Metallurgy and Foundry Engineering – Vol. 44, 2018, No. 3, pp. 133–144
http://dx.doi.org/10.7494/mafe.2018.44.3.133

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Analysis of influence of process parameters on temperature distribution in profiles extruded from 6xxx-series aluminum alloys

Analiza wpływu parametrów procesu odkształcenia na rozkład temperatury w kształtownikach wyciskanych ze stopów aluminium serii 6xxx

Abstract
Changing market preferences regarding expectations in terms of the functionality, properties, and appearance of a finished product place excessive demands on manufacturers. The 6xxx-series alloys are the most commonly used in extrusion, and they have broad applications (e.g., the construction, electronics, automotive, and shipbuilding industries). The development of deformation technology at the design stage reaps unquestionable benefits when planning the production process. Under real conditions, the extrusion of hollow profiles requires the use of pocket dies, whose proper design is a complex process. This paper presents the results of preliminary numerical investigations of the extrusion process of structural panels from the 6005A aluminum alloy intended for the construction of transport car bodies. The influence of selected parameters of the extrusion process on the temperature distribution was analyzed in the material. The calculations were made using FEM for a three-dimensional deformation state, taking into account the thermal phenomena occurring during the applied deformation scheme in the extrusion process carried out in a flat die.

Keywords: extrusion, aluminum panels, FEM modeling

Streszczenie
Zmieniające się preferencje rynku dotyczące oczekiwań w zakresie funkcjonalności, własności i wyglądu wyrobu gotowego stawiają przed wytwórcami wysokie wymagania. Stopy serii 6xxx należą do grupy stopów aluminium zawierających magnez i krzem. Mają bardzo szerokie zastosowanie w budownictwie, elektronice oraz przemyśle: samochodowym górniczym, chemicznym, spożywczym i stoczniowym. Opracowanie technologii odkształcania na etapie projektowania daje niekwestionowane korzyści podczas planowania procesu produkcyjnego. Proces wyciskania profili wymaga w rzeczywistych warunkach zastosowania matryc komorowych, których właściwe zaprojektowanie jest procesem złożonym. Zastosowanie nowoczesnych narzędzi

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informatycznych pozwala na wieloaspektową analizę zmian zachodzących podczas procesu wytwarzania wyrobu gotowego. W artykule przedstawiono wyniki wstępnych badań numerycznych procesu wyciskania współbieżnego paneli konstrukcyjnych z wybranego stopu aluminium serii 6xxx, które mogą znaleźć zastosowanie jako elementy konstrukcyjne nadwozi samochodów transportowych. Analizowano wpływ wybranych parametrów procesu wyciskania na rozkład temperatury w odkształcanym wyrobie. Obliczenia wykonano przy użyciu MES dla trójwymiarowego stanu odkształcenia, uwzględniając zjawiska termiczne występujące podczas zastosowanego schematu odkształcenia w procesie wyciskania prowadzonym w matrycy płaskiej.

Słowa kluczowe: wyciskanie, panele aluminiowe, modelowanie MES

1. Introduction

The extrusion process of aluminum alloy profiles is widely used in industry due to its many advantages (e.g., its good weldability and resistance to corrosion and cracking). The transport industry needs profiles with medium mechanical strengths but also complex shapes (open and closed profiles with variable thicknesses in the walls) to increase loading capacity and restrain construction and exploitation costs. The materials that are adequate for such a demand are the 6xxx-series aluminum alloys (especially 6005A). These alloys are characterized by relatively high strength (belonging to the group of medium-strength aluminum alloys) and good corrosion resistance; they are also suitable for decorative anodization. According to EN 755-2, their tensile strength ranges from 180 to 270 MPa, and they are applied to the manufacture of structural sections mainly for the transport industry and structural engineering.

The continuous search for ever-higher extrusion speeds and need for even better properties forced to the unceasing development in extruded materials and extrusion processes. In the automotive industry, there is a demand for closed shapes with high height-to-width ratios (the so-called panels [1]) and that are classified as N-section profiles [2].

Considering the high quality requested (such as in the flatness, dimensions, and surface quality), the production of complex profiles must be treated like a difficult process and needs to be optimized to achieve satisfactory results (both technically and economically). The number of factors affecting the technological process makes it rather complex to control. Among the factors significantly influencing the course of the process are, inter alia, billet and tool temperature, friction, punch speed, and die shape [3, 4].

