

G. SAMOŁYK*

STUDIES ON STRESS AND STRAIN STATE IN COLD ORBITAL FORGING A AlMgSi ALLOY FLANGE PIN**BADANIA STANU NAPRĘŻENIA I ODKSZTAŁCENIA W PRASOWANIU OBWIEDNIOWYM SWORZNIĄ Z KOŁNIERZEM ZE STOPU AlMgSi**

The orbital forging is one of the metal forming processes which enables the manufacture of products through worm or cold working. A characteristic feature of this technological process is the use of a special wobbling motion of one of the tools in order to reduce the required forming force. This is particularly advantageous during the formation of products in the shape of a disc or a flange pin. Unfortunately, typical constraints of cold orbital forging are: uncontrolled buckling, loss of shape stability ("mushroom effect") and cracks. They depend on the technological parameters of the process and their cause can be explained on the basis of e.g. workpiece stress state analysis, which is a difficult task due to the complexity of orbital forging process. The article discusses the issues of stress and strain in cold orbital forged parts of the flange pin type, made of AlMgSi aluminum alloy. The results of the presented FEM simulation, verified experimentally, explain the influence of the theoretical aspects of this process on its implementation conditions. It is assumed that orbital forging is performed on the PXW-100A press and the numerical model takes into account all possible variants of the process. Debate boils down to discussing the stress and strain state (e.g. analyzing the stress and strain rate fields) occurring in the workpiece in the context of chosen technological parameters and constraints of orbital forging process.

Keywords: orbital forging, stress and strain state, aluminium alloy, FEM, experiment

Prasowanie obwiedniowe jest jedną z technologii obróbki plastycznej, która umożliwia wytwarzanie wyrobów poprzez ich kształtowanie na zimno lub ciepło. Wyroby prasowane obwiedniowo charakteryzują się stosunkowo dużą jakością powierzchni oraz małą tolerancją wymiarową. Charakterystyczną cechą tego procesu technologicznego jest zastosowanie specjalnego ruchu wahającego jednego z narzędzi w celu obniżenia wymaganej siły kształtowania. Szczególnie korzystne jest to podczas kształtowania wyrobów typu tarcza lub sworzeń z kołnierzem. Typowymi ograniczeniami prasowania obwiedniowego są niekontrolowane wyboeczenie, utrata stateczności kształtu oraz pęknięcia. Zależą one od parametrów technologicznych procesu, a ich przyczynę można wyjaśnić na podstawie np. analizy stanu naprężenia panującego w wyprasce. Z uwagi na złożony charakter prasowania obwiedniowego jest to zadanie trudne. W artykule omówiono zagadnienia stanu naprężenia i odkształcenia w prasowaniu obwiedniowym części typu sworzeń z kołnierzem, która jest wykonana ze stopu aluminium AlMgSi. Przedstawione wyniki symulacji, zweryfikowanej doświadczalnie, wyjaśniają znaczenie aspektów teoretycznych tego procesu na jego warunki realizacji. Zakłada się, że prasowanie obwiedniowe jest realizowane na prasie PXW-100A, a model numeryczny uwzględnia wszystkie możliwe warianty realizacji procesu na tej maszynie. Dyskusja sprowadza się do omówienia stanu naprężenia i odkształcenia (analizując prędkość odkształcenia) panującego w wyprasce w kontekście wybranych parametrów technologicznych i ograniczeń procesu prasowania obwiedniowego.

1. Introduction

The orbital forging is a method of cold or worm working of parts, which is based on methods patented in 1920 by Slick and in 1922 by Massey [1]. The first machine, allowing for the production of parts using this method, was manufactured in sixties of the 20th century. In the same time, Marciniak and next Barnet developed an innovative mechanism driving the upper die what allowed for the realization of the orbital forging process with using different schemes of the wobble-die movement. This solution is currently used in most special machines, e.g., such as PXW series presses (produced by the no longer

existing company PLASOMAT – according to Marciniak's design), T series presses – from the Swiss company H.SCHMiD (according to Barnet's design) and MCOF series presses – from the Japanese company MORI IRON WORKS CO. The typical patterns of upper die wobbling motion schemes have been shown in Figure 1 [1-5].

