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THE DEVELOPMENT AND NUMERICAL ANALYSIS OF THE CONICAL RADIATOR EXTRUSION PROCESS

The article presents a newly developed method for single-operation extrusion of conical radiators. This is the author's radiator manufacturing method being the subject of a patent application. The proposed method enables the manufacture of radiators either with or without an inner opening and with an integral plate. Selected results of numerical computations made within Forge®3D, a finite element method (FEM)-based software program, were presented during the analysis of the process. A comparative analysis of the proposed manufacturing method using the double-sided extrusion method was also made.

The proposed manufacturing method is assumed to produce radiators in a single technological operation with the stock material being standardized 30 mm-diameter aluminium bars. The objective of the developed method is also to reduce the energy-force parameters.

Keywords: extrusion radiator, conical radiator

1. Introduction

The radiator, often called heat dissipator, is an element or a set of elements that carry away heat from the system to the environment with which it is in contact, such as the (air, water, etc.).

The radiator is a body purposefully formed of a metal (or its alloys) that well conducts heat, and has a developed surface on the outer side, usually in the form of fins or bars, to maximize the heat transfer. Radiators are normally made of aluminium or copper and are commonly used in electronics due to the large amount of heat released from small elements, which corresponds to their large power density. Radiators are most often manufactured by the extrusion, forging or pressure die-casting methods. The first and the second of the above-mentioned methods are used for radiators a cylindrical or rectangular prism profile, with a relatively small number of fins; while the third method is applicable to high fin-density radiators with irregular shapes and relatively thin fins. There is also a recently developed and patented method of forging radiators, but is only applicable to radiators of a rectangular prism body [1].

Extruded radiators are produced by cutting aluminium sections extruded in the single- or multiple-chamber bridge dies of a horizontal press into lengths. This is a very efficient method, but it performs best only in the case of rectangular-profile sections; also, circular cross-section shapes can be extruded by this method.

In practice, we deal with many types and applications of radiators, such as the fireplace radiator, the processor's radiator, the cooler (e.g. in the internal combustion engines), electric motor casings, heaters, LED or halogen lighting systems. Many a time, due to the construction of a device in which the radiator performs the function of carrying away or dissipating heat, the radiator must be conical shape and have an integral plate and an opening. An example can be the constructions of high-power lighting systems. Products of this type can be manufactured by using plastic forming methods, such as forging [6] or extrusion [5].

In this study, an extrusion method has been proposed, which is partly based on the author's developed extrusion method [2], while the radiator manufacture method presented in the article is the subject of a patent application [3]. The objective of the developed novel radiator manufacture method, aside from the capability to produce a unique products, is also an economical aspect. The charge for the production of the radiator by the complex extrusion [2] or double-sided extrusion method [4] can be standardized aluminium bar commonly available in the ferrous and non-ferrous metal market. This approach allows the need for using the costly operation of stock production by either casting or material-consuming machining to be eliminated. In the case at hand the processing of the stock is only limited to cutting the bar into suitable lengths.

Furthermore, the proposed radiator extrusion method enables the manufacture of products with a through channel, which eliminates the need for drilling holes or using machining. To sum up, the stock preparation method and the capability to manufacture products with an opening considerably increases the degree of material yield and makes the method discard-free.

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2. The core of the process and the modelling assumptions

The extrusion method is intrinsically universal to the extent that the radiator shape depends on the type of the die insert which will be placed in the tool container. The die insert is replaceable and enables radiators of varying shapes to be produced. The shape of the die insert used determines:

• the degree of outer radiator finning,
• radiator fin thickness,
• body profile (a cone, cylinder or cube),
• the number of bases (one or two),
• the diameter of the radiator and its core.

