EXTRUSION SIMULATION OF TI-6AL-4V FOR THE PRODUCTION OF SPECIAL SHAPED CROSS SECTIONS

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Abstract

The metallurgical and technological management of the hot extrusion process is related to the microstructural behaviour of the material which depends on its high temperature constitutive relation and on the adopted technological parameters. On the basis of the former determination of the sine hyperbolic constitutive relation and on the performed microstructural analysis, an approach based on the Navier-Stokes' equations has been used for the study of the extrusion of Ti-6Al-4V after a successful application in the hot rolling of micro-alloyed steel and in the extrusion process of austenitic and duplex stainless steels. The result of the simulation has shown the good suitability of this approach for the Ti alloys as well and it has allowed to confirm quantitatively some qualitative considerations stressed about the critical aspects involved in the extrusion of the special cross sections. Particularly, the role of the initial temperature, of the heat developed during the plastic deformation and of its mutual relation with the viscosity of the material, related also to the velocity field imposed to the material by the pulling through the die, have been pointed out.

Keywords
Hot extrusion; titanium alloys; microstructure; heat transmission, numerical simulation.

Riassunto

La conduzione metallurgica e tecnologica del processo di estrusione a caldo è collegata con il comportamento microstrutturale del materiale, che dipende dalla relazione costitutiva a temperatura elevata e dai parametri tecnologici adottati. In base alla precedente determinazione del rapporto costitutivo sen-iperbolico e all'analisi microstrutturale sperimentale effettuata, un metodo basato sulle equazioni di Navier-Stokes, già utilizzato con successo nel caso della laminazione a caldo di acciai HSLA e dell'estrusione di acciai inossidabili austenitici e duplex è stata applicato per lo studio dell'estrusione di profili speciali della lega Ti-6Al-4V. Il risultato della simulazione ha indicato la buona idoneità di questo metodo anche per le leghe del Ti ed ha permesso di confermare quantitativamente alcune considerazioni qualitative avanzate circa gli aspetti critici concernenti l'estrusione di profili speciali. In particolare in relazione al campo di velocità del materiale nella matrice, è stato messo in evidenza il ruolo della temperatura iniziale, del calore sviluppato durante l'estrusione ed il relativo rapporto reciproco con la viscosità del materiale.

INTRODUCTION

Titanium alloys have been widely used in automotive, aerospace, biomedical and energy applications due to their high strength,weight ratio, excellent toughness, fatigue resistance at elevated temperatures, and good resistance to corrosive environments. However, one of the most significant obstacles to the wide and fast diffusion of the titanium alloys is related to the difficulties about the performance of the plastic deformation processes. Methods such as rolling, extrusion, forging and drawing are typically used in the manufacture of Ti alloy products. Extrusion is a basic metal-forming process used in manufacturing long, straight products with constant cross-section, and forward extrusion process is most commonly used for the extrusion of steel and Ti alloys. In this process glass is applied as a lubricant because it softens at the extrusion temperatures and provides thermal insulation. In steel and Ti alloy extrusion, the billet is usually heated up to 900–1100°C. The glassy lubricant not only provides proper viscosity to lubricate the contact between the tool and the extruded product but it also prevents die chilling due to its insulation characteristics. Moreover, a good adhesion of the fluid glassy lubricant can avoid a fast oxidation of the metal surface or the adsorption of other detrimental gaseous species contained in the atmosphere.

