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EXPERIMENTAL ANALYSIS OF MECHANICAL CHARACTERISTICS OF KOBO EXTRUSION METHOD

The paper presents selected results of KOBO extrusion process of circular profile ϕ10 mm from aluminum alloy 2099. The main aim of the performed research was to determine the influence of the oscillation frequency of a die on the magnitude of extrusion force. During the process such parameters, as extrusion force, rate of stem and frequency of die oscillation were recorded; oscillating angle of a die was constant and equal ±8°. The die oscillation frequency was changeable in performed tests in the range of 2 ÷ 7 Hz. The obtained results allowed to determine the relation between the maximum extrusion force and the die oscillation frequency during extrusion of aluminum 2099 alloy.

The paper focuses on the experimental analysis of mechanical characteristics of the KOBO process. Basing on the recorded force versus stem position, three stages of KOBO extrusion process were determined, i.e. initialization, stabilization and uniform extrusion. Points separating these stages are two inflection points of recorded diagram. The analysis of each stage was made basing on the results of force diagrams and literature data.

Keywords: direct extrusion, KOBO extrusion, aluminum alloy 2099

1. Introduction

KOBO method is an unconventional method of extrusion with die rotation movement (as shown in Fig. 1). This method uses the phenomenon of changing a path of plastic deformation by introducing a die into cyclic oscillations by a given angle and with a given frequency [1,2]. This oscillating rotary motion of a die is the only difference comparing to traditional direct extrusion. KOBO extrusion method results in a significant reduction of extrusion force and obtained product is characterized by much greater fine-grained structure and ductility than in case of the conventional process [3,4]. During KOBO extrusion, a large number of point defects occur, which remain in the extruded material as nano-sized clusters. Theirs influence on the mechanical properties of extruded materials can be similar to the influence of the Guinier-Preston zones in metal alloys, what causes high mechanical properties and thermal stability of extruded profiles [5]. These products in further plastic forming operations may exhibit superplastic properties. In KOBO process, metal permanently keeping the solid state simultaneously acquires the typical features of a liquid [5-7]. In the deformation zone definitely dominates radial flow and the geometry of this stable zone is in the form of a cylinder with a cross-sectional base of a billet and height only ~2 mm. The viscous nature of the material flow in KOBO extrusion process allows for plastic working of low-tough alloys without preheating and forming complex geometry products by high speed processing. This process allows achieving a very high extrusion ratio. The course of the extrusion force in KOBO extrusion process is similar to a conventional direct extrusion process, however, the value of this force is at least twice lower [5].

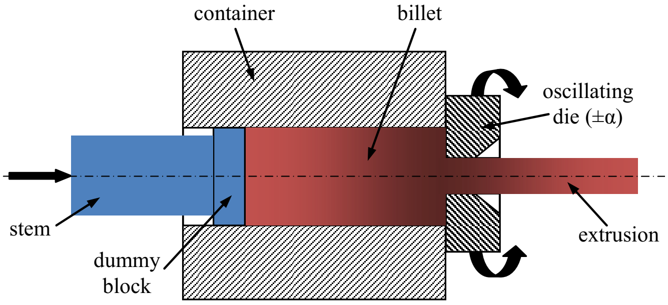

Fig. 1. Schematic of die rotation oscillating extrusion

There is almost no analysis of the KBO process in the literature based on its mechanical characteristics. The exception may be the work [8], but it is based mainly on numerical simulations and concerns a similar process of extrusion with

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rotating container. In the work [8] finite element simulation software DEFORMTM-3D was used to simulate three extrusion processes: traditional (direct extrusion), with rotating die and with rotating container. It was shown that, compared with the direct extrusion, the plastic area is larger in the container rotation extrusion and the 'dead zone' at the corner of the container is eliminated. The comparison of three extrusion force characteristics: the coextrusion, with the rotating die and with the rotating container showed that they have similar runs, but the lowest top extrusion force was obtained for extrusion with the rotating container (drop by 42.1%), larger for extrusion with the rotating die (drop by 16.2%) and the largest for traditional direct extrusion. It was also observed, that die rotation has the biggest influence on the change in the extrusion process temperature.