In production practice, designing the extrusion process and dies with complex shapes are mainly based on the knowledge and experience of designers. Any defects showing on the profiles can have a different characters and are usually fixed by multiple adaptations of selected process parameters. This is not satisfactory in the case when the quick introduction of new shapes or materials for production is needed. An appropriate numerical model construction seems to be necessary for the flexible design of the

optimal technology of profile extrusion, especially panels that are the complex and have specific elements with different functions (e.g., connectors).

The purpose of material deformation in a plastic-working method is to give it its required shape by applying appropriate plastic deformations that will not cause a loss to its cohesion. This is particularly important in the case of the extrusion process, where limit strains are the highest among the other plastic-forming processes, as the material deformation occurs in the presence of high compressive stresses. A precise theoretical analysis of the phenomena occurring in the deformation zone is very difficult because of the complexity of the plasticity theory equations. These phenomena result from the lack of more-precise constitutive equations that take into account the influence of many factors such as temperature, strain rate, and strain history as well as variability of the deformed area assuming the non-linear nature of the stress-strain relationship.

In the extrusion process, a particularly important element is the die; this is because it has an influence on the shape of the final product, its quality, and the effectiveness of the process. Depending on the type of extruded profile, properly designed dies are used for open (flat dies) and closed shapes (pocket dies/porthole dies) [4, 5].

In the case of large-sized aluminum panels, it is very important to introduce new structural solutions for the dies that will guarantee the most uniform as possible flow of metal into the die gap and high geometrical stability of the profile. As a result, the efficiency of the extrusion process will be improved.

The authors divided the research undertaken into two basic stages: extrusion into a flat die and extrusion into a pocket die. In this article, extrusion into a flat die was investigated because of the large concentration of deformation during the material flow through the calibrating zone (which appeared in our initial investigations). The results of our simulations will allow us to make an appropriate initial design for the shaping part of a pocket die in next stage of our research to assure the most uniform material flow.

2. Material and methods

The numerical investigations of the extrusion process of aluminum panels were made for billets consisting of the 6005A aluminum alloy and an extrusion die and other tooling made of H13 tool steel.

The chemical composition of the alloy is shown in Table 1.

Table 1. Chemical composition of typical 6005A aluminum alloy according to EN 573-3

Alloy type	**Chemical composition [wt.%]**									
	Si	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**	**others**	**Al**
6005A	0.50–0.90	0.35	0.30	0.50	0.40–0.70	0.30	0.20	0.10	0.15	rest

This is an alloy from the group of 6xxx-series medium-strength alloys. Due to the appropriate chemical composition, the material has good formability at elevated temperatures, especially necessary in the production of panels with various wall thicknesses and complex geometries that gives them a high accuracy of dimensions.

For a numerical analysis of the extrusion process by the finite-element method, the Forge2011® software package was used. The program allows for the modeling of extrusion processes in a three-dimensional state of strain. In this part of the research, the extrusion process of the profile was made in a flat die. The geometric models were built using CAD software and imported to the Forge2011® software. The billet and die were assumed to be visco-plastic and rigid, respectively. The visco-plastic model of a deformed body was defined by the Norton–Hoff law [6].

The material parameters of the billet are as follows: elasticity modulus = 69500 MPa; Poisson's ratio = 0.33; specific heat = 898 J/kg·K; mass density = 2700 kg/cm^3; and conductivity = 188 W/m·K. The stress-strain curves that describes the material properties in the hot forming conditions were described by Hansel–Spittel's equation [7] (Eq. (1)).

$$\sigma_p = Ae^{m_1 T} T^{m_9} \varepsilon^{m_2} e^{\frac{m_4}{\varepsilon}} \left(1+\varepsilon\right)^{m_5 T} e^{m_7 \varepsilon} \dot{\varepsilon}^{m_3} \dot{\varepsilon}^{m_8 T}, \tag{1}$$

where:

σ_p – flow stress [MPa],
T – temperature [°C],
ε – true strain,
$\dot{\varepsilon}$ – strain rate [s^{-1}],
A – determined coefficients; A = 34992297335728.2,
m_1 = 0.00991615586721407,
m_2 = 0.425470976910651,
m_3 = –0.377947705842881,
m_4 = –0.0000364328905458017,
m_5 = –0.00134305274310804,
m_7 = 0.00333222509245211,
m_8 = 0.0011522165270937,
m_9 = –5.07463020362585.