As the final products always require specified microstructure and mechanical properties, the plastic deformation has to be controlled and so it is necessary to optimize the process variables [1]. There are some fundamental aspects that must be taken into account in order to extrude bars without defects. The shape and the dimensions of the profile influence the geometry of the die that must be designed in order to obtain a correct flow of the hot

metal at the entry of the die and through it, avoiding gradient of temperature, stress and deformation rate which can produce not homogeneous zones in the final microstructure or fracture phenomena during the flow through the die itself [2]. An excessive not homogeneous velocity field of the metal flow through the die can separate the metal near the die boundaries from the main central flux and the separated portion of the material is then pulled down on the successive central flow. This phenomenon can produce the separation of surface fragments during the final tooling operation which can compromise the geometrical precision of the formed piece.
For titanium alloys, the deformation temperature is usually near the β-transus, and the temperature evolution during the deformation process will determine the final microstructure of the product such as phase composition and grain size. However, it is very difficult to obtain this information from experiments, since strain and temperature throughout the product section would vary significantly. The numerical methods can be used to reduce the trial and error experimental procedure in order to produce products suitable for final high performance applications [2,3,4,5]. However, there are few studies on the application of numerical method to the extrusion process of Ti alloys [1]. In the present study, the forward extrusion process for the production of special cross sections of Ti-6Al-4V billets was simulated using a finite volume software to study the influence of the main process variables on the product and compared with some experimental measurements [6], with the target to understand better the extrusion behaviour of Ti alloys. The mathematical model takes into account the main and easily measurable parameters of extrusion in order to describe both mechanical and thermal behaviour of the extruded alloy during the plastic deformation through the die.

THEORETICAL APPROACH

An alternative simulation [2,5,7] method has been preferred to the more popular slab analysis and finite element method (FEM) [8, 9] to analyse the plastic deformation during extrusion.
The hot metal is assimilated to a material featured by a specific viscosity [10,11] and on the basis of this assumption its behaviour is studied by the Navier-Stokes' equations. The use of this method permits to calculate the velocity field in the material starting from a little number of experimental data that can be easily taken from the industrial production practice. In the case of hot extrusion the study can be developed on the basis of few and easily measurable data: the 3-D shape of the extruding die, the forward velocity of the extruding press, the initial temperature of the billet to be extruded. The temperature at the entry into the press can be measured by an optical pyrometer. Provided the advancing velocity of the press, the velocity at the exit of die can be approximated on the basis of the flow conservation rule.
The model, provided the viscosity of the extruded material and starting from the measured data, calculates the velocity field without the need of difficult hypothesis about the friction, because a no-slip condition is imposed on the boundaries: the effect of the velocity gradient caused by friction is included in the study through the viscosity.
Because work hardening and flow softening occur during the plastic deformation process, a constitutive equation should be established to relate the deformation rate and the flow stress of the studied alloy. The flow stress behaviour of Ti-6Al-4V has been studied [6]. The flow behaviour could be well represented by a hyperbolic-sine constitutive equation [6,1]:

$$\dot{\varepsilon} = A[\sinh(\alpha\sigma)]^{n}\exp(-Q/RT)) \qquad (1)$$

EXTRUSION SIMULATION

The used Ti-6Al-4V is a two-phase titanium alloy with a β-transus ($\alpha+\beta \longrightarrow \beta$) which has been measured to be in the range of 1003-1012°C [6]. Two practical situations have been simulated to describe the plastic working conditions that are above and below the β-transus temperature (Table 1), in the same condition of experimental tests described in [6] to make a comparison possible. In order to describe the thermal evolution a finite difference method model is implemented to solve the Fourier equation. The material during the process is subjected to three different heat transfer mechanisms: conduction, convection and radiation, but in the die the main process of heat transfer is conduction. The Fourier equation is expressed taking into account velocities and a source term, q, linked to plastic deformation of the material [8]:

$$\rho c = \left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} \right) = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + q \qquad (2)$$

$$q = \varphi\sigma_{ijk}\dot{\varepsilon}_{ijk} \qquad (3)$$

The parameter φ represents the fraction of plastic deformation energy dissipated as heat: in the metal forming processes, only a small proportion of the mechanical energy is retained within the workpiece. This stored energy appears as an increase in crystal defects such as dislocations and grain boundaries and as microstructural change [12]. The most of the mechanical work heats the billet and rises the temperature of the extruded material. It has been reported that 92–93% of the mechanical work is transformed to heat for polycrystalline aluminium, 95–95.5% for single-crystal aluminium, 86.5% for steel, and 90.5–92% for copper [13]. For Ti alloys the fraction of mechanical work transformed in heat has been pointed out to be 94% [6].
On the first section of material it is imposed the

initial temperature (Table 1) measured on the billet surface when it enters into the press. Within the die, on the boundary side the heat transport by conduction can be regarded as inhibited because the process is very fast [1,6] and the material stays in the die for a very short time (4s). Therefore, heat emission was not considered in the computation. The physical data used in the simulations are reported in Table 2.