The entire extrusion process is essentially made up of two stages that are accomplished in a single punch operation. At the first stage, there occurs the process of localized pre-upsetting of the bar section, whose length should not be greater than three times the diameter. At the second stage, the die connected with the retaining ring moves downwards, and its chamber is filled with the heated-up bar being deformed on an ongoing manner. Figure 1 shows a schematic diagram of the radiator extrusion process with the division into individual stages.
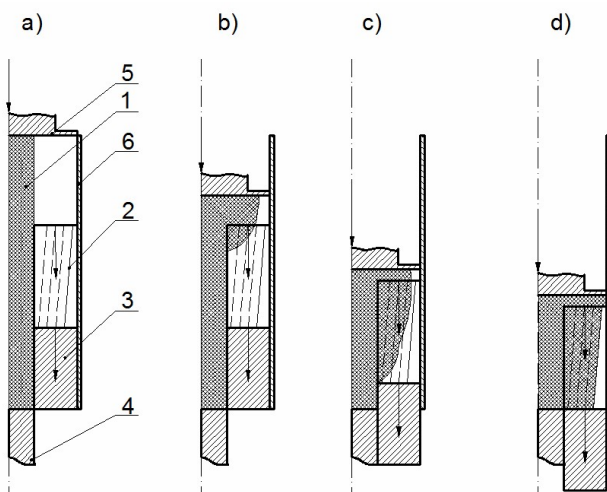

Fig. 1. A schematic diagram of the process of extrusion of a conical radiator with a base – see a description in the body text

The presented novel radiator extrusion method is a process in which charge 1 in the form of a bar moves inside die 2 and ring 3 that are initially fixed and connected with one another. From the bottom, charge 1 is restricted by fixed punch 4. From the top, the charge is deformed by punch 5. The whole instrumentation is housed in container 6. Initially acting on stock 1, punch 5 upsets the bar length situated outside the die. The upper die part is gradually filled with the upset metal. After attaining the relevant distance of punch 5 from die 2, which corresponds to the thickness of the radiator base, the process proceeds to the second stage. At stage 2 (Fig. 1b,c), by means of the press ejector, die 2 and ring 3 move downwards at a speed equal to that of punch 5, while punch 4 still remains motionless. It is important in the extrusion process that the distance between punch 5 and die 2

do not change. Under the pressure of punch 5, the deformed metal flows radially and fills the chamber of die 2. The process will be completed when ring 3 has become flush with punch 4 (Fig. 2d).

As the presented process includes a new product forming scheme, the first investigation stage will be computer simulations to be performed within Forge®3D, a finite element method-based computation program. Two radiator models, as shown in Fig. 2 as a view and a cut, were selected for numerical studies.
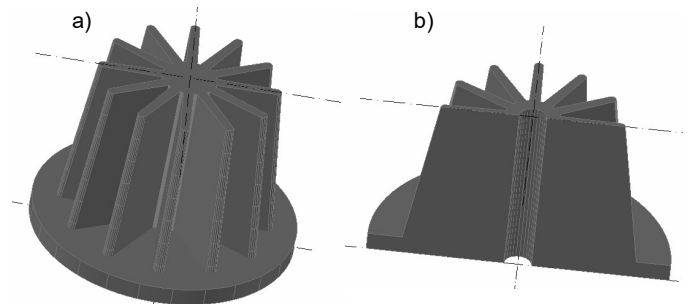

Fig. 2. 3D models of radiator extrudates: a) a solid radiator, b) a through-hole radiator

The model material for the extrusion of the radiators shown in Fig. 2 was be the AlMgSi (PA38) aluminium alloy. The aluminium alloy commercially marked as AW-6060 is characterized by average tensile strength and average fatigue strength. It is weldable and lends itself to decorative anodizing. It is widely used for production of aluminium bars and sections. Its high drawability allows complex-shape sections to be produced. It finds application in the manufacture of architectural elements, such as window and door sections, wall elements; it is used for production of interior decoration elements, frames, lightings, ladders, railings, fences, radiators, trailer and semi-trailer parts, office equipment, car furniture, etc. Aluminium AW-6060 is offered for sale, e.g., in the form of common 30-mm diameter bars, which also contributed to the choice of this material. The initial charge temperature was $T_0 = 550°C$. The rheological properties of the model AlMgSi material were taken from the database of the Forge®3D 2011 numerical program [4]. For solving the problems of three-dimensional plastic metal flow during extrusion, a mathematical model [7] was selected, in which the mechanical state of the material being deformed was described using the Norton-Hoff law [13,14], which can be expressed with the equation below:

$$S_{ij} = 2K(T,\dot{\varepsilon},\varepsilon)(\sqrt{3}\varepsilon)^{m-1}\dot{\varepsilon}_{ij} \qquad (1)$$

where:
S_{ij} – stress tensor deviator [10],
$\dot{\varepsilon}$ – strain rate intensity,
ε_{ij} – strain rate tensor,
ε – strain intensity,
T – temperature,
K – consistence dependent on the yield stress, σ_p,
m – coefficient characterizing hot metal deformation $(0 < m < 1)$.

The yield stress value is determined from the following formula [15]:

$$\sigma_p = A e^{m1T} \varepsilon^{m2} \dot{\varepsilon}^{m3} \varepsilon^{\frac{m4}{\varepsilon}} (1+\varepsilon)^{m5T} \varepsilon^{m7\varepsilon} \dot{\varepsilon}^{m8T} T^{m9} \qquad (2)$$

where: T – temperature, ε – actual strain, ε – strain rate, $A + m9$ coefficients characterizing the rheological properties of the material.

For the computation of the yield stress value, the coefficient values were taken from the material database of the Forge3® program. For the AlMgSi alloy, respective coefficients take on the following values: $A = 317,6$, $m1 = -0,00429$, $m2 = 0,055$, $m3 = 0,089$, $m4 = 0$, $m5=0$, $m7=0$, $m8=0$, $m9 = 0$. Due to the high strain intensity and the large strain value that occur during the formation of the radiator, Tresca friction model was used for numerical computations [15].

Prior to proceeding with computer simulations, the models of individual tools were developed according to the schematic diagram shown in Fig. 1. Figure 3 shows one of the tool models prepared for the computer simulation of the process.

The presented tool model functions in computer simulations both in the scheme shown in Fig. 1, where the movable tools are the punch, the die and the ring, as well as in the scheme, in which movable tools are the punch and the ejector. In the third method of forming the through-hole radiator, the punch with a mandrel of a length exceeding the die height was used in tool model in order to pierce the work after the first stage of the process.

Figure 3 shows the model of the tool assembly for carrying out of the process according to the scheme (Fig. 1)
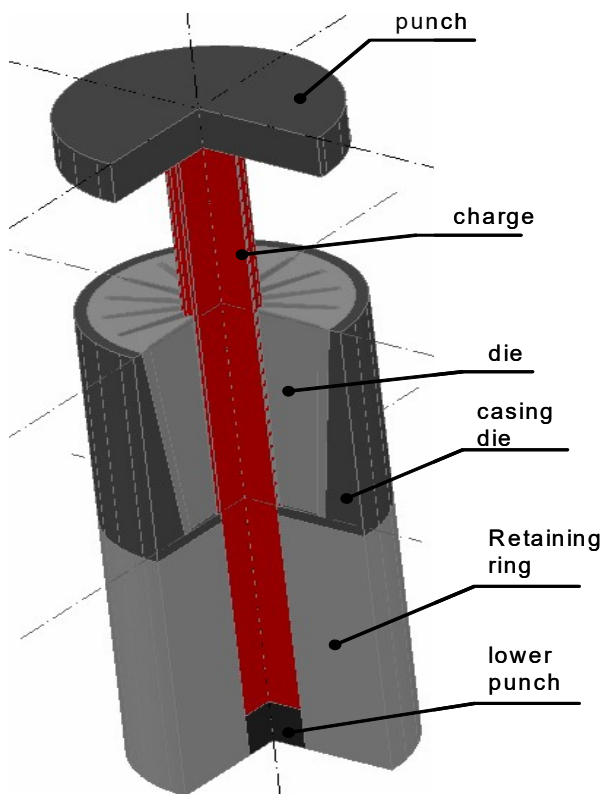