For the initial analysis of the extrusion process, a fragment of an exemplary panel profile with the most varying wall thicknesses was selected. The die was designed on the basis of the calculated center of gravity for the investigated cross-section of the profile and assumed dimension of the billet (see Figure 1).

The extrusion process was realized within a temperature range of 450–470°C. The die temperature was assumed to be 470°C, and that of the ram and container was 440°C. The ram speed equaled v = 1, 3, and 6 mm/s, respectively. The assumed dimensions of the billet were a diameter of φ = 60 mm and length of h = 100 mm. Extrusion ratio λ = 6.64.

a) b)

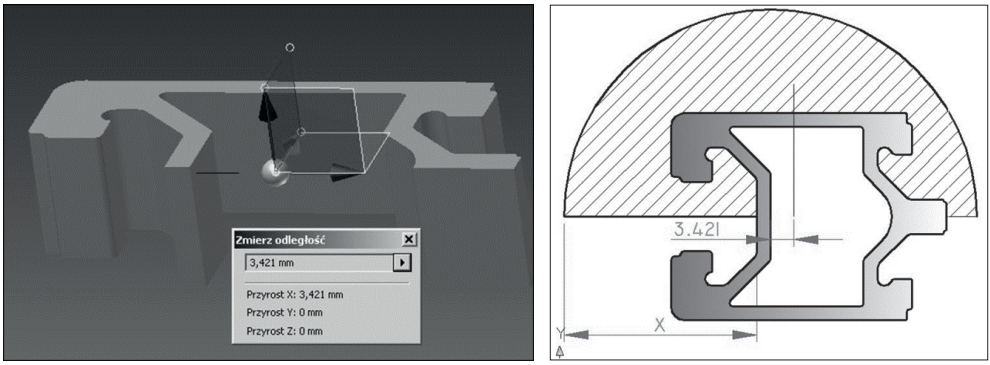


Fig. 1. Calculated center of gravity for investigated cross-section of (a) profile and (b) assumed billet

3. Results and discussion

In the extrusion process realized for the assumed parameters at the first stage of the material deformation, the profile bending in a symmetry plane of the die was observed (Fig. 2).

Fig. 2. Profile bending in symmetry plane of die for assumed process parameters

This was the result of the different flow rates of the part of deformed material – higher values for the wider thicknesses of the profile walls. The difference between the flow rates of these extreme parts of the profiles caused a progressive bending of the extruded profile. Thus, a reduction of these differences in the analyzed process was made by a displacement of the shape corresponding to the billet axis to a value of $x = 18$ mm (Fig. 3). In order to determine the effect of the impression position in the die on the curvature of the extruded profile, a series of simulations of the extrusion process were carried out for the value of the x parameter from the range limited by the die geometry – from $x = 32$ to $x = 18$ mm. It was observed that the curvature increased with increases

in the *x* parameter. The best effect (straight extrudate) was obtained for the value of $x = 18$ mm (Fig. 3). Additionally for this variant, simulations reducing the maximum length of the calibrating part were made in order to reduce the non-uniformity of the flow of the leading part of the profile (Fig. 4).

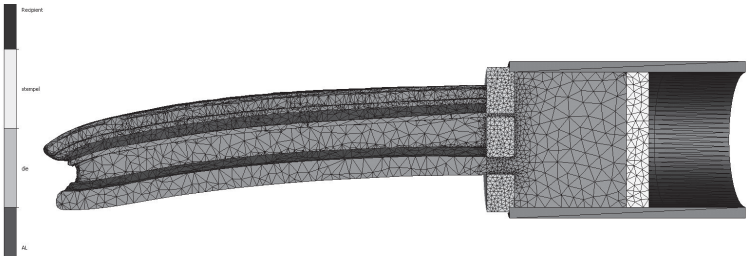


Fig. 3. Straight extruded profile after displacement of center of gravity by x = 18 mm