Results and discussion

The velocity fields obtained by the model based on the Navier-Stokes' equations give information about the flow of the material within the die. The component *w* describes the forward motion of the material along the extrusion direction. On the basis of the variations from the sections at the beginning of the die (section 2) to the one corresponding to the completely extruded bar (section 10) it is possible to note (Fig.1) that *w* values are greater in the central regions of the sections, whereas near the boundary they are reduced because of friction that is present even if lubricant is used.
It is worth noting the not plane profile of the *w* component of the velocity in all the sections of die (Fig.2): this implies that significant velocity gradients exist among different points of extruded material in the die. For the U-shaped section *w* values are higher in the centre of the angle connecting the horizontal parts and the vertical ones, while for the T-shaped section they show the greatest values in the central zone. Moreover, the values of *w* components, after an initial little decrease due to the entrance in the hole of the die of a great quantity of material, grow along the direction of extrusion. The velocity profiles just before the end of the die (Figure 3) point out the difference between the two profiles analysed in this work.
From the thermal model the temperature field is computed (Figure 4) and it is possible to recognize the hottest zones. The maximum temperature rise occurs at the die-billet interface, as predicted in similar study [1], and the temperature rise is over 200°C. In the final section of the U-shaped profile the hottest zones are located in the inner part of the angles, whereas the cool ones are concentrated in two positions: in the external part of the angles and at the extremity of the arms of the "U". In the

Table 1. Conditions of computation employed in the simulation of extrusion of Ti-6Al-4V alloy

Cross section	Heating temperature (°C)	Billet diameter (mm)	W_0 (m/s)
U	980 / 1020	100	0.038
T	980 / 1020	100	0.037

Table 2. Physical data used in the simulation

		Ti 6Al 4V
Density	_	4510 kg m^{-3} [14]
Viscosità	_	$(2.1\cdot10^{18}\cdot\exp(-0.0067\cdot T))$ kg m^{-1} s^{-1}
Characteristic constant of constitutive equation	A	$-13.65\varepsilon^3 + 1655\varepsilon^2+0.85\varepsilon+57.46$ s^{-1} [1]
Characteristic constant of constitutive equation	_	0.053 MPa^{-1} [6]
Constant of constitutive equation	n	6 [6]
Activation energy	Q	380000 J mol^{-1} [6]
Perfect gas constant	R	8.314 J K^{-1} mol^{-1}
Specific heat	c_p	522 J kg^{-1} K^{-1} [14]
Thermal conductivity	k	11 W m^{-1} K^{-1} [14]
Characteristic constant of heat generation	φ	0.94 [6]

