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Chapter 6

Numerical Modelling in Designing Aluminium Extrusion

Wojciech Libura and Artur Rękas

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/51239

1. Introduction

Hot extrusion process is commonly used for producing many types of aluminium alloy profiles which are widely applied in various branches of industry, especially in vehicle construction and building. Extrusion process is characterized by very high deformation degree, although such deformations are usually non-uniform in product's both cross section and length. It results from specificity of metal flow in the container and lack of process conditions stability, especially including temperature of outflowing metal. Metal flow in extrusion process depends largely on die's geometry, especially if multi-hole or porthole die is used. Metal flow may be predicted through numerical modelling and using programs based on finite element method.

In this chapter, the procedure of designing dies for complex cases of aluminium alloys section extrusion is described. Firstly, general principles of designing dies for multi-hole and pocket extrusion is briefly described. Multi-hole dies enable increasing the process' efficiency and decreasing extrusion force, which has special significance when extruding hard-deformable alloys. Pocket dies are, in turn, commonly used for extruding solid sections with complex-shaped cross-section, as well as when applying economical method of extruding "billet – to – billet" method, which requires welding consecutive billets. Using numerical, and occasionally physical, modelling helps to significantly limit the range and costs of otherwise indispensable extrusion tests. The designing procedure is presented based on selected cases of extruding hollow sections from aluminium alloys. The first stage includes numerical modelling with the use of DEFORM program based on finite element method with the use of rigid-plastic model of the material. The software enables calculations of metal particle distribution in the container, but also distribution of strain, stress and temperature of extruded material. Analysis of different variants of the process helps determine optimum ge-

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ometry of the die to guarantee obtaining good quality product. The second stage is testing the proposed dies in real-life conditions and, hence, it constitutes a form of validating correctness of the performed calculations.

2. Designing multi-hole dies

The presented work discusses cases of solid section extrusion, for which traditional flat dies are used. Multi-hole dies should be applied in hot extrusion process when deformation factor is to be limited. This, consequently, has profound impact on extrusion force. It is usually assumed that for soft aluminium alloys extreme extrusion ratio R, above which a multi-hole die has to be used, equals 40. For hard-deformable alloys, the ratio is significantly lower [1]. Excessive deformation factor results in increasing extrusion force, together with increasing velocity of outflowing metal. This may lead to forming fractures in hard-deformable alloys and make it necessary to decrease ram velocity. This, in turn, lowers extrusion effectiveness. Certainly, a multi-hole die should be used for extruding small-sized sections. Another case when it is required is extruding asymmetric sections, with considerably short diameter of circumscribed circle. Extruding such sections through single-hole die usually causes non-uniform metal flow and, thus, leads to geometrical instability of the product.



Figure 1. Entangled bars at press run-out, extruded through multi-hole die at non-uniform outflow velocity (Courtesy of Grupa Kęty).

Fig. 1 presents bars at press run-out, extruded through multi-hole die. Some of them are straight, but some are entangled as a result of non-uniform outflow velocity of individual bars from die holes. This, in turn, prevents a puller from being used at press run-out.

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Designing a multi-hole die properly is a complex task, requiring focus on various factors. The criteria to consider include material aspects, shape of product, but also die durability issues. The most important quality factor in extrusion through multi-hole dies is to maintain uniform velocity of metal outflow at each hole. Only such conditions allow proper reception and running products on die run-out. Good quality is guaranteed only if the puller (running trolley) is able to keep extruded products parallel. Hence, when designing multi-hole dies, strongest attention should be paid to such distribution of holes which enables to maintain uniform conditions of metal flow in each hole.

Round small-sized sections may be extruded by dies with a very large number of holes. Depending on bar diameter, the holes may be distributed around one, two or three circles on the die surface (Fig. 2). Distances between circles should be such, that they guarantee uniform inflow of product in each hole. Holes are not placed in the die axis, because it may precipitate very unwanted non-uniformity of product outflow.

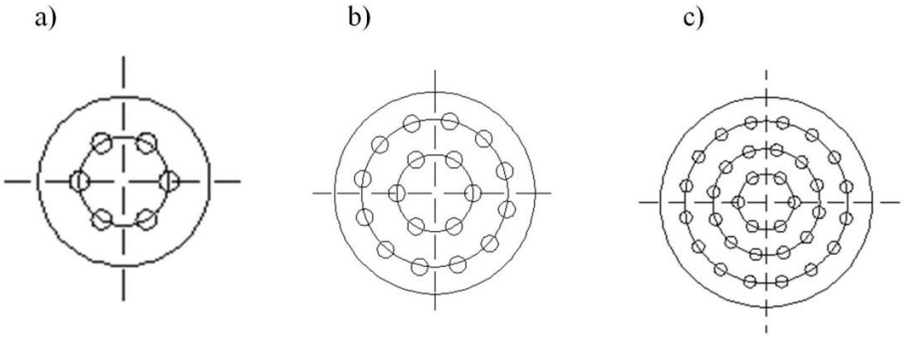


Figure 2. Distribution of round multi-hole dies, a) on one circle, b) on two circles, c) on three circles.

Sections which shape is other than round are usually extruded through holes placed on one circle on die surface [2].

Taking in to account the type of extruded material, one can state that practically every material could be subject to multi-hole die extrusion. The differences result from the number of holes used. Moreover, the type of extruded material influences the way it flows in container, that is, its geometry of its characteristic zones: main deformation zones (plastic zone), and dead zone. It is illustrated on Fig. 3 which schematically shows the area of main deformation zone and dead zones depending on number of holes in die. Fig 3a presents the size of main deformation zone and dead zone for hard-deformable material - both zones have significant volume, which results from high friction factor between the material and the tools. Significant changes were observed when a multi-hole die was used (Fig. 3b). There, main deformation zone seems to be divided into two smaller parts. An additional dead zone also appears between the holes. In this case, extrusion force will diminish as a result of both decreasing deformation degree as well as decreasing main deformation zone and dead zone.

By means of changing the holes' number and placement, one can influence the way material flows and, consequently, indirectly affect quality of product, characterized by its geometrical stability, structure and mechanical properties.

The third crucial factor for designing multi-hole dies is die durability. The distance between holes constitutes a very significant parameter. It should be as large as possible. Together with increasing the number of holes, die durability diminishes, although only seemingly. In fact, together with increasing the number of holes, extrusion forces significantly decrease, too. This means that the die load is high when the number of holes is small, whereas for larger number of holes, the load is lower. Another necessary condition is also symmetrical distribution of holes in die.