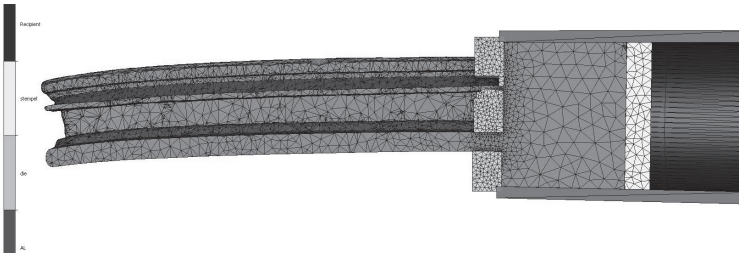


Fig. 4. Straight extruded profile after displacement of center of gravity by x = 18 mm and with smaller length of calibrating part

The coordination grid was applied to the longitudinal section of the billet to compare the nature of the material flow at the entrance of the die. The cross-section was chosen in such a way as to compare the amount of deformation when entering the material into the channel with the thinnest wall (2 mm) and that with the widest wall (8 mm). The way the material flowed and the corresponding values are shown in Figure 5.

It can be observed that the front of the profile is non-uniform because of the various material flow appearing due to the different wall thicknesses. To minimize this effect, the die was modified by reducing the length of the calibrating parts from 12 to 2 mm. Three regions (marked: 1, 2 and 3 on Figure 6) with thin walls that were responsible for the lower velocity of the material flow were chosen to reduce the length of the calibrating parts (as can be seen in Figure 6).

The results of the material flow after the undertaken changes are presented in Figure 7. As it can be seen, the unevenness of the front in the extruded profile decreased.