2. Experimental method

Experimental studies included extrusion on 2500 kN capacity press with KOBO oscillation die system. The press uses a hydraulic system and a stationary press support with a nominal power of 5000 kN capacity press. The KOBO press is equipped with a tool head with adjustable angle of the die oscillating rotary motion (±): 6°, 8° and 10°. The oscillation frequency of the die is adjustable in the range of 2 ÷ 8 Hz. The control panel of the press is used to adjust and record extrusion speed, initial force, oscillation frequency and other parameters. The KOBO press can also work as a classic coextrusion press with the maximum use of its load parameters.

The extrusion tests were carried out with a constant die oscillation angle of ±8° and a variable oscillation frequency of 3, 4, 5, 6, and 7 Hz. The stem velocity was constant in all tests and was equal 0.2 mm/s. The processes were carried out until reaching assumed value of 10 mm extrusion butt.

The material used in the research was aluminum alloy in 2099 grade (Table 1), i.e. the alloy used in aviation (lithium present in the alloy leads to a decrease in the material density). Extruded rods of this alloy with the diameter of ϕ59,5 mm (the diameter of the hole in the container was ϕ60 mm) were cut by machining into billets with length of about 62 mm. These cylindrical billets were the input preforms in the extrusion process. A round bars with diameter dimension ϕ10 mm were extruded; extrusion ratio was $\lambda = 36$. The extrusion process was carried out without pre-heating of billets.

TABLE 1

Chemical composition limits [wt%] of aluminum alloy 2099

Cu	Li	Zn	Mn	Mg	Ti	Zr	Fe	Si	Be	Al
2.85	1.85	0.73	0.35	0.39	0.044	0.070	0.043	0.029	0.00001	Bal.

The die shown in Fig. 2 was used in the studies. It was made of Inconel 718 alloy, which is a material well-suited to work in extreme environments subjected to pressure and heat. Superalloy Inconel 718 maintains its mechanical properties over a wide temperature range, which is a very beneficial phenomenon in high temperature applications, among others such as they occur during extrusion. The use of this type of alloy for making a die was suggested by the creators of KOBO method (patent [2]) and a press manufacturer. On the working face of the die, radial grooves were made to transfer the torque from the die to the billet. The "teeth" on the clutch surface served to take up the torque from a drive sleeve. This shape of the clutch surface was the original concept one of the authors of this work. The outer diameter of the die was ϕ48 mm and the die work hole diameter was ϕ10 mm.

During extrusion, the sequence of operations was as follow: 1 – placement of a die in a holder, 2 – placement of a billet and a dummy block in the press container, 3 – closing the working system (approaching working elements together), 3 – initial billet upsetting to the assumed force value 500kN, 4 – activating a die oscillation, 5 – a stem forward movement (starting extrusion), 6 – activating a water cooling, 7 – extrusion until reaching an established thickness of extrusion butt, 8 – stopping the forward movement of a stem and the die oscillation (ending of extrusion). All elements of the working space of the press, together with the tool and the billet, at the beginning of extrusion process were at room temperature, i.e. approx. 20°C.