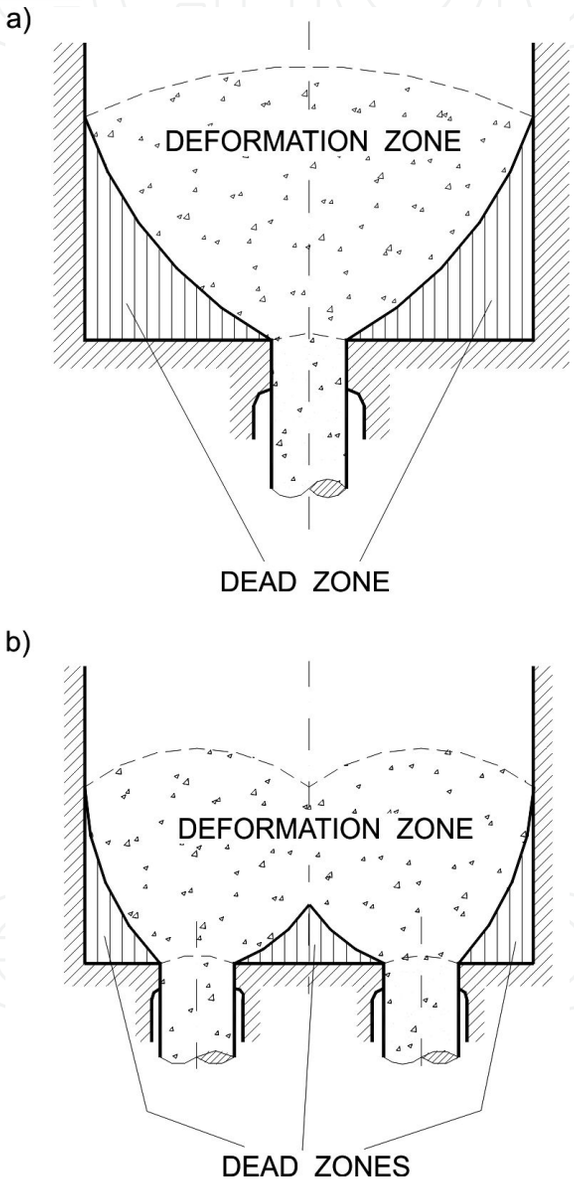


Figure 3. Flow character of hard alloy extruded through different dies, a) single-hole die, b) multi-hole die.

Supporting plates' structure also influences adjustments of distances between holes. They help to significantly limit die spring. Excessive die spring causes appearance of dangerous strain, which may end up destroying the die. Taking durability into consideration, when de-

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signing multi-hole dies one should also adapt the principle that holes laying on several circles are not distributed in one radial line. Appropriate hole distribution in such case is illustrated by Fig. 2 b and c.

3. Pocket dies

Pocket dies are used among others for obtaining products with highly differentiated section wall thickness, but also products with very small wall thickness [3]. They are also useful when applying "billet – to - billet" extrusion. In such case, there exists a need to weld two consecutive billets during process. Depending on pocket size, that is its size h (Fig. 4) and its width in relation to hole size, pocket may either facilitate or hinder metal flow into the hole, so as to obtain uniform metal particle velocity distribution in die hole. The works [3,4] present methodology of pocket shape selection for profiles with differentiated wall thickness based on local volume rates of metal flow criterion.

Volume rate of metal flow was defined as follows:

$$W = S \cdot v = const. \tag{1}$$

where, S - cross-section of given part of section, v - velocity of metal flowing into the given section part.

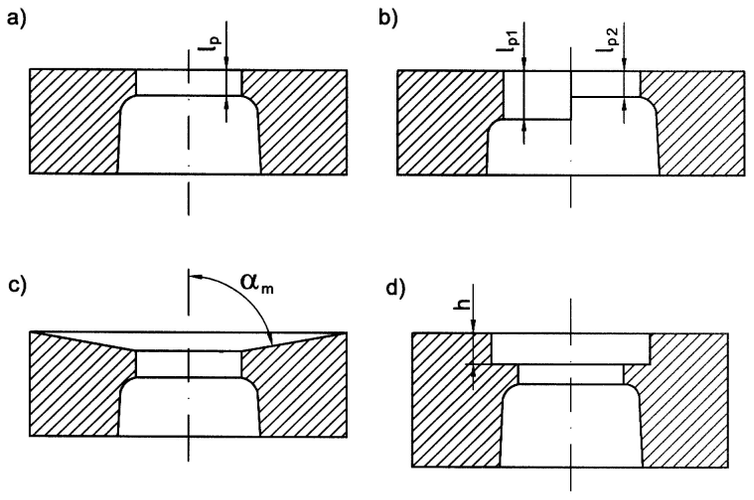


Figure 4. Schematic diagram of pocket die.

Pocket is also useful for multi-hole extrusion when one aims at equalizing velocities of metal flowing from holes distributed at different distance from die axis.

Currently, many problems connected with choosing extrusion die geometry are solved thanks to numerical modelling methods based on finite element method (FEM). There are many publications dealing with pocket die extrusion [3-9], but only a few works were devoted to application of numerical modelling for multi-hole die extrusion [10-12]. Calculation procedure using FEM, apart from die geometry, enables also strength parameters analysis, stress and strain factors, metal flow velocity, as well as temperature and time conditions.

The tests presented in this work concern various instances of extrusion in which die geometry was chosen considering numerical simulations in FEM-based program DEFORM™. The test procedure included:

- choosing multi-hole extrusion
- numerical modelling of different die variants
- experimental validation in industrial conditions.

For the purpose of the test, especially difficult instances were selected in which problems with quality of products were identified, as well as other technical difficulties. Materials used for the tests were medium and hard-deformable alloys. The data describing materials' rheology between 300 and 500°C and steel tool AISI H13 material characteristics was defined based on program DEFORM™'s material database.

4. Indirect extrusion through four-hole dies

Modelling indirect hot extrusion process of full AlMg1SiMn (6061) products with diameter 28 mm through four-hole dies aimed at analysing the influence of holes' distribution (Fig. 5) on metal flow and distribution of outflow velocity in die orifice. Inappropriate distribution of holes in the die results in unstable metal flow, and, as a result, extruded bars lean towards each other or away from each other. This hinders their movement at press run-out.

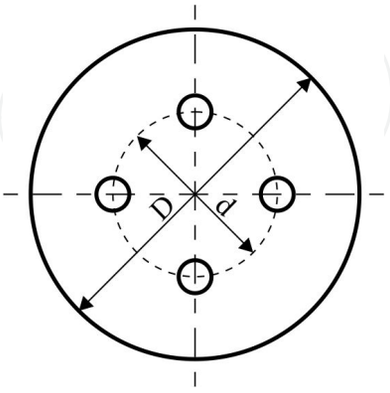


Figure 5. Schematic diagram of four-hole die.

For each analysed variant, a constant billet temperature was assumed at T_b = 340°C as well as constant tool temperature at T_t = 340°C. Calculations were performed at constant exit ve-

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locity v_e = 8 m/min, constant billet diameter of D_b = 246 mm and length L = 770 mm, assuming friction factor at m = 0,7. Extrusion ratio equalled 20,2.

At the beginning, calculations of indirect extrusion for flat dies were performed, analysing the influence of holes' distribution on quality of obtained products. Holes' distribution was determined taking into account a *k* indicator, defining relations between die surface area A_D and surface area of circle circumscribed on holes' axis, A_d, according to (2) (Fig. 5):

$$k = \frac{A_D - A_d}{A_d} = \frac{D^2 - d^2}{d^2} \tag{2}$$

where:

k – indicator defining location of holes in the die

D - diameter of die

d - diameter of circle circumscribed on holes' axis.

The change of diameter of circle circumscribed on holes' axis was determined according to (3):

$$d = \sqrt{\frac{D}{k+1}} \tag{3}$$

Indications in equation (3) as above.