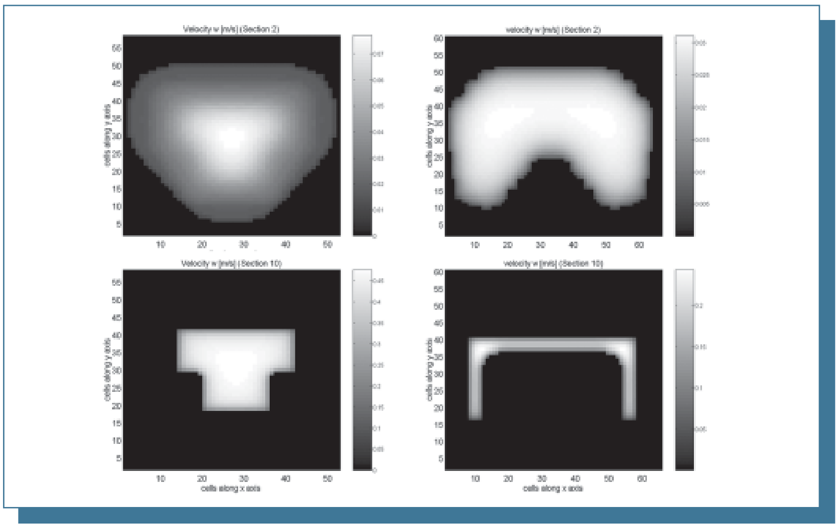

Fig. 1: Field of velocity w in two sections of T-type (left) and in two sections of U-type (right) for 980°C simulations.

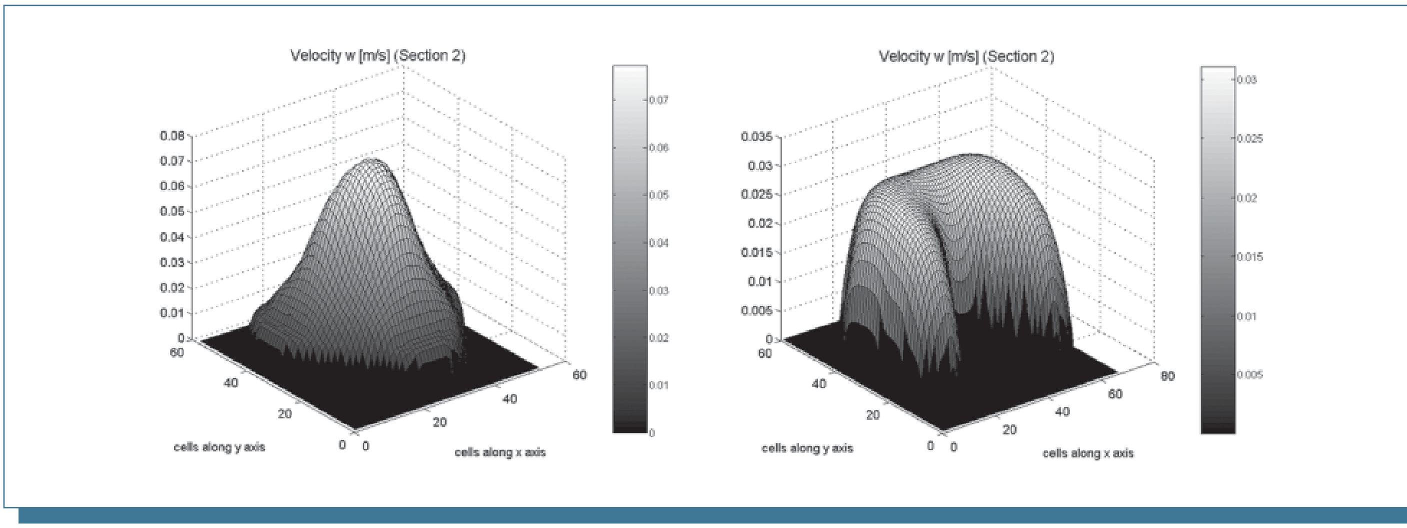

Fig. 2: Profile of the w component of the velocity for T-shaped and U-shaped section at the beginning of the die for 980°C simulation.