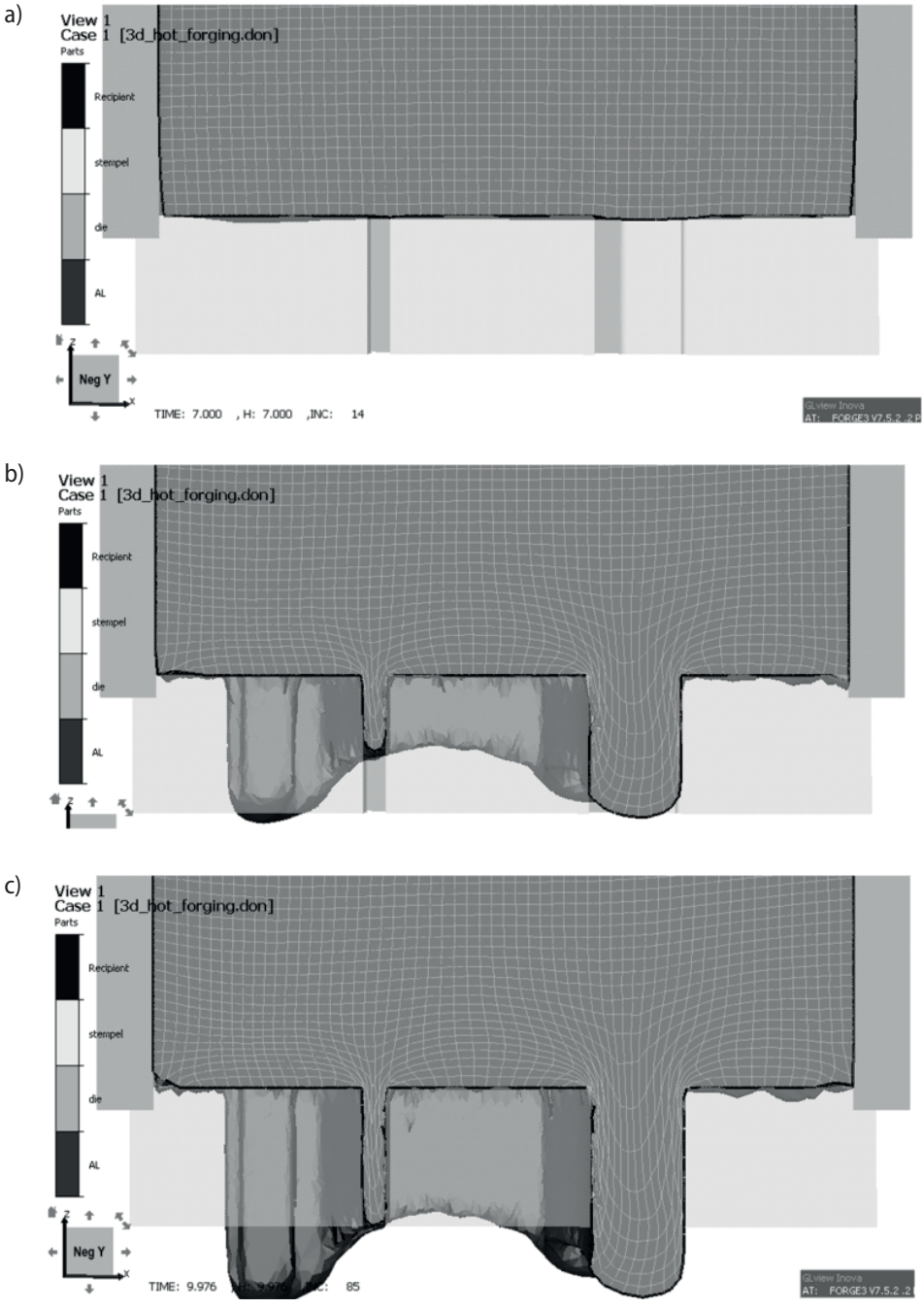


Fig. 5. Material flow in die calibration zone after moving ram to distances of a) 7 mm, b) 9 mm, and c) 11 mm

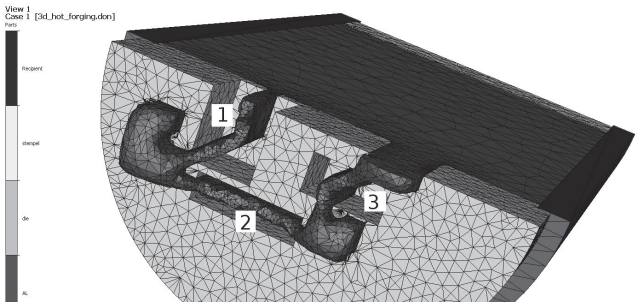


Fig. 6. Regions (1–3) with smaller length of calibrating parts of die

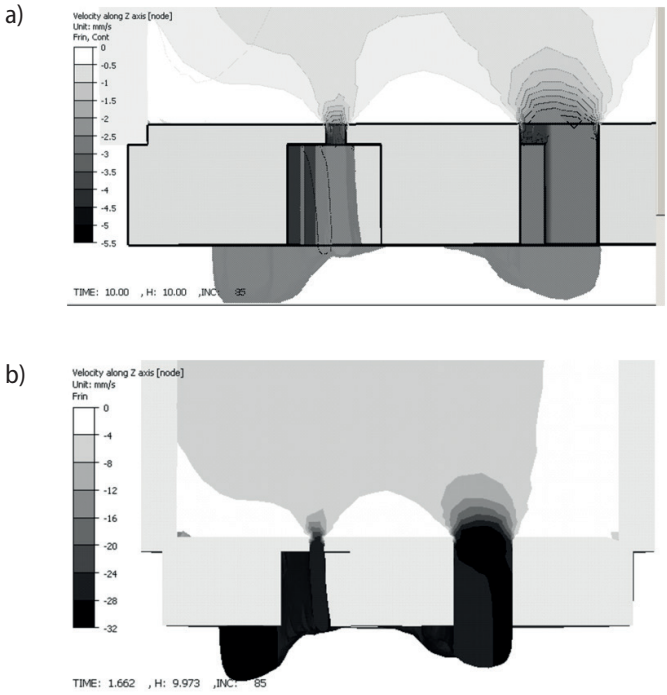


Fig. 7. Flow rate and shape of front in extruded profile for modified length of calibrating parts of die for ram speed of 1 mm/s (a) and 6 mm/s (b)

The velocity of the extruded material depends on the shape of the profile, extrusion ratio, and ram speed. For all of the investigated variants of the extrusion process, the highest values of the flow rate appear at the first stage of the deformation when the material flows into the die gap; at the next stage, it increases and has a non-uniform distribution at the profile cross-section that causes the formation of frontal unevenness in

the profile (Fig. 8). This can be regarded as a quasi-constant stage, both in terms of flow rate and extrusion force.