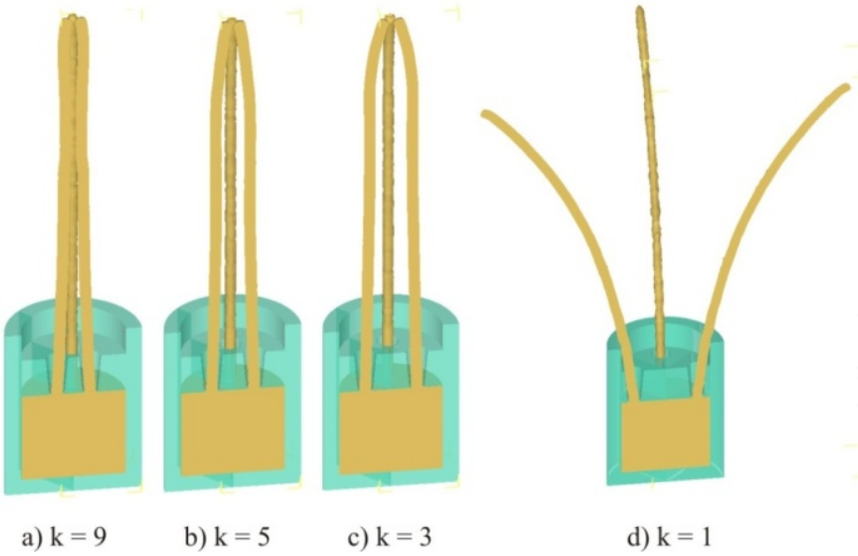


Figure 6. Metal flow at various holes' distribution in a flat die.

Numerical calculations for indirect extrusion through four-hole dies were carried out for four different hole distribution indicators, *k* = 1, 3, 5, 9. Results of modelling made it possible to observe product's reactions during extrusion process. For each *k* indicator value, diameter of the circle on which die holes are placed, changes. Low *k* value means high diameter, and

conversely. Change in *d* diameter influences metal flow in deformation zone. Optimizing hole placement should result in uniform metal inflow from outer layer and from billet's inside so as to ensure that rod exits die holes parallel to extrusion axis. For the assumed hole distribution indicators, satisfactory geometrical stability of the product was not obtained (Fig. 6). In the case of extrusion with indicators k = 3, 5, 9 (Fig. 6a, b, c), bending the product towards die axis is observed, until they touch. Extrusion with indicator k = 9 causes bending at the very beginning of extrusion process and non-axial metal exit (Fig 6a). Distribution of holes in the die with indicators k = 3 and 5 initially causes a similar effect to indicator k = 9, and then, during extrusion process, product axis approximates die holes' axis. However, during extrusion with holes' distribution for indicator k = 1 (Fig. 6d), strong outwards bending of product appears.

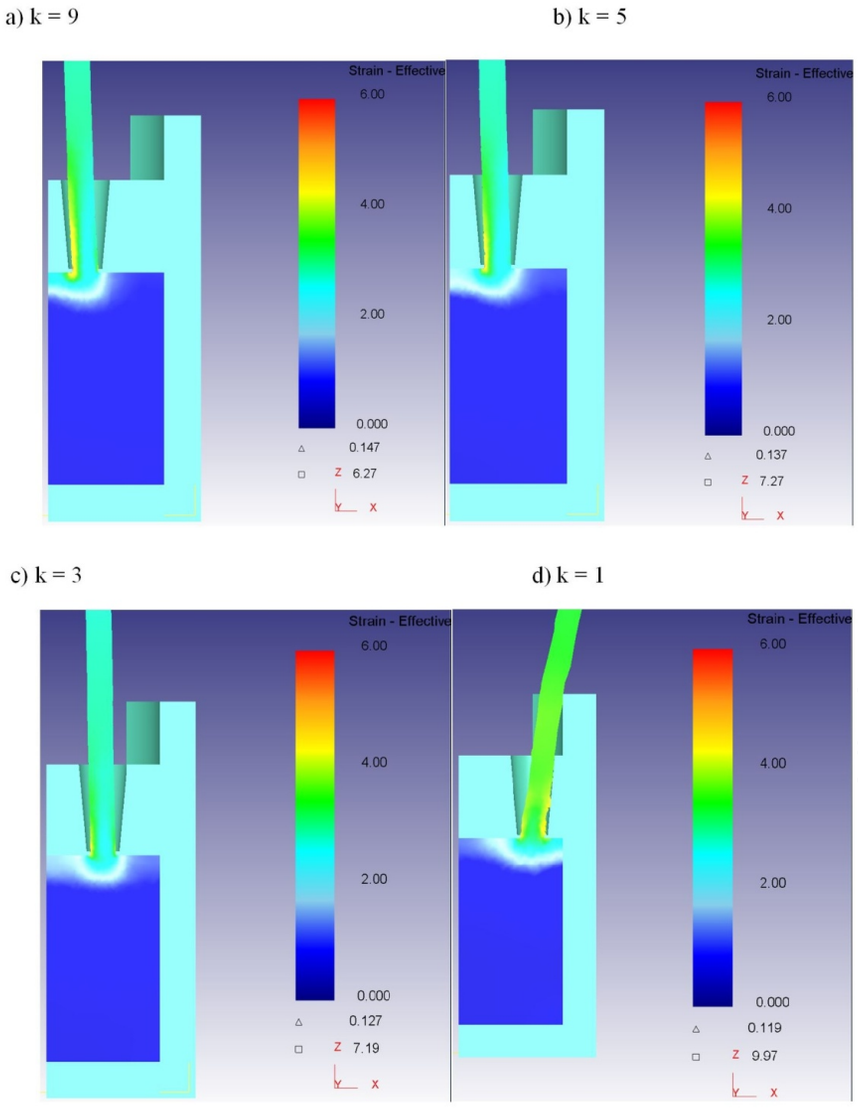


Figure 7. Distribution of effective strain for different hole's distribution indicators *k*.

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Fig. 7 presents of effective strain for different indicators *k*. Diversification of effective strain is visible in cross-sections of extruded bars, which leads to their deformation after exiting a die hole.

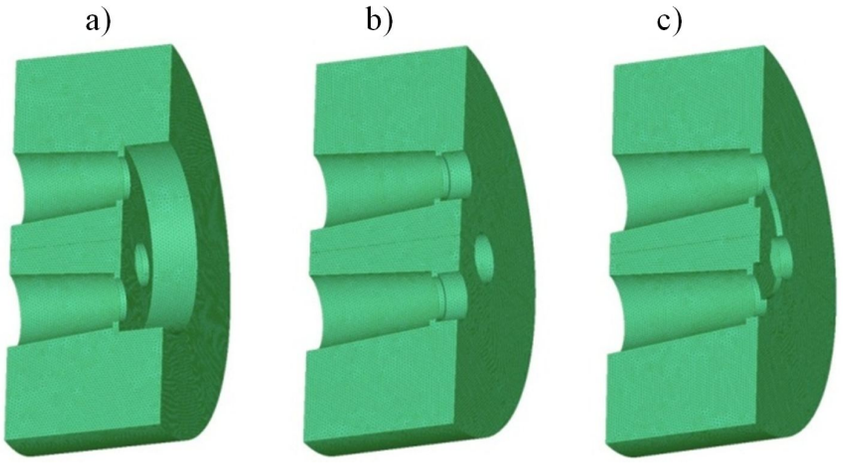


Figure 8. Four-hole pocket dies models for numerical calculations, a) central pocket die, b) local pocket die, c) ring-shaped pocket die.

