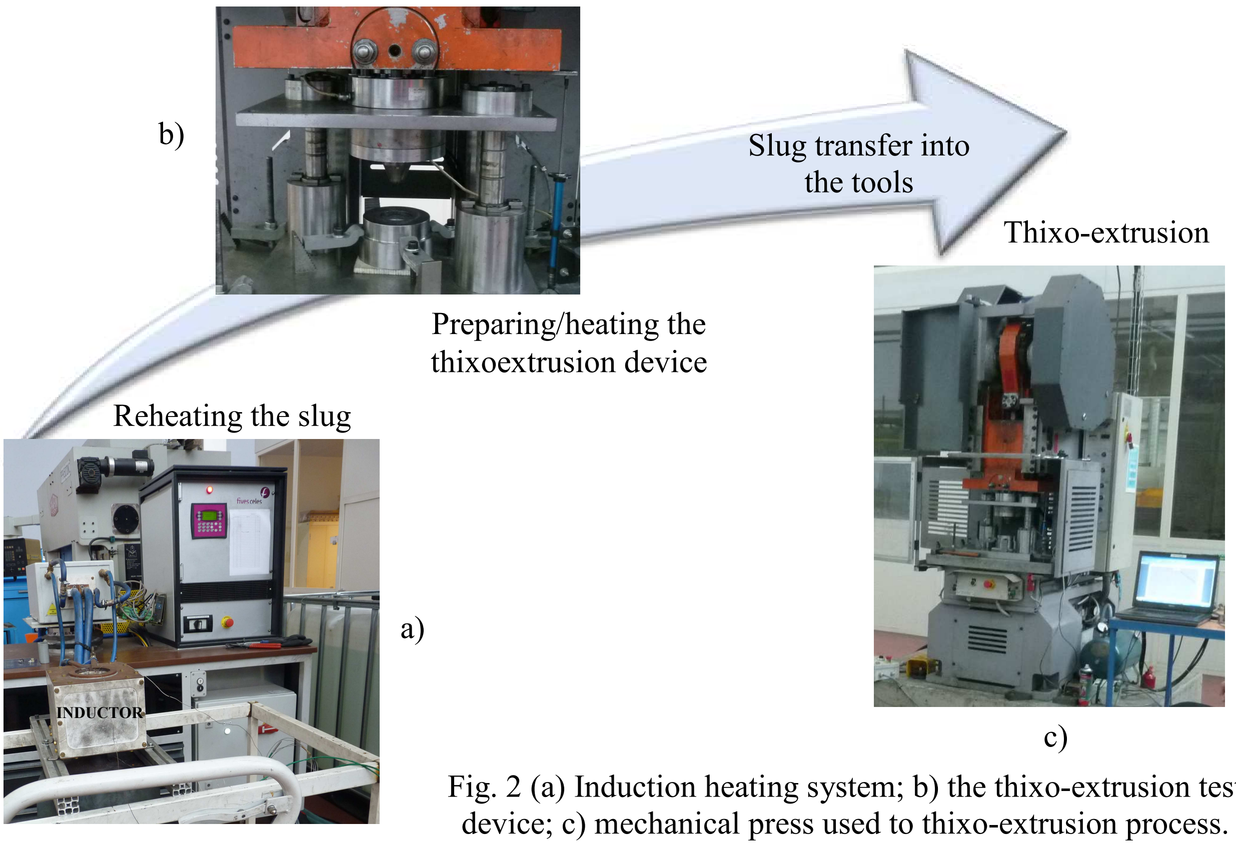


Fig. 2 (a) Induction heating system; b) the thixo-extrusion test device; c) mechanical press used to thixo-extrusion process.

Two holes of 2 mm in diameter were drilled into the sample (in the center and towards the edge) in order to insert a “K” thermocouple for controlling the temperature. The re-heating process must be accurately controlled to achieve a uniform temperature distribution in the slug. The heating route (that is relatively quick) consisting on a successive power stages was obtained by trial and error procedure. Consequently the re-heating cycles are programmed and applied on our equipment and these cycles are repeatable.

After the reheating process, the slug was removed from the furnace to the extrusion die. The semi-solid slug was transferred by a Nefacier© insulated grip, to the thixo-extrusion test device (Fig. 2b).