Fig. 3. The tool assembly model for the computer simulation of the process

Figure 4 shows finite elements with which the filling of the die chambers to form the radiator fins was modelled.
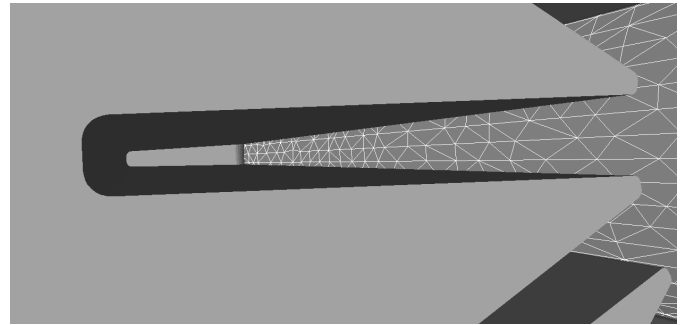

Fig. 4. A fragment of the tetragonal finite element grid in the radiator fin forming chamber

Modelling of thin-walled products requires the adequate number of finite elements to be used so that the correct fill of the impression be effected [9,11]. As the radiator is a conical shape, the generating lines in the die impressions are convergent. This makes the die chambers thin-walled, especially in the lower die region. At the radiator base at the entry to the fin forming chamber, the die wall spacing is about 4.2 mm, while at the chamber end, about 3.2 mm. In the lower die part, the chamber wall spacing dimensions are, respectively, 3.2 mm and 2.2 mm. The dimensions of the finite element grid were selected so as to have at least four tetragonal finite elements across the entry to the die chamber in the upper part and at least two elements in the lower part.

3. Computer simulations of the process

Computer simulations were performed for the analysis of the radiator extrusion process, where the stock material was 30 mm-diameter aluminium alloy bar. The stock material deformation scheme was consistent with the schematic diagram shown in Fig. 1. In addition, computer simulation of the process of extrusion of a similar radiator with a through hole was carried out during the studies. In that case, in order to obtain the hole inside the radiator, the punch with a mandrel of a diameter of $d = 15$ mm, being equal to the radiator hole diameter, was employed. As the proposed process is novel in character, the numerical studies first covered the evaluation of the correctness of the product shape and the die impression fill, and then the analysis of the strain rate fields and the analysis of the energy-power parameters.

Figure 5 illustrates the process of numerical modelling at individual extrusion process stages on the example of temperature distribution.

The schematic diagram of the process (Fig. 1) assumed that the upset material would be forced into the die openings from the top, and part of the material would flow radially to gradually fill the die space. However, the computer simulations did not confirm that assumption. As indicated by Fig. 5, which
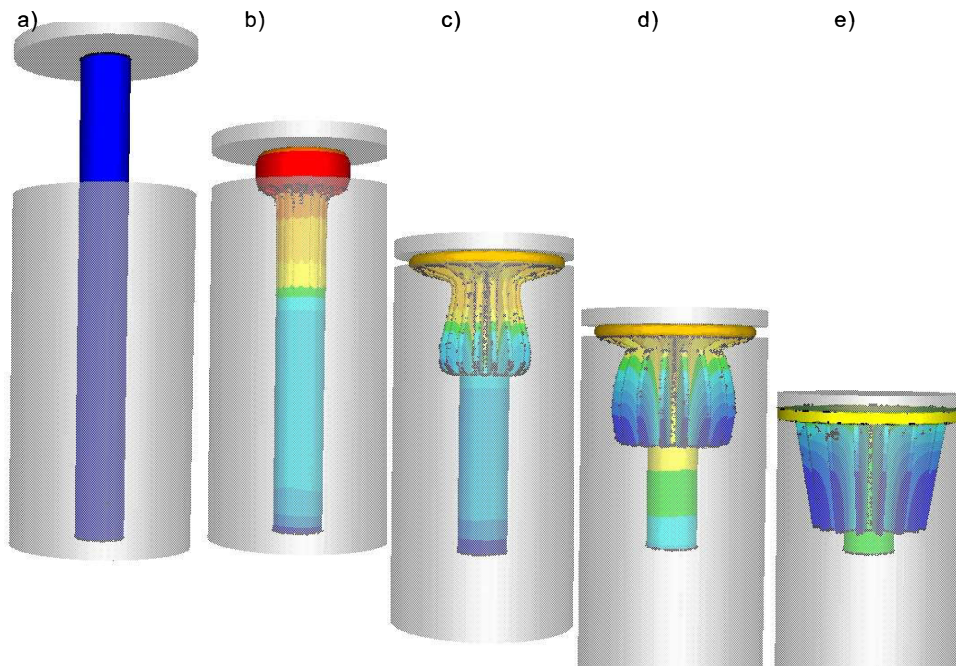
Fig. 5. Computer simulation of the process of extrusion of the solid conical radiator with a base