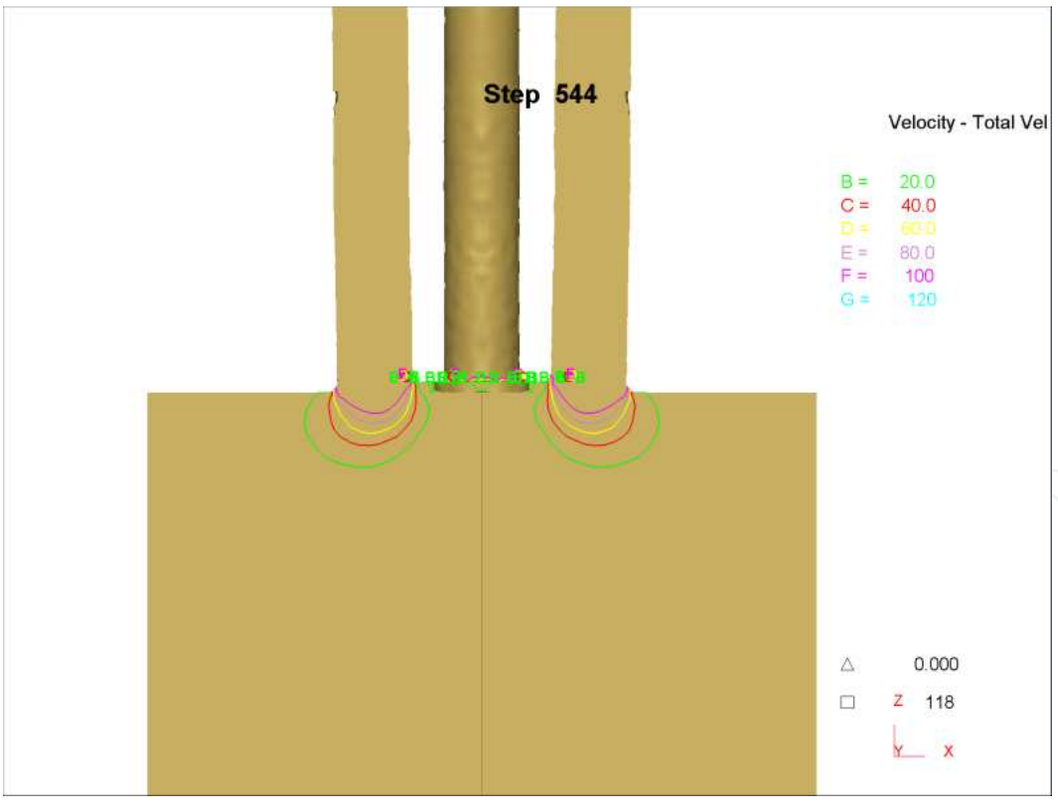


Figure 9. Distribution of metal particle exit velocity upon extrusion through ring-shaped pocket die.

Calculations have shown that, theoretically, in order to achieve the most beneficial extrusion, indicator *k* should equal 2 ÷ 3. Unfortunately, die set structure of press does not provide for

such wide setting of die holes. In this situation, calculations were carried out for several pocket dies with various geometry (Fig. 8a, b, c). Depending on its geometry, a pocket may be useful at controlling metal flow into individual die holes. In such case, pocket helps to regulate intensity of metal inflow into die holes. Central pocket (fig. 8a) intensifies metal flow in central part of ingot, whereas local pockets, i.e. individual for each hole, are supposed to reduce influence of non-uniformity of flowing in deformation zone. The ring-shaped pocket (fig. 8c) combines both abovementioned reactions. The final goal is to obtain uniform velocity distribution in die holes. For each of the analysed extrusion variants, a constant value of holes' distribution indicator was assumed at $k = 9$. It turned out that the optimum die featured a ring-shaped pocket with height $h = 2$ mm (Fig. 8c). Fig. 9 presents distribution of particle velocity upon extrusion through segmented pocket die, and Fig. 10 shows intensive strain distribution. Both distribution of particle velocity and distribution of intensive strain display satisfactory uniformity which helped design such die for industrial tests.

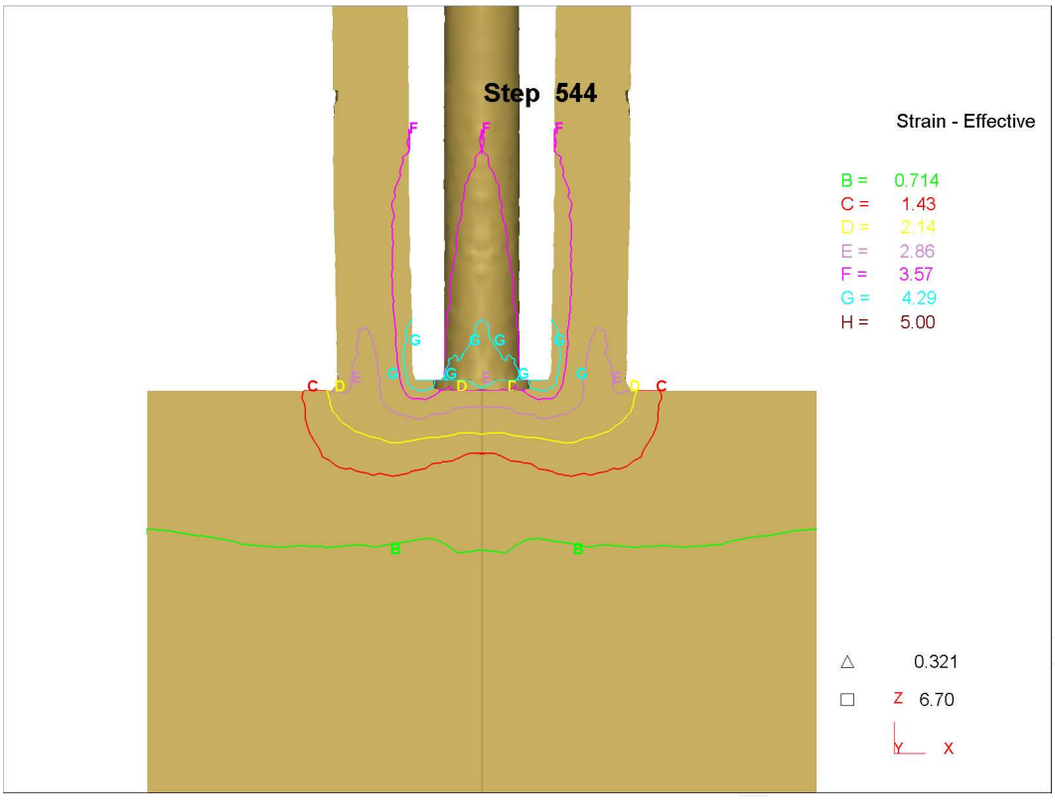


Figure 10. Distribution of intensive strain upon extrusion through ring-shaped pocket die.