Testing tools

A non-isotermal backward extrusion experiment was developed in a simple closed die (Fig. 3). The dies design allows the investigations of the material flow depending on the draft angles of the side walls of the upper and lower dies; of the radius connection and at the same time ensures the part extracting. The thixo-extrusion die was axisymmetric. Due to the fact that the flow material is conditioned by the temperature, the die was designed to reduce the heat losses between the heating and the forming stages, in order to have a certain die filling control. The filling length is also controlled by the dies shape.

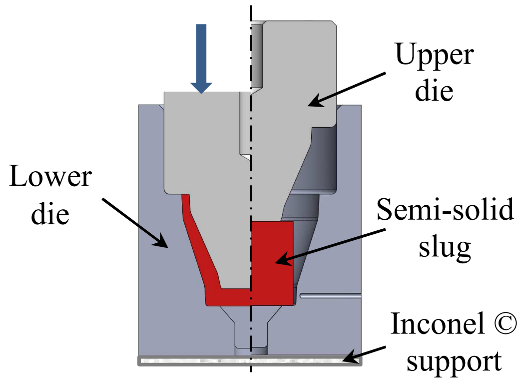


Fig. 3 Principle of the extrusion test.

The die is at room temperature (20 °C), or to avoid the brutal contact of the high temperature slug with the thixo-extrusion die, the upper and lower die were heated (up to 350 °C). The temperature of the thixo-extrusion device was measured by an optical pyrometer.

The thixo-extrusion tests were carried out using the mechanical eccentric Press X50CNR4 presented on Fig. 2c and located at the "Arts et Métiers ParisTech" Metz. Fig. 3 shows the principle of the extrusion test. In this configuration, the lower die is fixed on the press table. An Inconel© support was placed between the lower die and the press table to reduce heat losses. The slug is posed in the lower die. The upper die is also fixed to the press.

The movement on semi-solid state must be fast, so the maximum working ram speed applies in our experiments were 416 mm/s. The entire equipment is controlled by sensors. The physical parameters, load and displacement are recorded by data acquisition boards, through the Scaime sensor and the linear potentiometer Penny&Gilles. The load sensor is placed above the upper die and measures only the extrusion load involved in the thixo-extrusion process. The extrusion is done in about 0.3 s depending on piston speeds (maximum 416 mm/s).

A tool protection coating is sprayed before each extrusion test to protect tool surface against wear and chemical attack of aluminium on steel. Acheson Pulvegraph D31A which is a graphite base lubricant was used as tool thermal protector agent to limit thermal exchanges and friction with the extrusion tool and also to limit aluminium chemical attack.

The transfer time of the slug to the thixo-extrusion die, fixed on the mechanical press and up to start of the deformation, is about 5 s.

At the end of the thixoextrusion process the thixo-extruded parts were cool in water to the ambient condition at room temperature.

Results and discussion

Semi-solid microstructure before thixoextrusion

The microstructure corresponding to the slug after the re-heating process is shown in Fig. 4. The reheated slug was directly quenched in the water in order to preserve the former structure at the semi-solid state. Samples used to analyze the microstructure were ground with grit paper, polished using diamond paste, etched using Keller reagent and optical micrographs were taken.

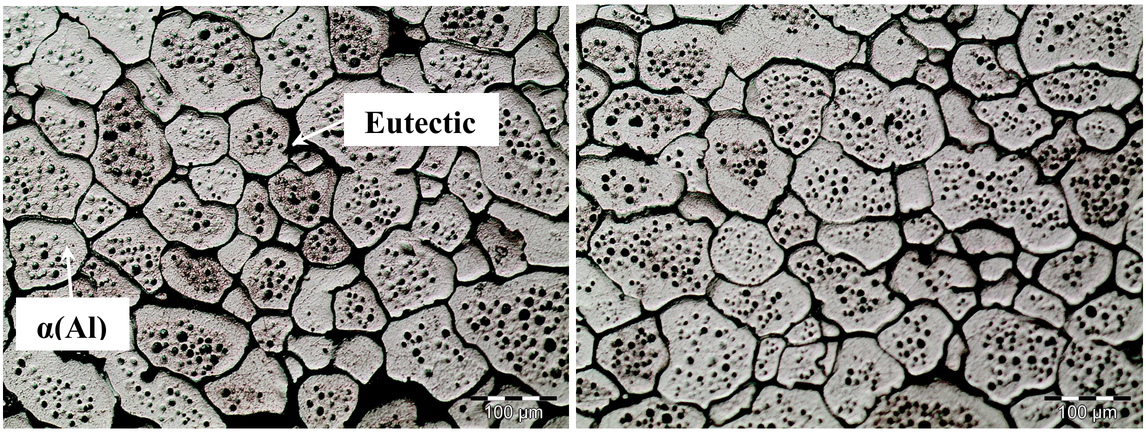
a)  b)