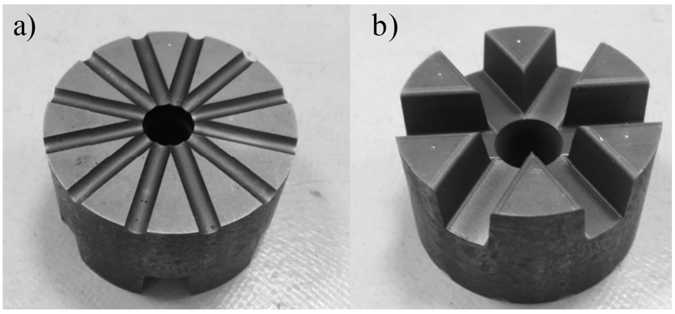

Fig. 2. The die used in the tests: a) working surface, b) "clutch" surface

3. Results and discussion

The only variable parameter of extrusion processes was the die oscillation frequency (five different oscillation frequencies). The recorded data allowed for drawing diagrams of the force and the frequency of die oscillation versus the stem position as it is shown in Fig. 3. The variation character of the extrusion force is the same for all oscillation frequencies of the die. At the very beginning of the process, the force reaches maximum value, which gradually decreases during extrusion. The value of this maximal force depends on the die oscillation frequency (Fig. 4). When the oscillation frequency increases (from 3 Hz to 7 Hz), the top extrusion force decreases (from 2298 kN to 1109 kN); in the both cases it is more than the double change in value. This reduction of the maximum extrusion force is the main advantage of the KOBO method. Extrapolation line of the graph (not marked in Fig. 4) allows to determine the maximum extrusion force at zero oscillation frequency on the level of ~3200 kN. This is a very likely value of the extrusion force of a traditional foreword extrusion process of aluminum alloy 2099 with extrusion ratio $\lambda = 36$ (e.g. estimated by Siebel equation).

On the force diagrams shown in Fig. 3, apart the point of maximum force, one can notice two points of inflexion. These points divide the curve charts into three parts that have been named: initialization, stabilization and uniform extrusion, as it is shown in Fig. 5. At the beginning of the stem feed movement the force grows rapidly to its maximum value. At this stage of the extrusion process, the billet material remains in solid state and it is strongly hydrostatically compressed. The edges of the radial grooves on the oscillating die face act as a cutting tool edges for the billet face surface. This cutting action involves heat generation and chips formation. Chips are accumulated in the die grooves and then are removed with the extruded material and they are visible at the beginning of the extruded rod. Additional heat source are friction forces acted on the contact billet – die interface. All these phenomena cause grow of the billet temperature. This state is short-lived, because the top value of extrusion force initiates the process of plastic flow through the die hole a material to be extruded. This plastic deformation is associated with arise of additional heat and this process, in the beginning stage, is an adiabatic phenomenon. This is the reason for a rapid grow of material temperature and reduction of its strain resistance and decrease of the extrusion force what is visible in graphs shown in Fig. 3 and 5. From the very beginning of this stage, the nature of deformed material changes from elastoplastic to viscous, which is the result of drastic increase in crystal lattice defects, mainly point defects and changes in mechanical state of material as described in the literature [5-7]. It can be assumed that at this stage of the extrusion process the deformation zone is reduced (shortened) to a thin, a several millimeters layer (2 mm as it was proved in [5]).