In practice, two basic variants of workpiece forging are encountered. In one of these variants a tool makes a wobbling motion. This basic form of orbital forging, handled by, e.g., PXW presses, is characterized by the fact that the upper die makes a spherical motion around a fixed point lying in contact with the shaped material (Figure 1). The lower die together

* LUBLIN UNIVERSITY OF TECHNOLOGY, 38 NADBYSTRZYCKA STR., 20-618 LUBLIN, POLAND

with the ejector moves in a straight line along the main axis of the press. In some works, the orbital forging process, in which the upper die makes an agreeable motion with the circular movement scheme, is also called a rotary forging. The second variant of workpiece shaping is rotation forming (sometimes called an orbital rolling), in which all the tools and the shaped material make a rotary motion relative to the main axis of the press and the upper die oscillation effect is obtained through its defined inclination relative to the main axis of the press [1-4].

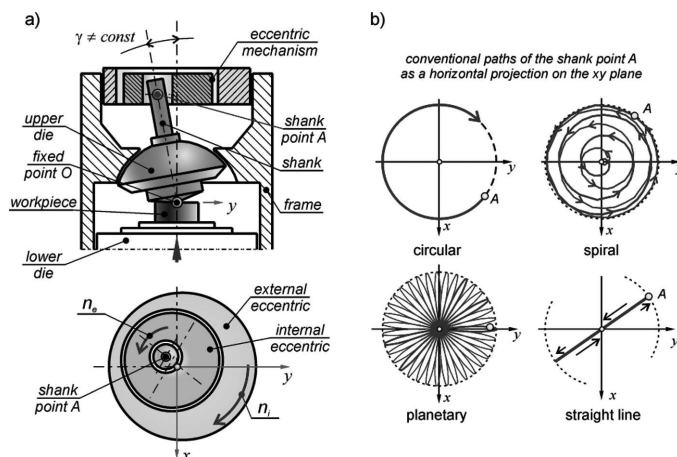


Fig. 1. The technical solution of the orbital forging machine developed by Marciniak (a) and the four typical schemes of wobbling motion of an upper die used on PXW-series presses

Many scientific papers discuss the forging process, either rotary or orbital, in which the upper die makes a simple circular movement (Figure 1). The investigations, which relate to orbital or rotary forging and based on numerical analysis, are carried out continuously for over 30 years, e.g. [2-4, 6-9, 12-18]. Detailed study of these papers indicates that this topic is relatively difficult and the theoretical and technological knowledge about the orbital forging is still incomplete. Particularly noteworthy are several works, which significantly enriched the knowledge about the orbital (or rotary) forging process. For example, Ziółkiewicz and Garczyński [5] done a general overview of the state of knowledge. Oh and Choi [6, 7] adopted the upper-bound method to analyse the stress state and calculate a forming force. Next, Canta et al. [8] described the major aspects of energy distribution in a rotary forging. Liu et al. [12] discussed e.g. the mushroom effect and Decheng et al. [13] explained the other important limitations of the process. Guangchun et al. [15] analysed cold rotary forging the ring parts using the rigid-plastic FE model. While, Han and Hou [16-18] adopted the elastic-plastic FE model to analyse a rotary forging the ring and cylindrical parts. Whereas, Rusz and Dyja [19] presented the influence of the chosen technological parameters on the orbital forging process. For several years at the Lublin University of Technology intensive research has been conducted aimed at extending the current state of theoretical knowledge about the processes and technology of orbital forging, e.g., [3, 4]. The scope of these works has been included both experimental studies using PXW-100A production press, as well as finite element method (FEM) numerical analysis [4, 10, 11]. This article presents the selected results of the research, which discuss the issues of stress and strain

in the flange pin type workpiece, orbital forged with the use of different upper die wobbling motion schemes. In there has been presented the relationship of these theoretical aspects to the major technological parameters of the cold orbital forging, too. Finally it should be noted, that the presented results of FEM calculation, which relate to different schemes of wobbling motion of the die, was obtained by the author for the first time.