represents the course of the extrusion process, initially, the work which is situated outside the die, is first upset. The bar in the die channel is partially deformed in such a manner that fins are formed on its surface. Once the die with the ring start to move down, the metal starts to fill the lower portion of the die. After completely filling the lower die portion, the metal gradually fills the remaining portion of the tool. Throughout the process, the deformation of the metal follows the radial extrusion scheme [8]. When designing the tool models, an edge curvature radius was employed in the die, which gradually releases the stock material as it retracts together with the ring. This curvature radius has probably contributed to the fact that the metal starts in this region to flow most intensively, causing the die to be gradually filled from the bottom to the top. Figure 6 shows the distributions of strain rate fields in a sectional view.

The strain rate field distribution confirms the findings from the computer simulations. Initially, the highest strain rates are observed in the upset bar located beyond the die region (Fig. 6a). After passing on to the second stage of the process, where the die moves downward, the highest strain rates occur in the die bottom region (Fig. 6b), where the metal fastest fills up the die space and then gradually, rising up as the process progresses, fills the radially arranged die channels (Fig. 6c,d).

The computer simulations determined the values of the energy-force parameters for the conical radiator extrusion process. Figure 7 represents the diagram of the dependence of extrusion force on the punch path.

The maximum extrusion force value at the first process stage amounted to 332 kN. This value was attained when the punch approached the die at a distance equal to the radiator base thickness. The radiator fins were finish formed at an extrusion force of 600 kN, that is after the punch had covered a distance of 220 mm. The subsequent increase in force is associated with the
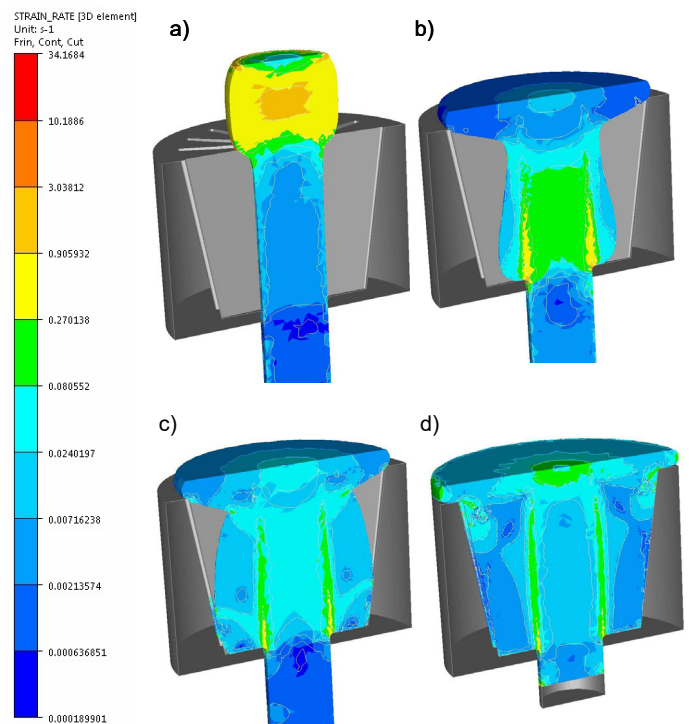

Fig. 6. Strain rate field distributions

formation of the radiator base diameter, where the metal fills up the space between the die, the punch and the container. The punch pressure force has at that case a value of approx. 1400 kN. An important indicator of the process energy intensity is the averaged value of the extrusion force. For the process under examination, the average extrusion force value was 210 kN.