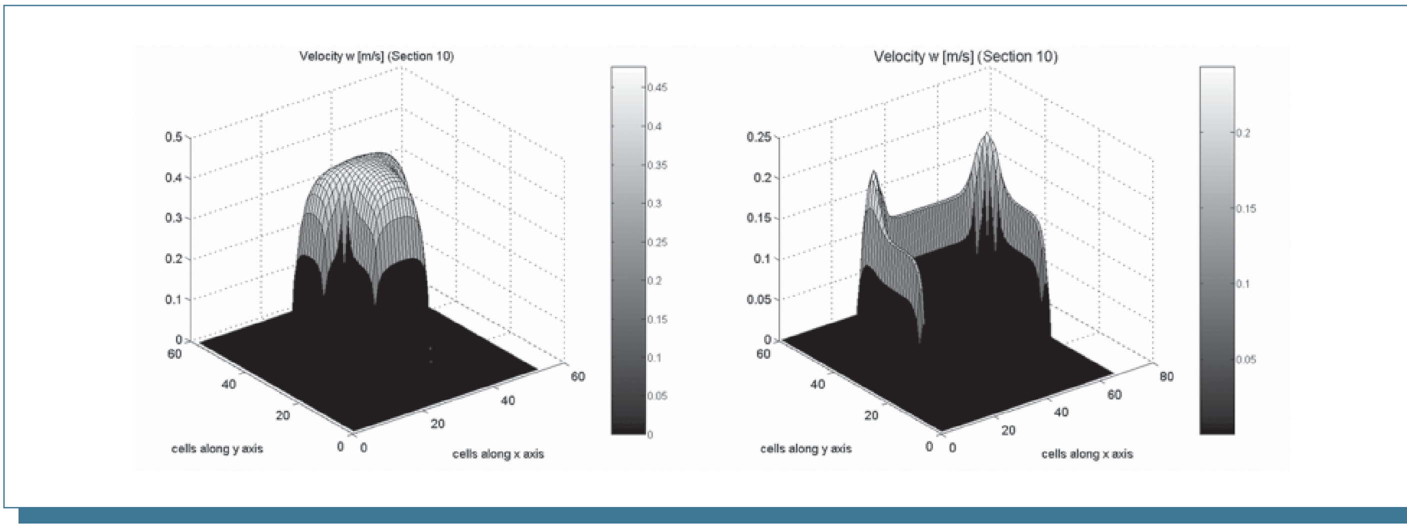

Fig. 3: Profile of the w component of the velocity for T-shaped and U-shaped section just before the end of the die for 980°C simulation.

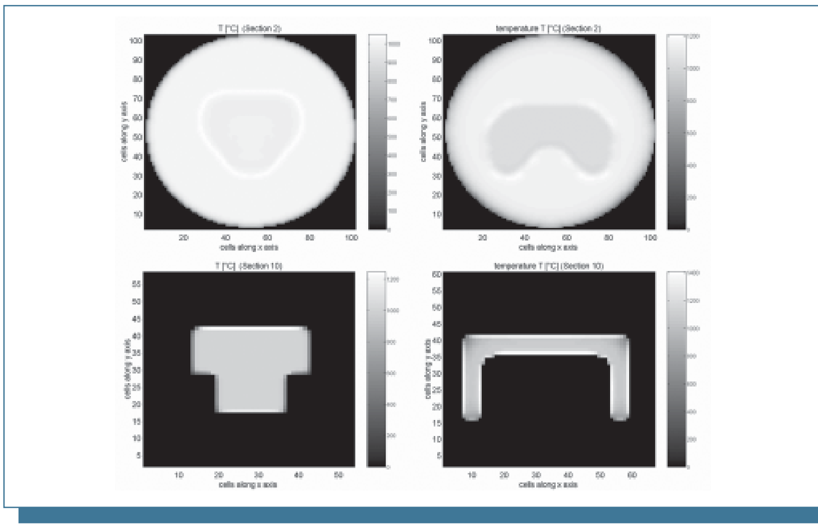
Fig. 4: Field of temperature T in two sections of T-type (left) and in two sections of U-type (right) for 980°C simulations.

case of T-shaped profile it is evident the homogeneity of temperature in the section for both the initial thermal conditions (1020°C and 980°C): the only, very small, cold zones, that can be recognized, are near the edges. It is possible to put in evidence that also the final microstructure, pointed out by metallographic analysis [6] is homogeneous. It is interesting to note that also in other types of material, i.e. micro-alloyed steel and duplex stainless steel[1,5,7], the temperature has been found to be the most important parameter in the hot rolling and extrusion to grant the microstructural homogeneity. On the other hand, the value of the temperatures appears at the exponent of an exponential function ruling the ricrystallization and growth phenomena. The temperature values on the final part of the material are compared to the experimental data (Table 3). The discrepancy between the values is within reasonable limits, considering the difficulty to realize the measurement during the industrial process, in particular for thin cross-section like U-type, and to know the exact boundary condition for simulation.