Fig. 4 Optical micrographs of 7075 aluminium alloy re-heated to 615 °C and then quenched: a) on the edge and b) on the center of the slug.

After a reheating time of 100 s at 615 ºC ($f_S = 0.7$), the recrystallisation occurred and the primary α(Al) elongated phase particles (that characterizes the extruded bar [8]) was turned into globular microstructure. In Fig. 4 can be observed that a fine equiaxed microstructure suitable for subsequent thixo-extrusion process was produced. The light primary solid phase and the dark eutectic phase, corresponding to the solid phase and to the liquid phase which are supposed to be present in the semi-solid state, can be clearly seen on the edge (Fig. 4a), and on the center (Fig. 4b) of a longitudinal slug section. The liquid droplets are present in a large number of particles [8]. These intragranular liquid droplets possibly originate from the internal inhomogeneity of the primary solid, which is caused by chemical segregation [9]. The large intragranular liquid droplets were probably a result of liquid droplet migrating [10-11].

Non-isothermal extrusion test

A significant number of tests have been carried out (more than 50) to illustrate the forming load stability for backward extrusion. These results allowed us to identify the influence of the tool temperature, initial slug temperature and of the high working ram speed (to complete our previous work [12]), on the material flow and on the forming load. All the rheological experiments are performed with a high solid fraction.

Table 2 illustrates a synthesis of the experimental results. The up mentioned parameters mainly affect heat exchange between slug and dies. This influences the forming slug temperature and as a result it's solid fraction and therefore, the viscosity and consistency, the desagglomeration of the solid skeleton, the forming load, the type of flow and finally the microstructure of the thixo-extruded parts and consequently its mechanical properties [13].

Table 2 Influence of slug temperature, die temperature and ram speed on 7075 aluminium backward thixo-extrusion.

Slug temp. °C	Dies temp. °C	Ram speed mm/s	Load max. kN
605	20		249
610	20	416	130
615	20		117
620	20		67
600			90
610	200	416	87
615			64
600	350	416	108
610			58

Similarly to the results from previous investigations, Fig. 5 illustrates typical evolution of forming load versus ram displacement at the maximum load determination on experimental curves.

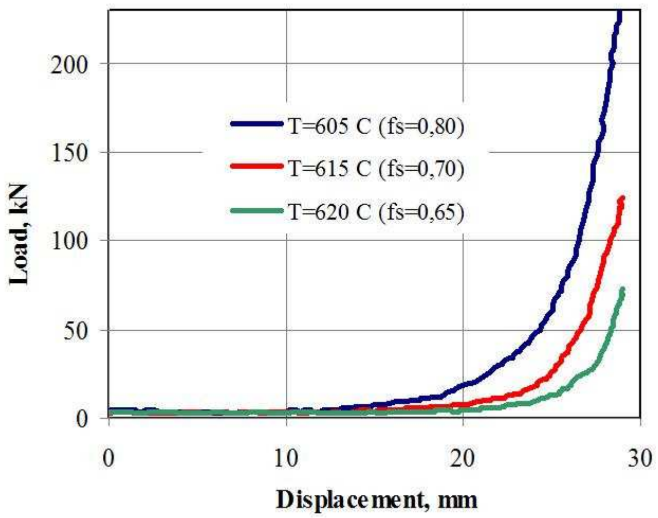


Fig.5 Load-displacement evolution during the thixo-extrusion process for various slug temperatures.

Fig.6 Thixo-extruded part.

In this case, the thixo-extrusion process was conducted using the dies at room temperature.