Figure 11 presents a view of ring-shaped pocket die, designed for experimental tests. Extrusion tests of round 28 mm diameter 6082 aluminium bars through four-hole dies were performed on indirect press with nominal force of 28 MN. The press is a modern solution, featuring so called water wave designed for solutioning of extruded products directly at press run-out. Test parameters were identical as in numerical modelling, with the exception of temperature, as because of necessity to maintain isothermal extrusion conditions and

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product solutioning at press run-out, taper billet heating was applied 500/510/520/530°C, and container temperature was 500°C.

Upon extrusion through flat die, bars were bent towards extrusion axis, which, consequently, led to bars' joining at press run-out. Extrusion through ring-shaped pocket die caused expected effects, that is, good quality product together with maintaining shape stability. Fig. 11b features a photograph from the test performed, to show how product exits the die parallel to its axis from the start of the process.



Figure 11. Extrusion tests in industrial conditions through four-hole die, view of ring-shaped pocket die, b) view of extruded bars at press run-out.

5. Indirect extrusion through 17-hole dies

In this case, the subject of analysis was indirect extrusion process of 9,5 mm diameter AlZn6MgCu (7010) alloy bars. This alloy is characterized by high strength, but also hard-deformability, that is why practically used extrusion velocity does not exceed 1,5 m/min. Based on observations of real process with the use of 17-hole flat die, it was stated that initially, middle bars exit die at higher velocity than bars located around circle edge. During the process, velocities are equalized, and later outer bars begin to exit much quicker than ones in the middle. As a result, high differentiation of inner and outer bars' exit velocity is observed at particular stages of extrusion.

In this case, numerical modelling procedure was applied for different die variants: a flat die and two pocket dies.A pocket, as it has been mentioned in chapter 2, may accelerate or decelerate metal flow into die holes in specified place. Pocket dimensions are also important. A narrow and tall pocket decelerates metal flow before die hole, whereas a wide and low one causes volume of metal entering die hole to increase. The first variant featured narrow prechambers used on outer holes in order to decelerate metal exit velocity from those holes. With such thin bars, pockets should not be too deep, as it hinders removing bars from die holes. In the second case, a wide ring-shaped pocket was used. It was 3 mm deep and was

placed on inner holes (Fig. 12). Such a pocket facilitated metal flow at entering inner holes, which was supposed to result in equalizing velocities between inner and outer bars. In this case, experiences gained when analyzing four-hole die where taken into consideration. For each analysed variant, constant billet temperature was assumed at T_b = 350°C and constant tool temperature at T_t = 340°C. Calculations were performed for extrusion velocity at 2 mm/s (exit velocity v_e = 1,2 m/min). Billet diameter was 252 mm, length - 300 mm, extrusion ratio R = 41 and friction factor on the contact surface of billet and tools m = 0,7.

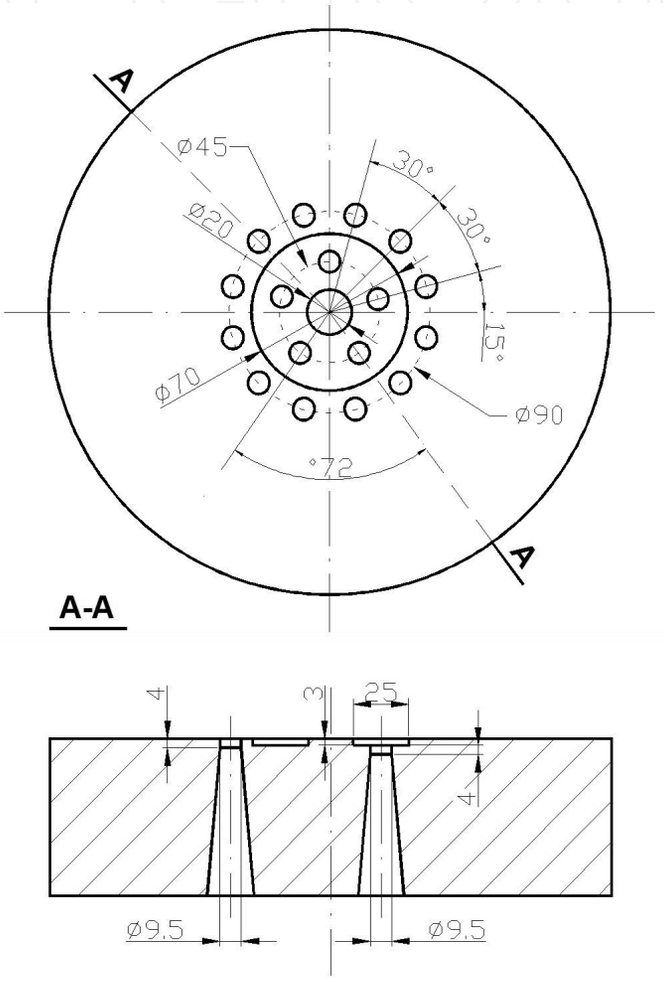


Figure 12. Schematic diagram of 17-hole die with ring-shaped pocket, dimensions in mm.

With the use of flat die, at the very beginning of the process, bars from inner holes exited slower than from the outer ones (Fig 13).

The aim of extrusion through 17-hole die with local pockets applied on outer holes was to hinder metal velocity within outer layer. However, the influence of local pockets was so strong, that in practice extrusion took place from the inner holes.A ring-shaped pocket die turned out to be a much better solution, though comparable with flat die, as upon its use, uniform metal outflow velocity was obtained from each die hole (Fig. 14).

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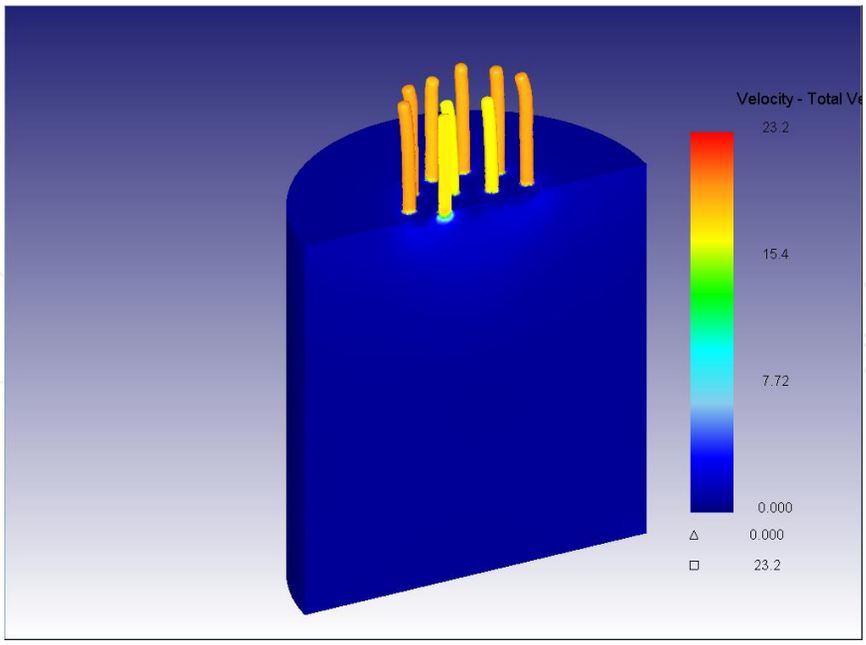


Figure 13. Distribution of metal particles exit velocity during extrusion through 17-hole flat die.