During the industrial tests [6], the cracks have been concentrated in the U-type cross-section in correspondence of the lowest temperature of extrusion (980°C), below the β-transus: the results of the simulations can explain the causes of the failure. It has been already pointed out [6] that the ratio between the final contour perimeter of the cross section and its area is 0.35m^{-1} for the U type cross section and 0.17m^{-1} for the T-type one. This means that the U-type cross section is composed by thinner sections than the T-type and offers a larger area of interaction between the die and the extruded material. The local strain rate of the U type cross section is greater than the one of the T type, it is proved also by the heat globally developed during the extrusion process as it has been witnessed by the average greater thermal increase observed in experimental measures and confirmed by the simulation data (Table 3): the

Table 3. Heat temperature of the extruded product at the exit of the die

Cross section	Heating temperature (°C)	Experimental average surface temperature (°C)	Average calculated surface temperature (°C)
U	980	1032±6	1067
	1020	999±42	1070
T	980	959±24	973
	1020	878±27	895

simulation at initial temperature of 980°C shows strain rate values higher than the one developed in 1020°C simulation, in particular in boundary zones (Fig.5) the maximum values are reached . The differences $\dot{\varepsilon}_{1020} - \dot{\varepsilon}_{980}$ are very small, but always negative. The high thermal increase concentrated on the surface exalts the difference of the viscosity of the material between the surface itself and the core of the extruded bars. This produces a difference in the flow velocity of the material within the die, as noted before (Fig. 3). It is worth noting that the fracture events have been observed where the numerical solution shows the largest velocity, thermal and strain rate gradients (Fig.6, Fig.7).

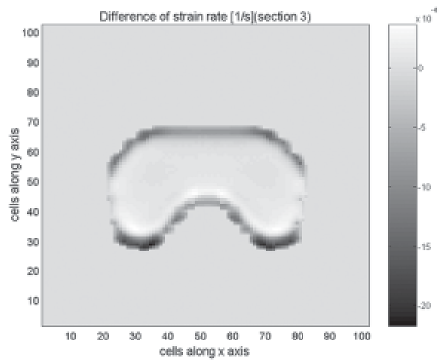

Fig. 5: Examples of differences between calculated strain rate values for U-type cross section extruded at 1020°C and 980°C.

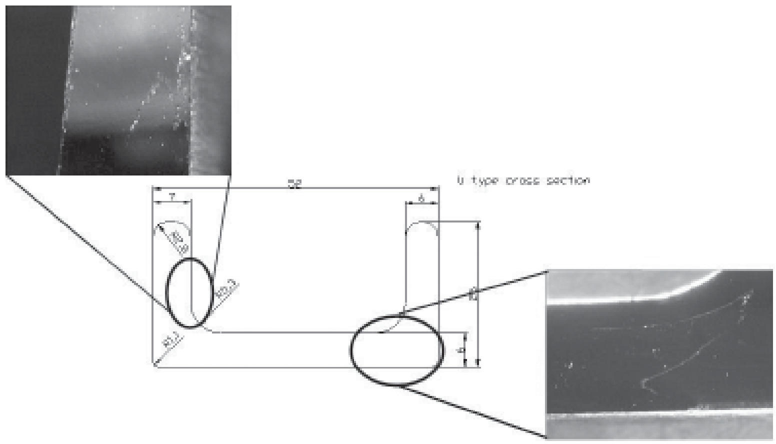

Fig. 6: Some internal defects found in failed samples.