2. Scope of studies

2.1. A numerical model of orbital forging process

Numerical analysis was performed using the finite element method (FEM) based on a commercial software DEFORM-3D. The geometric scheme of a model of the orbital forging process is shown in Figure 2. Tools (upper die, lower die and ejector) are modelled as rigid bodies, while the workpiece is a rigid-plastic body divided into 80 thousand tetragonal four-nodal elements. The calculation assumes that the workpiece is made of AlMgSi aluminium alloy (chemical composition provided by Tabal Co., Poland), for which the strengthening curve was assumed in the form of equation (1) determined in own research published at the previous work, e.g. [3, 21].

$$\sigma_p = 684 \cdot \phi^{0.098} \cdot \dot{\phi}^{0.134} \cdot \exp(-0.0058 \cdot T) \quad (1)$$

where σ_p is yield stress, ϕ is plastic strain; $\dot{\phi}$ is strain rate and T is temperature of workpiece.

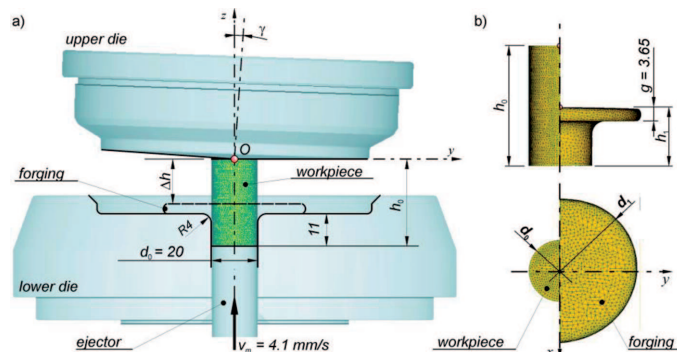


Fig. 2. Numerical model of orbital forging process of a flange pin (a) and the dimensions of workpiece and the forging, where: h_0, d_0 are initial dimensions; h_1, d_1, g are final dimensions; γ is upper die inclination angle (2°)

Friction acting on the contact surface of the material with the tools was determined on the basis of constant friction model, for which the friction factor $m = 0.45$ was adopted. Although the workpiece is cold worked (initial temperature is equal to 20°C), the calculation uses the full thermo-mechanical model for which the heat transfer coefficient between the objects is equal to $24 \cdot 10^3 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$.

The study assumes that the diameter of the initial workpiece $d_0 = 20 \text{ mm}$ and its initial height h_0 is 34 mm . Simulation of the forging process was performed assuming a constant velocity of the lower tools (lower die and ejector) of maximum value $v_m = 4.1 \text{ mm} \cdot \text{s}^{-1}$. After the workpiece reached the desired flange thickness $g = 3.65 \text{ mm}$, the lower die and ejector were stopped in order to obtain the effect of calibration of

the flange frontal area by the wobbling die. Then, after 0.6 seconds, the upper and lower dies were moved away from the workpiece with the velocity of $40 \text{ mm}\cdot\text{s}^{-1}$. This resulted in the effect of removing the part from the lower die with the use of the ejector.

2.2. Modelling the wobbling motion of the upper die

A key task of numerical modelling of the orbital forging process is the proper definition of upper die motion, which is a particular type of spherical motion around the centre O. It is needed to properly program precession, rotation and nutation of the die – ideally as a function of time. The starting point to model the die motion is the kinematics of the wobbling tool drive mechanism, in which a system of two eccentrics plays a key role. Rotational speeds of these eccentrics are known (for the PXW-100A press they are equal to 150 rpm), so analysis of the kinematics of this mechanism has allowed the author to develop a mathematical relationship between the rotational speeds of the eccentrics and angular velocities closely linked to the upper die. These velocities are shown schematically in Fig. 3. Summarizing, the essence of wobbling motion modelling is: adoption of the coordinate system $\{x, y, z, z'\}$ with the centre in point O and defining a pair of angular velocities ω around two properly chosen coordinate axes.