The load-displacement curves have been recorded considering the same transfer conditions of the slug. On the first part of ram displacement, the load increases very slowly with the displacement: this step is not recorded by the load sensor because the sensitivity of the sensor we used was lower than the loads that appeared in the slug in this stage. With increasing the temperature, the load value decreases due to the decrease of the solid fraction that makes the material to be less resistant to flow. Under the influence of the temperature increasing the resistance of the solid particles skeleton decrease, improving the flow of the semi-solid material in the deformation mechanism. The dies temperature and the initial slug temperature are significant in terms of load level due to the solidification rate of the semi-solid material. The slug reheated between 610 - 615ºC (f_s = 0.70 - 0.75) and extruded in heated dies reveal a complete die filling (exact shape and a good surface state - Fig. 6).

Forming simulation/ Temperature evolution

In the semi-solid state, the slug includes solid phase and liquid phase, so the forming process is complex compared to the conventional forging and the numerical simulation is also much more difficult.

The simulation of semi-solid material flow is carried out using the software Forge 2009® with the original multi-scale micro–macro model [14]. The initial and boundary condition imposed for the simulations are as closed as possible to those recorded for the experimental tests. Because 3D analysis is so intensive in terms of computational time, considering one quarter of the geometrical model was an advantage. A friction law of Coulomb-Tresca was used (m_bar = 0.6; μ = 0.3). The heat conduction transfer coefficient (between the dies and the slug) was considered homogeneous and equal to 20 kW/m^{2}K. The initial slug temperature was between 605 °C and 620 °C, the dies temperature 20 °C and the ram speed 416 mm/s.

In the numerical simulations has been taken into account the transfer time of the slug to the extrusion device. So, the initial solid fraction before loading is calculated under the same conditions of heat transfer during this transfer period.

In a first approach, using the previously selected parameters for the micro–macro model, we have adjusted only the rheological parameters of the solid phase. Fig. 7 shows the evolution of the load-displacement curves for simulated extrusion tests using three values for the initial slug temperature (605-615-620 °C).

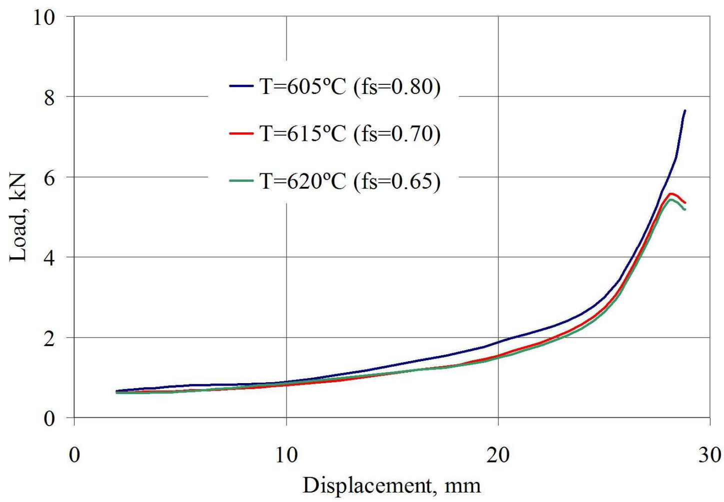


Fig. 7 Load-displacement evolution during the thixo-extrusion process using the micro–macro model.

As the solid fraction increase, naturally, the extrusion load increase up to a maximum. The curve obtained at 0.8 solid fraction (on the initial slug) sharply increase (on the last step) probably due to an increase of the material consistency (agglomeration processes). We didn’t propose in this stage to precisely fit the curves. The goal of our tests was to reproduce the tendencies of the experimental curves, preserving the same parameters of the micro–macro constitutive model, for each value of solid fraction.

The temperature and the solid fraction distribution in the parts at the final step are presented in Fig. 8 and Fig. 9.