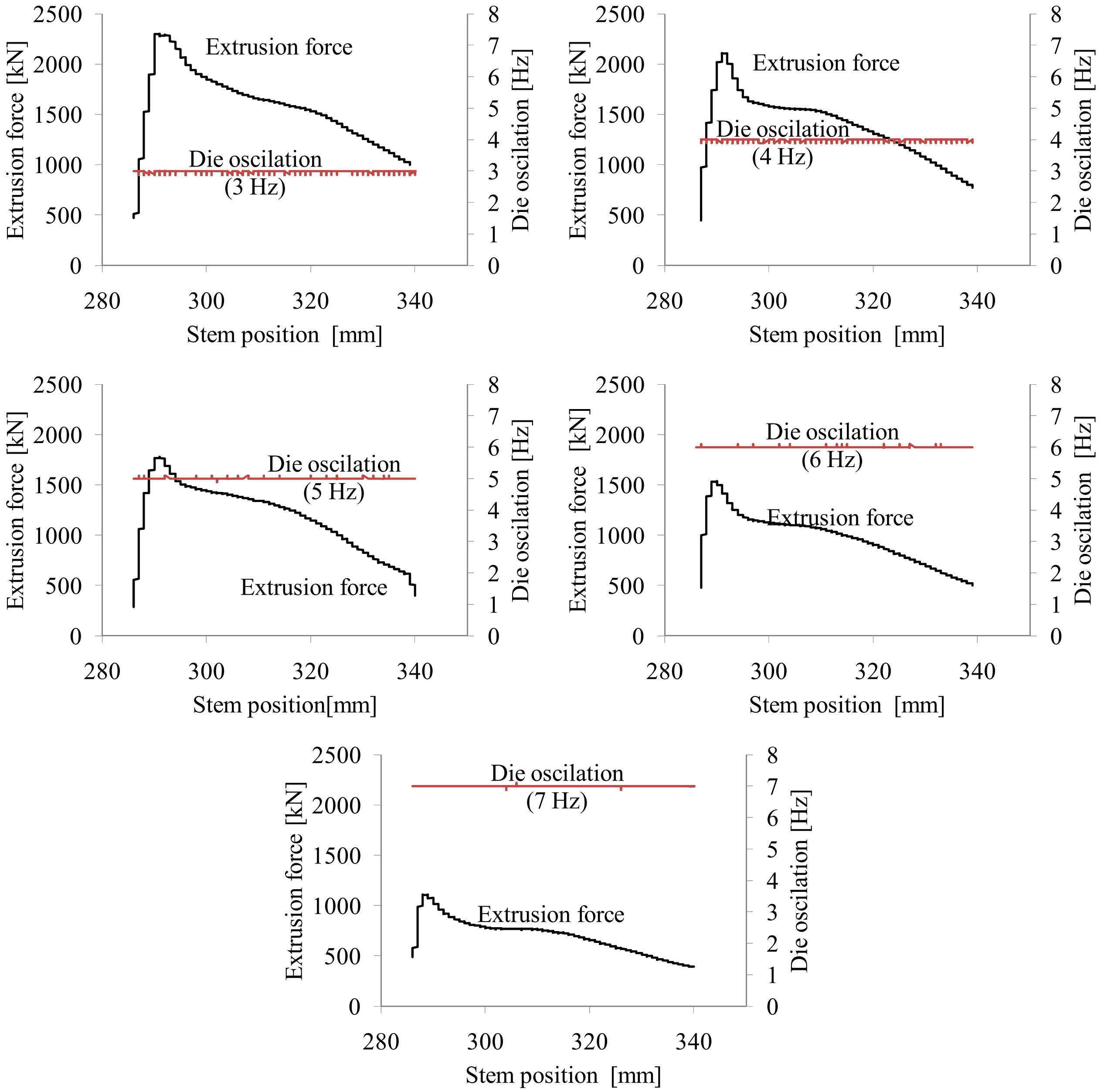

Fig. 3. The diagrams of extrusion force versus stem position recorded in KOBO extrusion tests for different die oscillation frequency