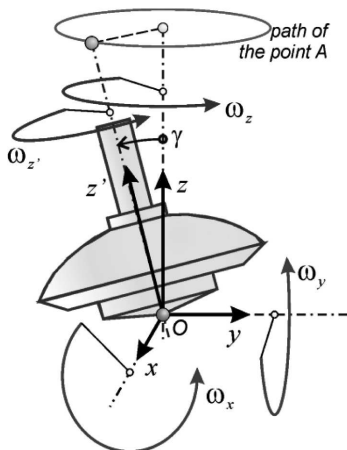


Fig. 3. Diagram used to model the upper die wobbling motion, where: O is the centre of spherical motion and coordinate system; $\{x,y,z\}$, i.e., the Cartesian coordinate system; $\{z\}$ is main axis of the press and precession; $\{z'\}$ is axis of the upper die and its rotation; γ is nutation angle; ω is modelled angular velocities

In the case of circular scheme of die motion, the tool inclination angle γ is constant, which means that the spherical component of motion, i.e., nutation is zero. Therefore, it can be assumed that the angular velocities about two axes $\{z\}$ and $\{z'\}$ (i.e. the axis of the press and the axis of symmetry of the upper die) are constant over time and are $\omega_z = 15.71 \text{ rad}\cdot\text{s}^{-1}$ and $\omega_{z'} = -15.71 \text{ rad}\cdot\text{s}^{-1}$ respectively. This way of motion modelling is well-known and universally used, e.g. in works [3, 7, 10]. The second case is the straight line scheme of the die motion. Here only nutation is nonzero – which means that it is enough to define only one angular velocity, for example ω_y , which must be expressed as a function of time. The calculation assumes that the value of this velocity varies in the range -0.6 to $0.6 \text{ rad}\cdot\text{s}^{-1}$. The tool inclination angle γ varies

in the range 0 to 2° and a full cycle of this motion coincides with one cycle of motion according to the circular scheme. In the remaining cases the spherical components of the upper die motion are nonzero. In this situation it is recommended to define the angular velocity with respect to two orthogonal axes $\{x\}$ and $\{y\}$ – it is author’s way of motion modelling. The calculation assumes that the velocities ω_x and ω_y are variable in time and their values are chosen to obtain the planetary or spiral motion schemes, both being fully correlate with the PXW-100A press. In the first case, the full cycle of upper die motion corresponds to 19 cycles of circular motion of the tool; in the second case – to 6 cycles. In order to automate the creation of the upper die motion model, an authorial computer program was developed. Also other way of wobble-die motion modelling which requires applying as many as three orthogonal angular velocities is well-known. It was developed by Maximov et al. [20].

2.3. Experimental verification of numerical model

Experimental verification was performed in conditions provided by the Laboratory of Metal Forming of Lublin University of Technology, using with a special PXW-100A press. In order to measure the force, a measuring system consisting of, e.g. pressure transducer PT-5261H/32MPa (Spais Co., Poland) with accuracy class 0.6 was used. The transmitter was connected to the hydraulic power system of the press, while a computer system supporting the transducer provided the results of the measurements in the form of shaping force versus time function.

Exemplary comparison of the measured shaping forces F of the workpiece with the force calculated with the use of FEM for the circular and planetary motion schemes are given in Fig. 4 and Fig. 5, respectively. The conditions of orbital forging test in both the FEM analysis and the experiment was been the same. In summary, verification of the numerical model confirmed the high correlation with the real process, both quantitative and qualitative. This allows concluding that the theoretical results concerning the stress and strain state acting in the workpiece obtained from FEM simulation are correct, sufficiently.