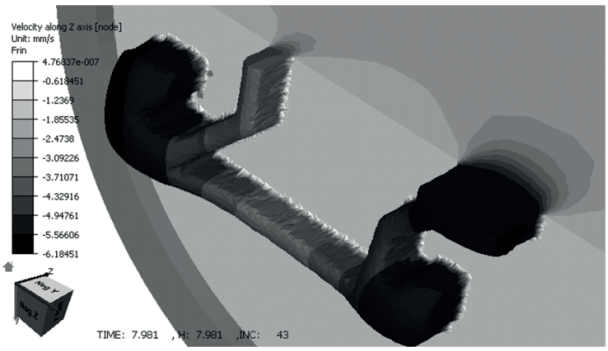
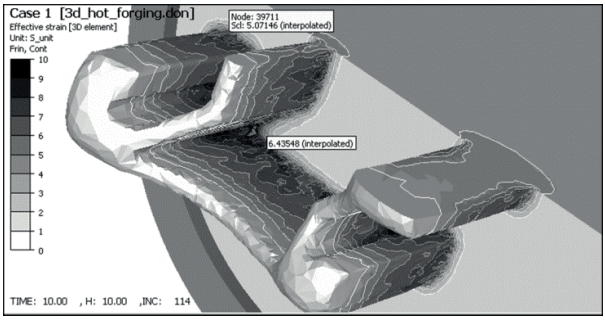


Fig. 8. Distribution of velocity along Z axis in cross-section of extruded profile for ram speed of 1 mm/s

The non-uniform distribution of the flow rate also causes non-uniform deformations (as can be seen in Figure 9).

a)



b)

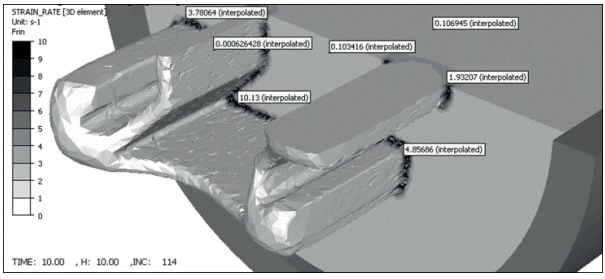


Fig. 9. Distribution of effective strain (a) and strain rate (b) for extrusion at temperature of 450°C and ram speed of 1 mm/s

The highest values of deformation appear in the zones where the material flows into the die, and a rapid elongation of the surface layers at the contact with the walls follows; this results from the rapid reduction of the cross-section and friction against the narrow walls of the profile. For extrusion at ram speed of 1 mm/s, the maximum strain rate is about 10 s^{-1}, while for a ram speed of 6 mm/s, the maximum values of the strain rate are about 32 s^{-1}.

The temperature of the profile during the extrusion process and the strain rate have a great importance on the formation of the product. As shown in Figure 10, the temperature of the profile increased with a change of the extrusion speed from 1 mm/s to 6 mm/s (more than 20%).