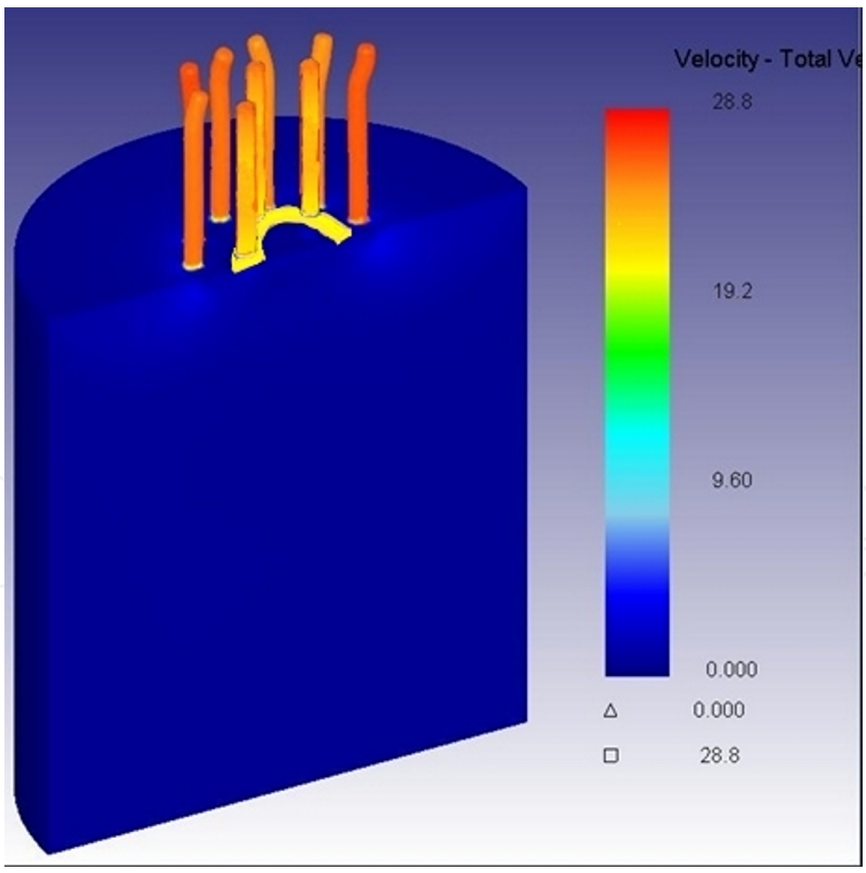


Figure 14. Distribution of metal particles' outflow velocity upon indirect extrusion through ring-shaped pocket die on outer holes.

Based on numerical calculations, two variants of 17-hole pocket die were designed. In the first variant, outer holes were equipped with pockets, whereas in the second one, a ring-shaped pocket was applied on inner holes. (Fig. 15).

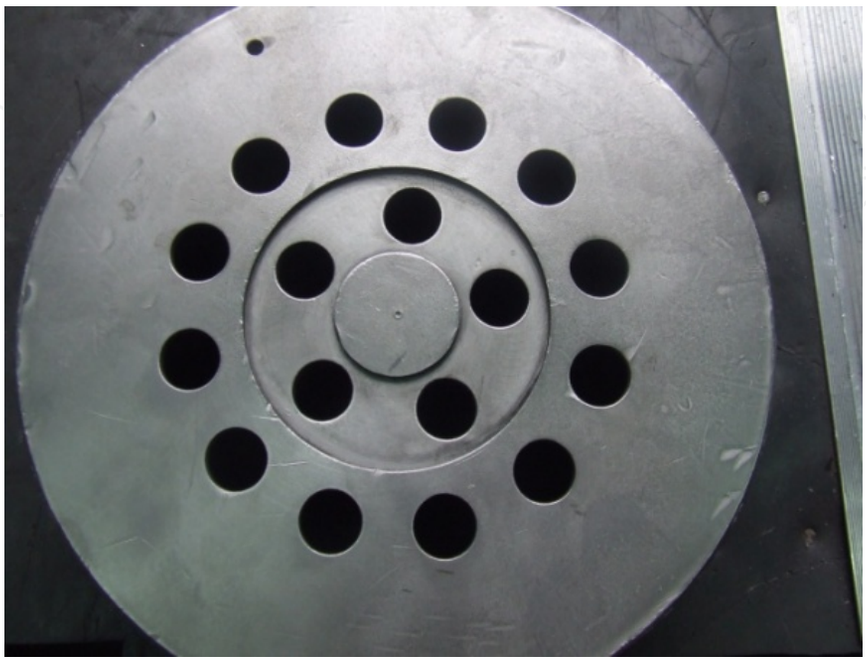


Figure 15. Schematic diagram of 17-hole die with ring-shaped pocket.

Tests were performed with following basic parameters:

- billet diameter 246 mm,
- billet length 770 mm,
- container diameter 252 mm,
- billet temperature - taper heating 350/360/370°C
- container temperature 340°C
- ram velocity v_0 = 0,5 mm/s.

The extrusion tests were performed on a 28MN capacity indirect press. Positive results were achieved with the use of 17-hole die with ring-shaped pocket encompassing all inner die holes. 7010 alloy which was used for the test is a hard-deformable material which is extruded with very low velocity. As a result, one billet extrusion time is about 20 minutes. In such conditions, temperature changes in deformation zone which result in change of metal flow mechanics during the process. This, in turn, is followed by change in velocity of metal's exiting both inner and outer holes. According to flow mechanics during extrusion, inner bars move initially faster, but soon outer bars accelerate significantly. It happens so in case of traditional flat dies. Using ring-shaped pocket on inner holes proved to be a good solution, as it caused permanent acceleration of metal exiting inner holes, which lasted until the end of the

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process. Fig. 16 presents bars extruded through 17-hole die with ring-shaped pocket, initial phase (a) and advanced state when the use of puller was possible (b). The difference in total length of bars from inner and outer holes was about 2 m, which constituted about 7% of their length. Such results are acceptable from the point of view of effectiveness (small material loss). It is important, however, that in such conditions one can safely use a puller so that no rippling occurs on press run-out (Fig. 16b).



Figure 16. Extrusion of bars through a 17-hole die with ring-shaped pocket,view of bars after exiting the die, b) guiding puller (courtesy of Grupa Kety).

In case of extrusion through a 17-hole die with local pockets placed on outer layer holes, the influence of pockets was so effective that metal exited the die practically through inner holesonly. It needs to be added that such result of the test turned out appropriate for indirect extrusion. In case of direct extrusion, when metal flow is significantly different and unfavourable, optimum die geometry solution might be different.