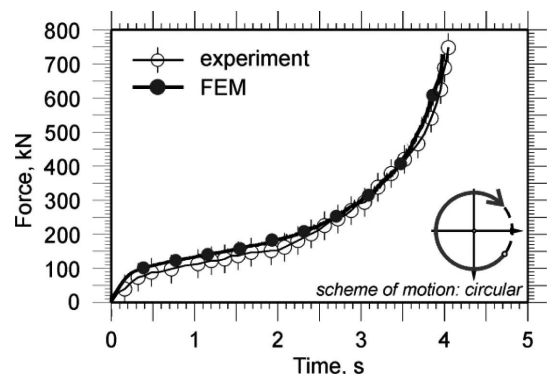


Fig. 4. Comparison of the workpiece shaping forces measured in the experiment and calculated in FEM simulation when the upper die moves according to the circular motion scheme

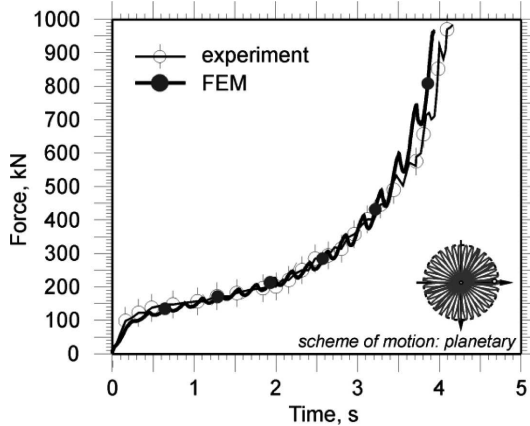


Fig. 5. Comparison of the workpiece shaping forces measured in the experiment and calculated in FEM simulation when the upper die moves according to the planetary motion scheme

3. Selected results and discussion

3.1. The circular and spiral scheme of an upper die motion

Figure 6 shows schematically the top surface of the workpiece, on which the contact area with the upper die was marked. This area is divided into three distinctive zones. Area (1) is the “input” to the deformation zone, where the normal stresses reach maximum values. Another area of contact, designated as (2) represents the “intermediate” zone, while the area (3) is the “output” from the deformation zone. Based on the presented division of the die-workpiece contact surface, three cross sections of the workpiece were chosen: A-A, B-B and C-C, for which the stress conditions and strain rates in the material in a set forging phase were determined. Generally, at this stage, which is about 56% of orbital forging progress, possible defects in the workpiece can begin to develop, e.g. as a result of the shape stability loss (so-called “mushroom effect”) or due to workpiece buckling. Figures 7 to 9 show a typical stress distribution and strain rate for the forging process when the upper die operates according to the circular scheme of die motion.

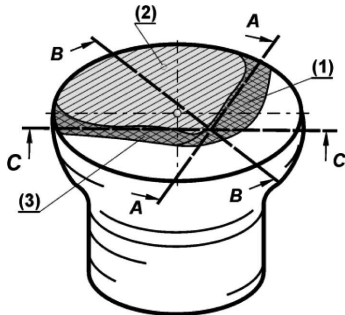


Fig. 6. The top surface of the workpiece with three zones of the upper die-workpiece contact area marked and orientation of the three cross sections; it is showed for typical stage (i.e. progress is 56%) of orbital forging process when is applied the circular or spiral scheme of motion

In each cross section of the workpiece there is a certain central area of the material in which there is a state of

isotropic compression. The remaining areas of the material, usually found close to the surface, are characterized by a different, sometimes highly unfavourable stress state. Generally, the stress state in orbital forging is heterogeneous and very complex. Wobbling motion of the tool makes the individual stress (and also strain) states in the zones change cyclically. At the same time, it is concluded that the direct impact of the upper die on the workpiece promotes dominance of compressive stress.

As it can see in Figures 7a, 8a, 9a, close to the top and lateral free surfaces of the workpiece, where there is no direct impact of the upper die, isotropic tensile stress prevails (5). In the vicinity of this area, just close to the lateral surface of the workpiece, there is a stress state in which the axial stress σ_z is compressive, while the tangential stresses σ_θ and/or radial σ_r are tensile – zone (4) or zone (2). Between the zones (2), (4), (5) and area (1) there is a transitional region (3), in which only the tangential stress σ_θ is tensile. Thus, reducing the contact surface of the upper die with the workpiece causes that in the material some zones appear in which there is no direct impact of the die. As a result, at least one normal stress is tensile. This stress state is considered negative, as it could increase the probability of cracks developing [4, 10, 11, 21].