As many forging operations are carried out on double-punch presses, computer simulation of the process of extrusion of a similar radiator using a movable lower punch was also
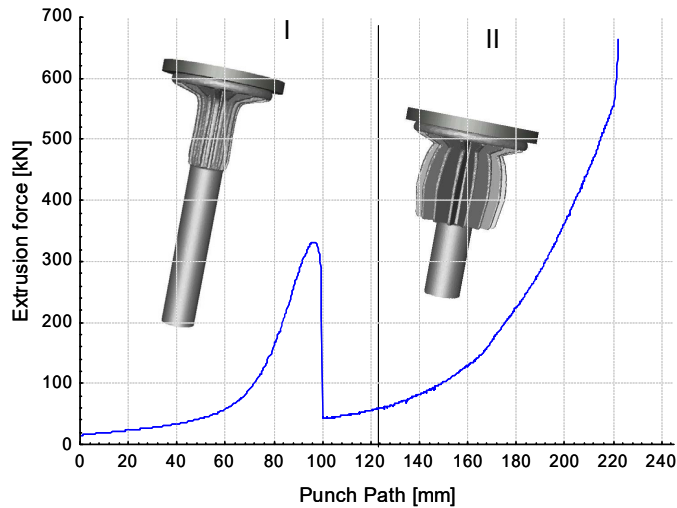
Fig. 7. Extrusion force as a function of the punch path

performed. The tool assembly is identical, with the only difference being the fact that the die and the ring are both fixed tools, whereas the work is deformed by the simultaneous action of the upper and lower punches. The deformed material showed an identical flow pattern, but due to the change in tool kinetics, different friction forces occurred in both processes. This had a crucial effect on the force parameters of the process; therefore, the comparative analysis covered the values of the extrusion force. Figure 8 shows the diagram of extrusion force variation as a function of the punch paths for the radiator extrusion process using two oppositely moving punches.
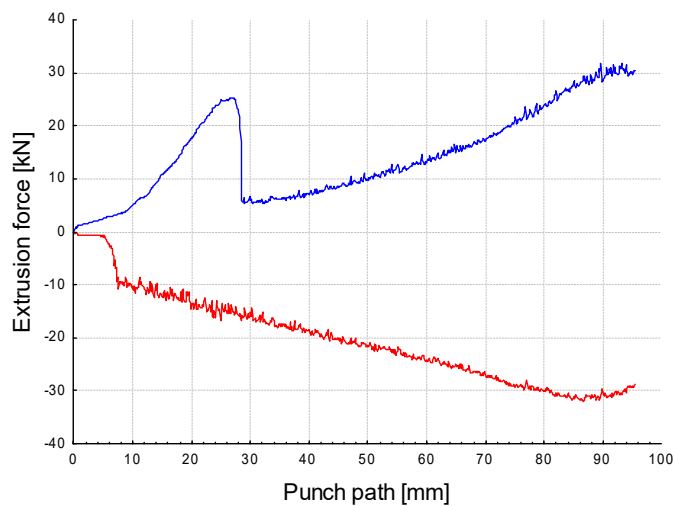

Fig. 8. Extrusion force as a function of the punch paths

During the course of the process, the tools moved independently in two opposite directions; for this reason, the force parameters obtained from computations are presented with two graphs. The upper curve represents the extrusion force computed for the upper punch, while the lower curve shows the force computed for the lower punch. As the lower punch moved in the direction backward to that of the main tool (upper punch), the Forgre® program determined the extrusion force values

as minus. As shown by the presented computation results, the maximum extrusion force for the upper tool was approx. 300 kN, while for the lower tool, 315 kN. The average extrusion force value for the entire process was 350 kN.