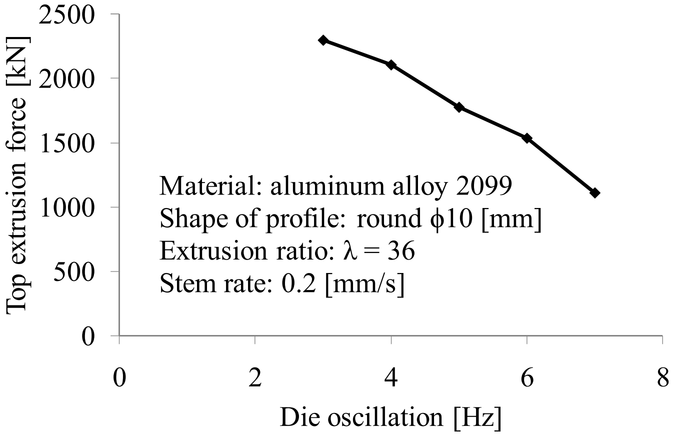

Fig. 4. The top extrusion force versus the die oscillation

The beginning of water cooling of the die and the die holder slows the force drop process as well as heat propagation to "cold" volume of billet and container (which initial temperature was a room temperature) and the point of inflection (1) appears in the graph. From this point all ways of cooling intensify the process of heat removal from the die and the deformation zone. This causes the process of temperature rise in the deformation zone to slow down or even to temperature decrease. At the same time, the extrusion process is always running, shortening the length and the side surface of the billet. In the next, second inflection point (2), the thermal phenomena of the extrusion process, i.e. the generation and removal of heat from the deformation zone, are balanced. It can be assumed that the temperature of the deformation zone as well as its thickness are stabilized and from this moment they remain constant. A further, almost uniform drop in the extrusion force (beyond the point (2)) is the result of reducing the length of the billet and its lateral surface, i.e. the surface where the frictional forces act. In the case of a traditional direct extrusion process the extrusion force is approximately equal to the friction force needed to push the billet through the container and that for the material deformation at the die [9,10]. The friction force is proportional to the actual length of the billet in the container; the deformation force is the force actually needed to deform the billet to the section shape. As it is shown in Fig. 5, in the KOBO extrusion process, from point (2) the extrusion force decreases almost proportionally and taking in to account the stable conditions of deformation zone, the most probable reasons for this is frictional resistance on the billet – container interface.

The approximate positions of inflection points of three force charts are shown in Fig. 6. It can be seen that the width of the uniform extrusion stages increases with increasing the oscillation frequency and the total width of the initialization and stabilization stages decreases. The individual width of the initialization and stabilization stages (and position of the point (1)) depends mainly on the starting moment of the cooling action. In the case of the smallest oscillation frequency of 3 Hz, the greatest force was needed to start the extrusion process, that is why the cooling was engaged at the latest and the initialization stage is the longest. It can be assumed that in the case of the force