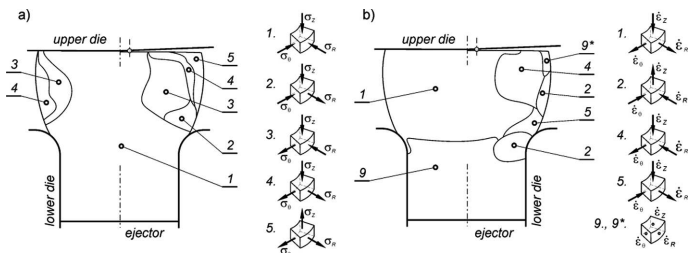


Fig. 7. Stress (a) and strain rate (b) fields in cross section A-A – according to Figure 6

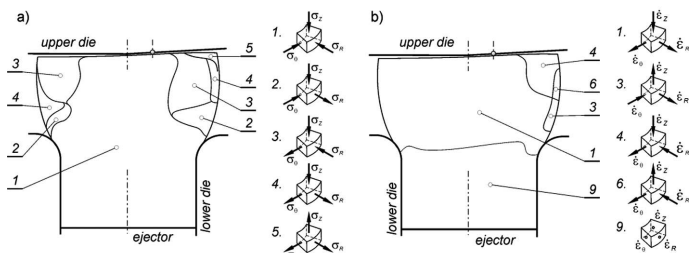


Fig. 8. Stress (a) and strain rate (b) fields in cross section B-B – according to Figure 6

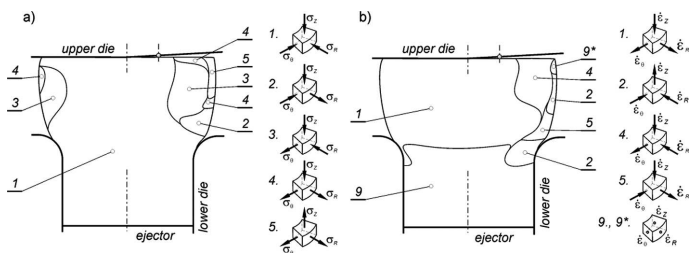


Fig. 9. Stress (a) and strain rate (b) fields in cross section C-C – according to Figure 6

Based on the strain rate distribution (Figure 7b, 8b, 9b) it can be stated that the centre of the workpiece (9) located in the lower die does not experience plastic deformation. The upper part of the workpiece (1), which is located directly between the upper die and the lower tools, is characterized by the greatest intensity of material flow. In the axial direction the material is compressed, while in the other two directions it is stretched. The remaining area of the material, located near the lateral surface of the workpiece, has a very complex material flow. In cross section A-A (Figure 7b) and B-B (Figure 8b), surrounded by top and lateral workpiece surfaces, there is a extra rigid zone (9*). Using the sign “*” is aimed at emphasizing that it is a particularly significant zone on account of rising defects in the workpiece. It should turn the comment to the material zone (4), which directly adjacent to the top free surface of the flash separates zones (1) and (9*) and partly zone (2). This zone is characterized by the fact that the only direction in which the strain is tensile is the tangential one and intensifying an influence of zone (9*) on arising, e.g., cracks in a flange of the workpiece.

Analysing the strain rate in cross section C-C (Figure 9b) allows concluding that there is no additional rigid zone in the workpiece (9*). Surrounded by the lateral free surface the material is stretched in the axial direction, while in one of the remaining directions (radial or tangential) the strain is compressive. In summary, these areas of the workpiece, which are most intensely deformed, are characterized by a favourable stress state (Fig. 10). The metal flow scheme is such that the axial cross section of the workpiece is increased at the expense of reducing its height. The remaining volume of the material, which is located close to the free surface of the workpiece and at the same time is not directly affected by the upper die, is characterized by complex, not very favourable stress and strain states. Due to the low intensity of stress and strain rate, local dimension changes of the workpiece are unnoticeable. However, in extreme cases this can lead to a cyclical “bending” of the workpiece fragment, resulting in a “mushroom effect” fault.