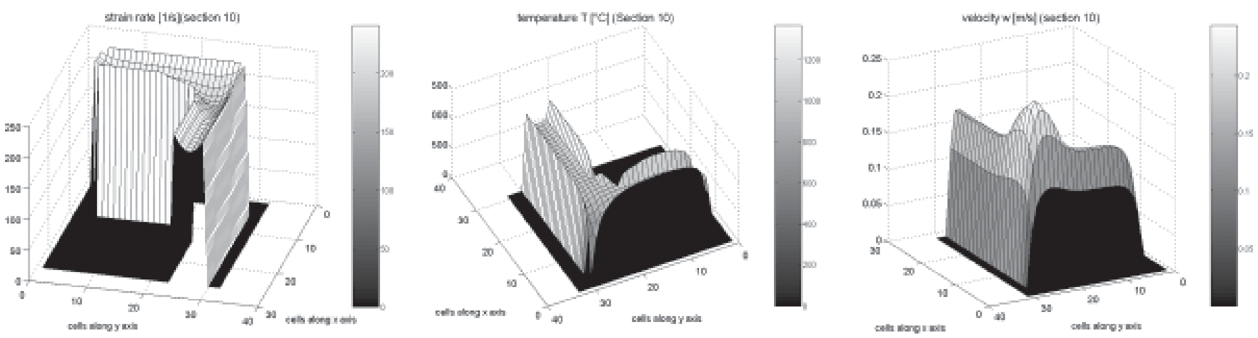

Fig. 7: Calculated a) strain rate b) temperature and c) velocity field in U-type cross section extruded at 980°C.

CONCLUSIONS

(1) The simulation of the extrusion of Ti-6Al-4V alloy have been performed by a new approach based on the Navier-Stokes' equations which can run through the acquisition of few and easily measurable data. The power of such an approach is due to the clear description and determination of the velocity field which is the critical factor to avoid the fracture of the extruded material due to excessive difference in the displacements of the material.

(2) The simulation has pointed out a general homogeneity in the thermal distribution on the final cross section at the exit of the die. This explains the microstructural homogeneity revealed by the metallographic observation.

(3) The homogeneity of the temperature distribution is strongly related to the deformation and deformation rate imposed during the extrusion. From the performed simulations the temperature has been revealed to be the strongest factor of influence determining the final microstructure characteristics and the related mechanical ones.

(4) High ratio between surface and area of the cross section and temperature below β-transus are unfavourable to a successful extrusion because they promote a not homogeneous temperature distribution and a sharper gradient in the velocity and strain rate fields.

LIST OF SYMBOLS

- A strain dependent parameter
- α characteristic constant of the constitutive equation ($MPa^{-1}\ s^{-1/n}$)
- p characteristic constant of heat generation
- c_p specific heat ($J\ kg^{-1}\ K^{-1}$)
- $\dot{\varepsilon}$ effective strain rate (s^{-1})
- ε current strain
- $\dot{\varepsilon}_{ijk}$ strain rate in the generic cell (i,j,k) (s^{-1})
- k thermal conductivity ($W\ m^{-1}\ K^{-1}$)
- μ viscosity (Pa s)
- n characteristic constant of the constitutive equation
- q heat generated by the plastic deformation ($J\ m^{-3}$)
- Q activation energy of the process ($J\ mol^{-1}$)
- R perfect gas constant (8.31 $J\ K^{-1} mol^{-1}$)
- ρ density ($kg\ m^{-3}$)
- σ stress (Pa)
- σ_{ijk} stress in the generic cell (i,j,k) (Pa)
- T temperature (K)
- u velocity in x-direction ($m\ s^{-1}$)
- v velocity in y-direction ($m\ s^{-1}$)
- v_i generic velocity component ($m\ s^{-1}$)
- w velocity in z-direction ($m\ s^{-1}$)
- w_0 velocity in z-direction at the beginning of the die ($m\ s^{-1}$)
- w_f velocity in z-direction at the end of the die ($m\ s^{-1}$)
- x horizontal direction of the perpendicular to z-axis section
- x_i generic space direction
- y vertical direction of the perpendicular to z-axis section
- z direction of the development of extrusion

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