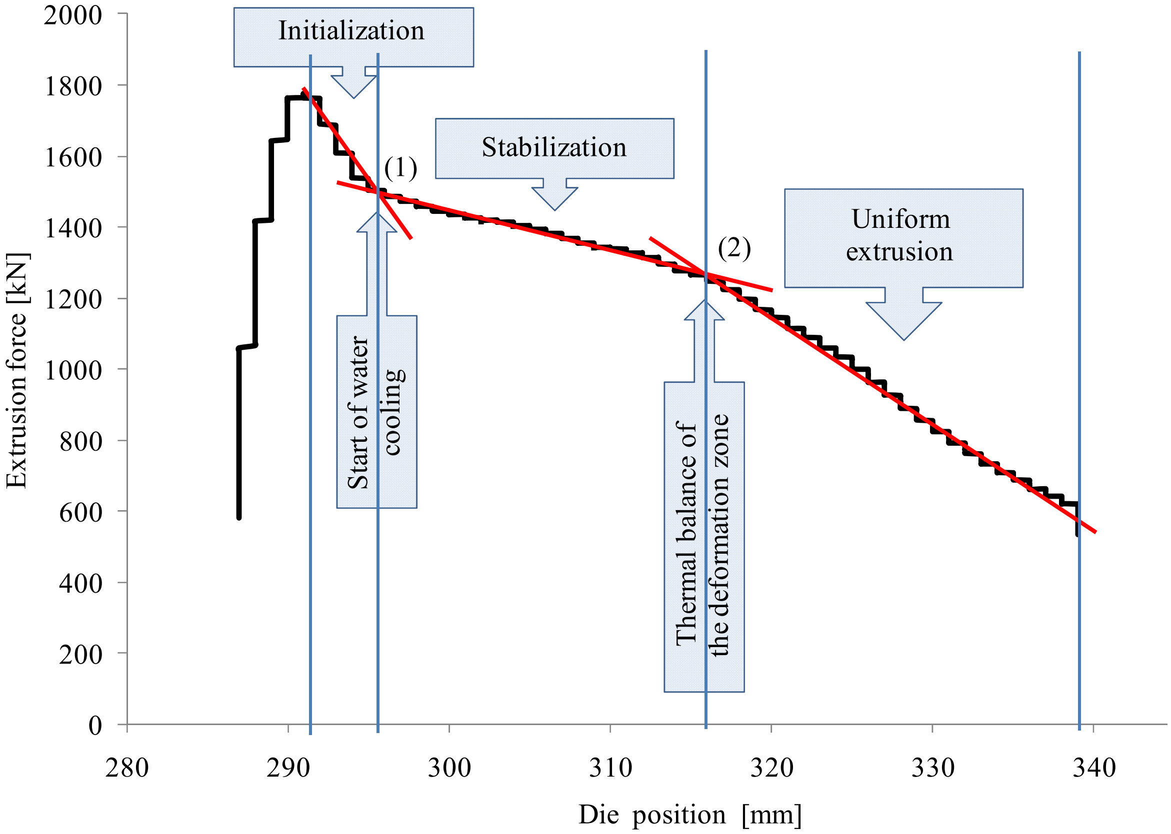

Fig. 5. Extrusion force versus stem position diagram obtained for 5 Hz oscillation frequency

diagram for 5 Hz oscillation frequency the water cooling was engaged at the optimum moment of the process; the initialization stage is the shortest and the points of inflection are the most expressive.

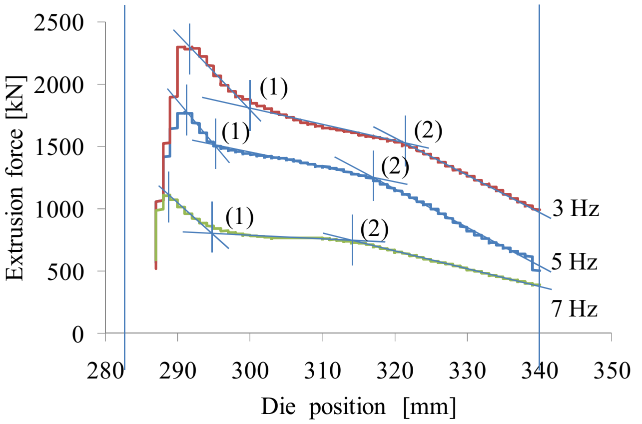

Fig. 6. The approximate positions of inflection points of force charts for three different oscillation frequencies: 3Hz, 5Hz and 7Hz

The above description of the force characteristics of KOBO extrusion process and drawn conclusions should be treated as an authors' interpretation formulated mainly on the collected numerical data of the extrusion process parameters and additionally on studied literature data. Confirmations of this interpretation should be sought in structural studies of the extruded profiles, particularly giving grounds for the second inflection point (2) separating the stabilization and uniform extrusion stages as it is shown in the force graphs in Figures 5 and 6. It also seems very important to carry out the extrusion with the billet and the container heated to the hot working temperatures of material to be extruded and compare to the currently presented results.

4. Conclusions

The force characteristics of the KOBO extrusion process, collect a lot of information about the phenomena and the course of the extrusion process. Interpretation of these data has been presented in the work, however, it requires confirmation by further studies of the extruded products and the process parameters. The difficulty is in that the deformation values obtained during KOBO extrusion are so great that their justification for the mechanisms of plastic deformation in materials with a crystalline structure is insufficient.

The maximum extrusion force depends on the oscillation frequency of the die. Increasing the frequency of oscillations causes a decrease in the maximum extrusion force. When extrusion aluminum alloy 2099, more than twice reduction of the maximum extrusion force was obtained when the oscillation speed was increased from 3Hz to 7 Hz.

The mechanical characteristics of KOBO extrusion process can be divided into three separate stages: – initialization of extrusion, – stabilization of extrusion conditions and – uniform (stabilized) extrusion. The boundaries between these stages are the inflection points of the force graphs as a function of the stem position (or the process duration).

Presented article focuses only on the assessment of mechanical characteristics of the KOBO extrusion process. Other aspects of the carried out research, i.e. the assessment of microstructure and the variability of mechanical properties along an extruded section, constitute a research material prepared for a separate publication. The aim of this article was to draw attention to the specific nature of the mechanical reaction of extruded material and extrusion process conditions when using the KOBO method.

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