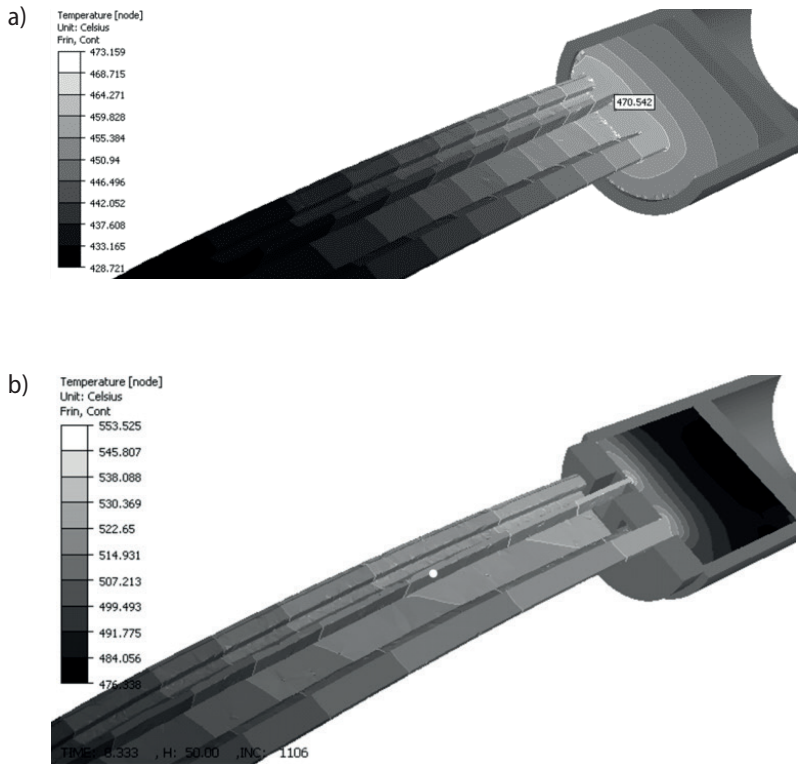


Fig. 10. Temperature distributions for extrusion temperature of 470°C and ram speed of 1 mm/s (a) as well as extrusion temperature of 470°C and ram speed of 6 mm/s (b)

Both the material and the ram speed influence the required pushing force [5]. An example dependency of the extrusion force in the aspect of the initial temperature and ram speed applied in the process is shown in Figure 11.

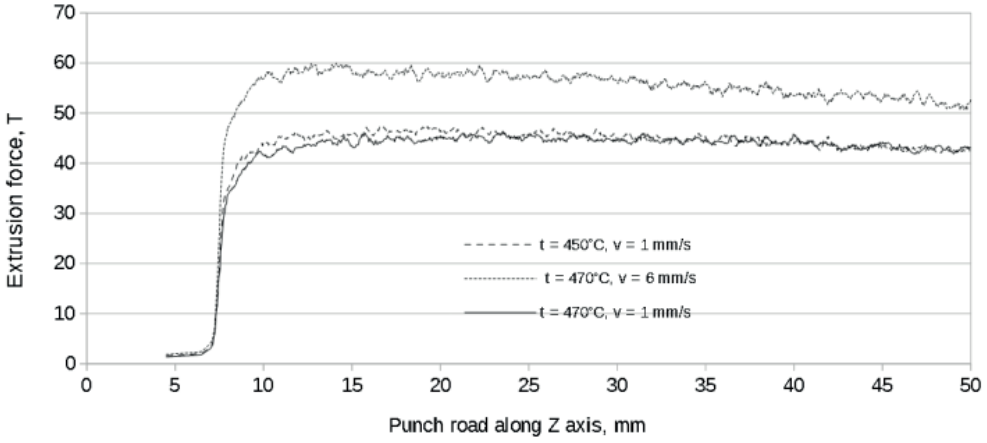


Fig. 11. Dependence of the extrusion force and punch road

An increase of 450° to 470°C in the temperature of the extrusion process and a ram speed of 1 mm/s caused a slight decrease in the pushing force value. Thus, an increase of 1 mm/s to 6 mm/s in the extrusion speed for the same temperature caused an increase of the force at more than 30% (Fig. 11).

4. Summary

The use of flat dies allows for the analysis of selected parameters on a small area of the calibration zone in which the greatest deformations occur that affect the temperature change of the extruded profile. The increase of the extrusion speed causes increases in the temperature inside the deformed material. The higher the temperature of the deformed material, the smaller the compression resistance and the lower the wear on the tools and machines. In order to obtain a greater dimensional accuracy of the product, optimal temperatures from the plastic area for a given alloy should be used. The extrusion speed has an important influence on the required pushing force. Additionally, heat treatment should be applied in order to obtain sufficiently high strength properties; this consists of the proper cooling of the profile at the exit of the die.

The real technological process of aluminum panel extrusion is realized in pocket dies. The design of such a die is complex and needs many corrections to obtain the most uniform flow of extruded metal and highest geometrical stability of the profile.

The performed investigations will help to determine the main courses in the design of particular parts of pocket dies.

Acknowledgement

The project is co-financed by the European Union from the European Regional Development Fund under the Intelligent Development Operational Program 2014–2020.

The project is implemented as part of the National Center for Research and Development competition: Action 4.1 "Research and development works," Sub-measure 4.1.4 "Application projects," No. POIR.04.01.04-00-0016/17.

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