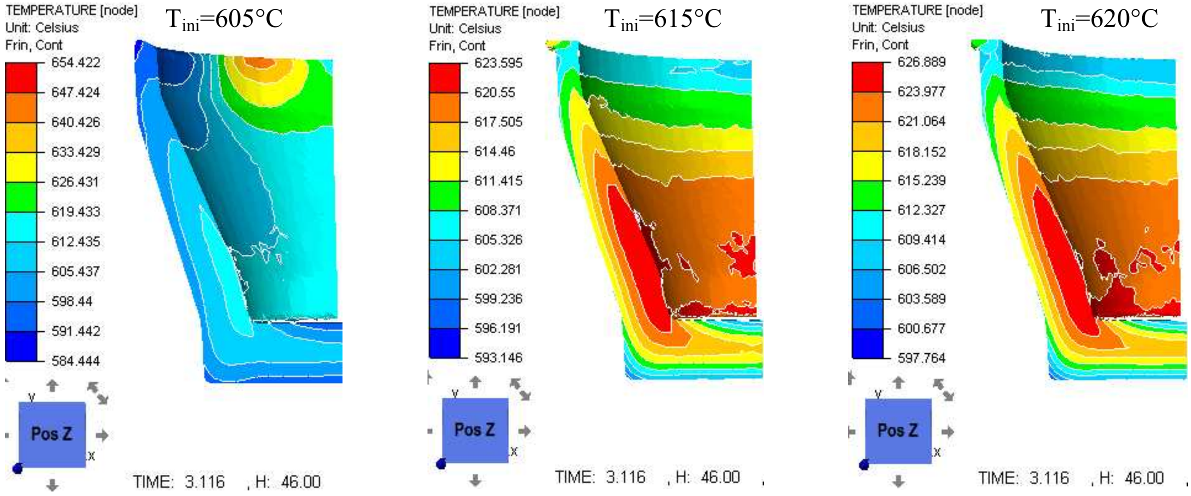


Fig. 8 Temperature distribution at three values for the initial slug temperature: final step on micro-macro modeling.

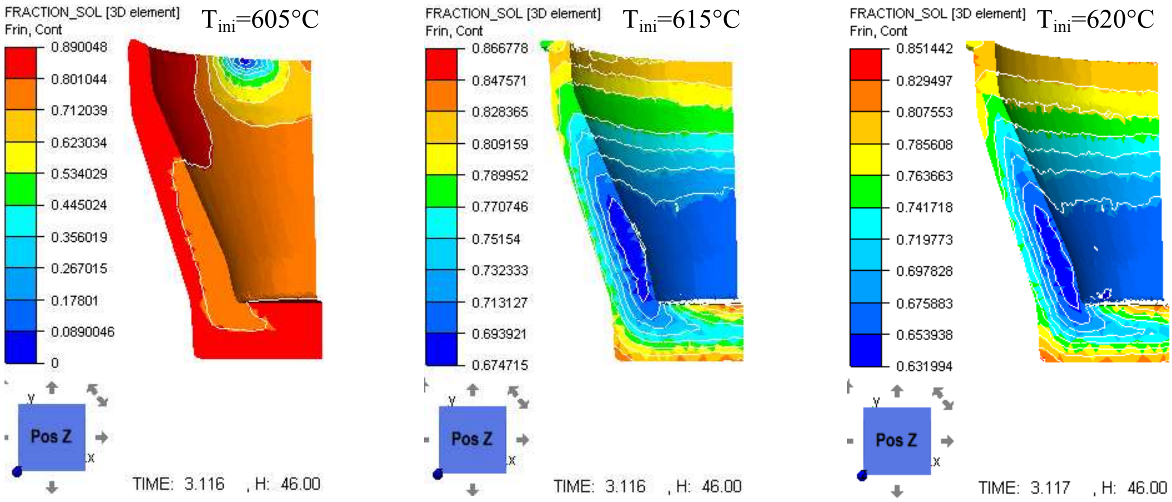


Fig. 9 Solid fraction distribution at three values for the initial slug temperature: final step on micro-macro modeling.

During thixo-extrusion the temperature change (Fig. 8), thus the solid fraction volume change (Fig. 9) because of viscoplastic dissipation or/and thermal exchanges between the dies and the slug. This phenomenon is accentuated by the fact that the test have been made in non-isothermal conditions. In the temperature field a predictable heat loss appears (Fig. 8). The most important heat loss appears in the case of the part having an initial temperature before loading of 605 °C (reach 70 °C). The heat loss decrease with increasing the initial temperature, reaching only 29 °C in the case of the slug heated at 620 °C. This observation can be one of the possible explanations concerning the sharply increase of the load on the last step of extrusion in the case of 0.8 initial solid fraction.