6. Direct extrusion of asymmetric S-type profile

Extruding asymmetric profiles is especially difficult because of complexity of metal flow which often leads to geometrical instability of the product in the form of twisting or bending, as well as its non-homogenous structure. In such case, either different lengths of die land are usually used or pocket dies. Such product is exemplified by AlMg4,5Mn (5083) alloy profile presented in Fig. 17.

This alloy belongs to hard-deformable materials extruded with low exit velocity. Extrusion of the profile presented in Fig. 17 in industrial conditions occurs on a flat die. Different lengths of die land were used there (5 and 12 mm) in order to regulate metal flow. Nevertheless, the hollow section was subjected to intense twisting upon extrusion. Torque was so strong that the product was torn from puller. Probably, the reason for such phenomenon was inappropriate metal flow velocity distribution in die hole. It was proposed to use a die with pocket of variable width. Reaction of metal in real conditions, as observed in this case,

suggests that twisting is caused by significantly non-uniform metal inflow to die holes in the whole deformation zone. Even application of a two-hole die cannot considerably alter metal reaction in deformation zone, as it is impossible to precipitate symmetric flowing.

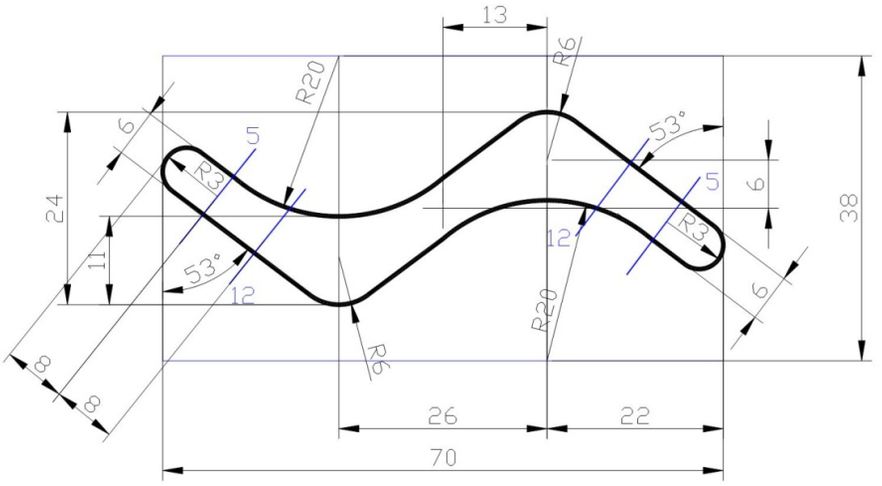


Figure 17. Asymmetric S-type AlMg4,5Mn extruded profile geometry.

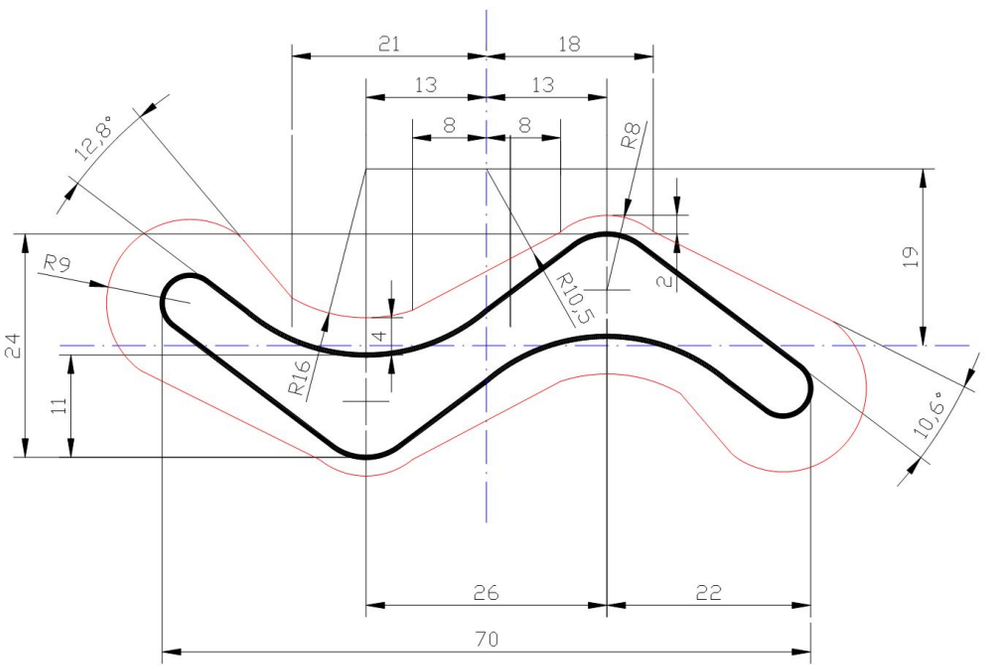


Figure 18. Design of pocket die for extruding asymmetric profiles.

Such reaction of metal may be corrected by means of applying a die with pocket of appropriate geometry. When designing the pocket die, the main parameter for choosing pocket dimensions was so called volume rates of metal flow criterion, as defined in equation (1). It

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assumes that relation between velocities of metal flowing from container and entering individual parts of pocket corresponds to relationship between surface areas of cross-sections of extruded profile's fragments. In addition, pocket shape (Fig. 18) was corrected taking into account change in profile radius. Designing a die for such sections requires considerable experience as well as constructor's intuition. In the illustration, pocket shape was marked red. Depth of pocket was 8 mm.

In the first stage of tests, numerical modelling was performed for traditional flat die and pocket die. Fig. 19 presents distribution of metal velocity in die hole for both flat die and pocket die. One can notice strong diversification of velocity in flat die hole (Fig. 19a). Velocity at central part of the profile is almost three times higher than at its ends. As it may be seen, the use of die lands of much different length is not sufficient. For apocket die, diversification of metal flow velocity is relatively low (Fig. 19b). This confirms that the application of pocket is more efficient.