Radiators are also often provided with though holes that are used for mounting a lighting or passing through conductors. The proposed extrusion method enables the production of a radiator extrudate with an inner through hole of an arbitrary diameter. This requires an additional mandrel of an appropriate diameter to be used in the upper punch. For the process to run correctly, two prerequisites must be met. The length of bar that is above the die may not be longer than three times its diameter, and the stock must be set in the die in such a manner that assures its stability and the alignment of the process. Computer simulation performed for analogous temperature and speed conditions to those in the processes in Figs. 7 and 8 has demonstrated that it is possible to carry out the hole radiator extrusion process according to the deformation scheme proposed in this article. Numerical modelling of the through-hole radiator extrusion process, as illustrated in Fig. 9, was conducted in such a manner that, at the first stage, the punch gradually pierced the work and formed the radiator base. The through hole was made completely at the first stage (Fig. 9a-d). At the second stage of the process (Fig. 9e), the deformation scheme was analogous to the preceding two extrusion schemes.

Figure 9 shows the modelling of the hole radiator extrusion process in a sectional view, on the example of strain rate field distributions.
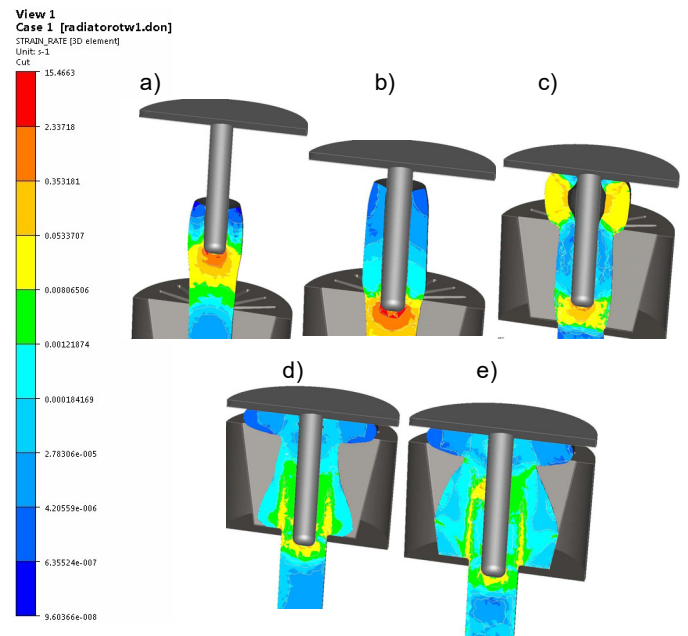

Fig. 9. Computer simulation of the process of extrusion of the conical solid hole radiator

5. Summary

This study puts forward a proposal for a novel method of extrusion of radiators with finning on their perimeter and presents computer simulation-based preliminary studies carried

out in Forge®3D, a finite element method-relying program. The purpose of the numerical modelling was primarily to evaluate the possibility of carrying out the process using the author's method of extruding hollow products, where movable dies are used. As has been demonstrated by the numerical modelling, the process of making a radiator using a movable die with a ring and with the use of two independently moving punches is possible to carry out. The obtained computation results show that the die impressions are filled correctly and the obtained product is identical to the 3D model assumed prior to the studies. The analysis of the obtained force process parameters has shown that by using the movable die the average extrusion force is reduced by approx. 50% compared to the double-sided extrusion method. This confirms the results of studies conducted on the plastic forming of deep hollows, where decreases in extrusion force value by about 40% were noted for a similar deformation scheme. An unquestionable advantage of this method of extruding radiators is the freedom of imparting them arbitrary shapes. The flow patter involved in the radial extrusion of radiator fins from prismatic bar allows them to be given quite complex shapes. For conventional extrusion, obtaining fins of complex or circular shapes is fairly difficult and requires the application of high stock temperatures or large extrusion forces.

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