Summary

The thixo-extrusion tests were realized on 7075 aluminum alloy. Experiments has been realized between 605 °C and 620 °C because the low sensitivity to temperature variation of the material. The observation on the parts obtained at 615 °C (fs = 0.70), in heated dies, for an extrusion ram speed of 416 mm/s, shows a good quality of the surface (higher cohesion of the material) without cracks that usually can occur in the cold dies.

The micro–macro constitutive model was used to follow the evolution of the temperature and of the solid fraction during the thixo-extrusion process.

- It was observed that the simulation curves tendencies are in accordance with the tendencies of the experimental curves, except the last step of the ram displacement, where the maximum load is still lower than in experimental conditions.
- Concerning the initial slug temperature used for thixo-extrusion, it was observed that, if it grows, leads to a decrease of the heat loss on the extruded part.
- The non-isothermal modeling of the backward extrusion test requires on the future more detailed investigations.

ACKNOWLEDGMENT: This paper was supported by the project "Development and support of multidisciplinary postdoctoral programmes in major technical areas of national strategy of Research - Development - Innovation" 4D-POSTDOC, contract no. POSDRU/89/1.5/S/52603, project co-funded by the European Social Fund through Sectoral Operational Programme Human Resources Development 2007-2013.

References

[1] Kirkwood, D.H., Sellars, C.M., Elias-Boyed, L.G., 1992. Thixotropic materials. European Patent No. 0305375 B1.

[2] S. Chayong, H.V. Atkinson, P. Kapranos, Thixoforming 7075 aluminium alloys, Materials Science and Engineering A 390 (2005) 3–12.

[3] Li Yuan-dong, Apelian Diran, Xing Bo, Ma Ying, Hao Yuan, Commercial Am60 alloy for semisolid processing: I alloy optimization and thermodynamic analysis, 11th Int. Conf. on semi-solid processing of alloys and composites (2010) 29-35.

[4] D. Larouche, C. Laroche, M. Bouchard, Analysis of differential scanning calorimetric measurements performed on a binary aluminium alloy, Acta Materialia 51 (2003) 2161–2170.

[5] G. Vaneetveld, A. Rassili, H.V. Atkinson, Influence of parameters during induction heating cycle of 7075 aluminium alloys with RAP process, Solid State Phenomena Vols. 141-143 (2008) 719-724.

[6] A. Bolouri, M. Shahmiri, C.G. Kang, Study on the effects of the compression ratio and mushy zone heating on the thixotropic microstructure of AA 7075 aluminum alloy via SIMA process, Journal of Alloys and Compounds Vol. 509/ 2, (2011), 402–408.

[7] M. Suery, Mise en forme des alliages métalliques à l'état semi-solide. Traité MIM Mecanique et Ingénierie des Matériaux, Ed. Lavoisier, 2002.

[8] A. Neag, V. Favier, R. Bigot, M. Pop, Microstructure and flow behaviour during backward extrusion of semi-solid 7075 aluminium alloy, J. Mat.Proces.Tech. 212 (2012) 1472– 1480.

[9] A. Neag, V. Favier, M. Pop, E. Becker, R. Bigot, Effect of Experimental Conditions on 7075 Aluminium Response During Thixoextrusion, Key Engineering Materials Vols 504–506 (2012) 345-350.

[10] Bolouri, A., Shahmiri, M., Cheshmeh, E.N.H., Microstructural evolution during semisolid state strain induced melt activation process of aluminium 7075 alloy, Trans. Nonferrous Met. Soc. China 20 (2010), 1663-1671.

[11] Q. CHEN , G. ZHAO, D. Shu, Study on microstructural evolution of deformed magnesium alloy during partial remelting, Solid State Phenomena Vols. 192-193 (2013) 246-250.

[12] A.Neag, E.Becker, M.Pop, E.Henrion, R.Bigot, Influence of Experimental Conditions on Material Response During Thixoextrusion Process, ACTA TECHNICA NAPOCENSIS - Series: Applied Mathematics and Mechanics No.54, Vol. II, 2011.

[13] E. Becker, R. Bigot, L. Langlois, Thermal exchange effects on steel thixoforming processes, Int. J. Adv. Manuf. Technol. (2010) 48:913–924.

[14] V. Favier, P. Cézard, R.Bigot, Transient and non-isothermal semi-solid behaviour: 3D micromechanical modelling, Materials Science and Engineering A 517 (2009) 8–16.