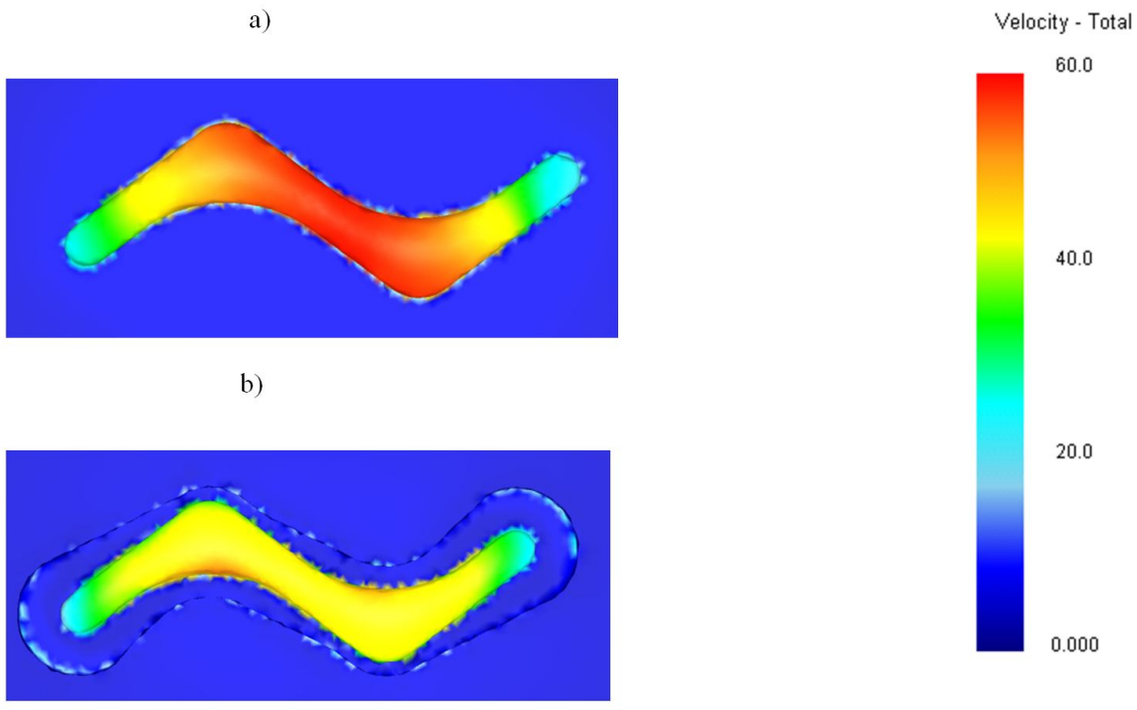


Figure 19. Distribution of metal exit velocity in the die orifice in case of, a) flat die, b) pocket die.

In order to establish how the obtained distribution of velocity influence section reaction after exiting die hole, visualization of this phenomenon was carried out in DEFORM program and was presented in Fig. 20. The images show twisting which practically occurs upon section extrusion (Fig. 20a). Pocket die makes it possible to minimize this unfavourable phenomenon, as, in this case, twisting is reduced to minimum.

In order to verify correctness of pocketdie design, profile extrusion tests were performed in industrial conditions. Tests of AlMg4,5 (5083) alloy profile extrusion were carried out on a

direct press with nominal force of 25 MN with the use of designed pocket die. Extrusion conditions were as follows:

- billet diameter - 215 mm and length - 230 mm,
- extrusion ratio R = 58,
- billet temperature 470°C,
- exit velocity 3m/min.

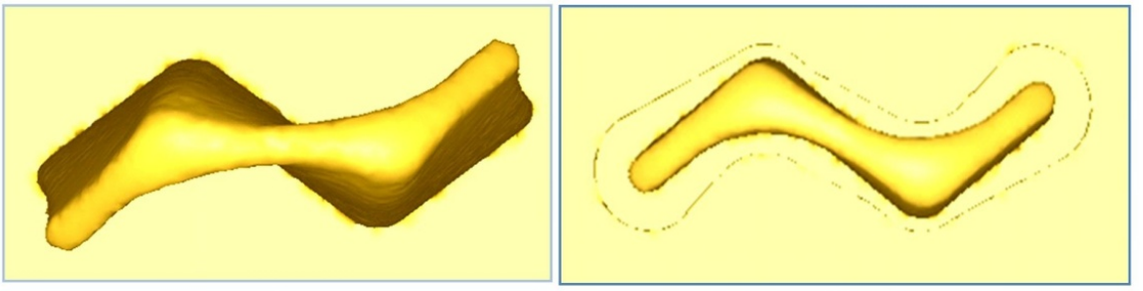


Figure 20. Visualization of twisting a profile extruded through, a) flat die and b) pocket die.



Figure 21. View of 5083 alloy profile at press run-out extruded through pocket die (Courtesy of Grupa Kety).

http://dx.doi.org/10.5772/51239

Fig. 21 presents a profile extruded through pocket die. Due to slight profile twisting, it was easily driven by puller at press run-out. Profile extruded through traditional flat die twisted several times during extrusion test. Thus, the results of industrial test confirmed the assumptions of numerical simulations.

Non-uniform metal flow velocity distribution in die hole usually results in non-uniform material structure on product's cross-section. In the case of hot extruded aluminum alloys, it is most often manifested by so called coarse grain layer. For this reason, extruded sections were subjected to metallographic tests in order to reveal their structure on cross-section. Macrostructure tests have shown differentiation of grain size on profile cross-section. More non-uniform macrostructure was present on cross-section of profiles extruded through flat die (Fig. 22a). In most part of profile, coarse grain layer covers the whole cross-section. In case of section extruded through pocket die, (Fig. 22b) coarse grain layer exists, but its thickness does not exceed 2mm. Still, this proves to be a more favorable structure than the one resulting from using flat dies, as inner cross-section is made of fine grain, which improves product strength. Such layer may be decreased by appropriate selection of extrusion conditions.

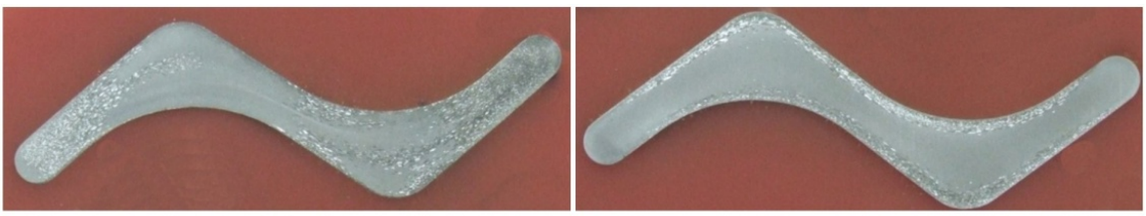


Figure 22. Macrostructure of cross-section of profile extruded through flat die (a) and pocket die (b), etched with Tucker's reagent.

7. Conclusion

The research method applied in the work was based on numerical modelling and facilitated designing multi-hole dies and pocket dies for extrusion of various aluminum alloys, especially hard-deformable alloys. Extrusion through multi-hole dies is an efficient way of improving extrusion process effectiveness. It has become key question to design multi-hole dies so that uniform metal flow velocity in each hole is guaranteed.

Analysis of three cases of extrusion helped identify variants displaying best expected conditions of real material flow. Particularly, in each analyzed case, application of pocket dies turned out to be the best solution. Upon extrusion through four-hole die, designed based on numerical simulations, the desired parallel flow of each 6082 alloy bar. It was original to use a ring-shaped pocket for 17-hole 7010 alloy extrusion. Similarly to calculations, almost identical bar flow velocity was observed from outer and inner holes, which enabled a puller to be used effectively on press run-out.

In an exceptionally difficult case, i.e. extruding asymmetric section from hard-deformable 5083 alloy, based on calculations, die variant with changeable width pocket was rightly selected. Its application helped reduce section twisting after exiting die holes. The results of the tests indicate that using pocket dies is a very good way of controlling metal flow, especially in case of asymmetric profiles. Another advantage of using such dies is that when applying them, one can avoid the difficulty of reconstruction the whole die set. Such necessity emerges when the optimum calculated hole distribution in the die would require increasing diameter of the die itself. However, this solution is possible, but quite costly and it requires recalculation of durability of individual die set elements. Die constructions designs have been validated in real conditions upon extrusion of selected profiles on an industrial press. Properly designed die also helps to avoid various defects of extruded products, related with their geometry and material structure.

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