It was noticed that in the material zone, contained between the upper die-workpiece contact surface and the lower die, there is increased stress and strain intensity (Fig. 10). The most strained zone is located between the lateral free surface of the workpiece and its main axis. This stress distribution is determined only by the local upsetting of the material, which is located between the upper die surface and lower die. By analysing the mean stress distribution σ_m (Figure 10a) present in the workpiece it can be concluded that in the free surface surrounding the stress state is unfavourable. The value of σ_m in this zone is positive and stress intensity reaches a significant value. Thus, the material flow occurs only in the flange part of the workpiece between the upper die-workpiece contact surface and the lower die, while the maximum strain rate values are located at some distance from the lateral free surface of the workpiece (Fig. 10b). Additionally, in Fig. 11 a distribution of the strain effective which was get in the final stage of orbital forging has been shown (about 84.5% of the progression of this process). On its base it is possible to state that the greatest degree of deforming material is in a central zone of the flange. There is also noticed that the edge of the flange deformed in the very little degree. Considering research results described

at the previous work [4], this zone of flange covers with the space, in which the first cracks of material occur.

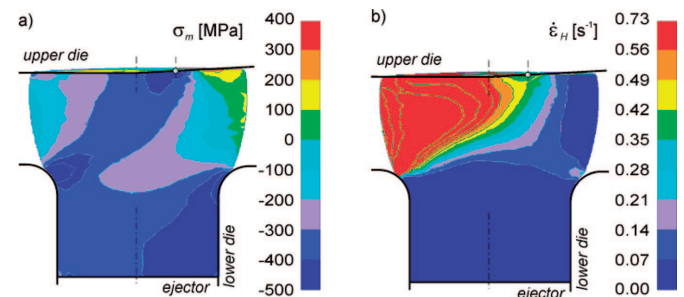


Fig. 10. Mean stress (a) and effective strain rate (b) distribution in cross section B-B – according to Figure 6

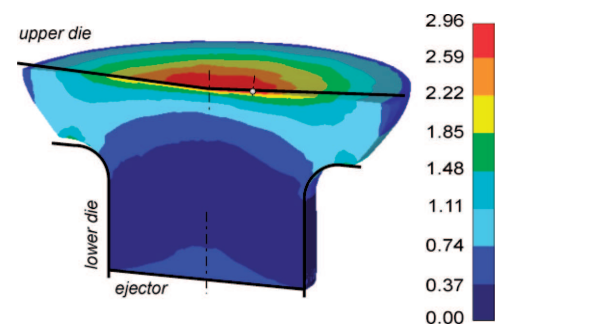


Fig. 11. Effective strain distribution in cross section of workpiece when the progress of orbital forging process is 84.5%

In the case of orbital forging, when the upper die moves according to the spiral motion scheme, for most of the process the stress-strain scheme is the same as for forging applying the circular motion of upper die. When the upper die inclination angle $\gamma = 0.5$ to 2.0° , the workpiece shaping process boils down to the traditional orbital forging (i.e. circular motion scheme). Since the value of the angle γ varies with time, the area of contact of the upper die with the workpiece changes. As a result, the size of the different stress-strain state zones changes. When the angle $\gamma = 2.0^\circ$, the upper die-workpiece contact surface is the smallest and ranges from 46 to 68% in relation to the total top surface of the workpiece – this value is highly dependent on the lower die velocity. However, when $\gamma = 0$ to 0.5° , the upper die is in contact with the whole frontal area of the workpiece, while the scheme of stress-strain states is the same as during traditional upset forging of a cylindrical part.

3.2. The planetary and straight line scheme of an upper die motion

Figure 12 shows schematically the top surface of the workpiece, on which the orientation of the cross section was marked. In a set phase of orbital forging the stress and strain distributions were determined for this cross section. This figure covers the case where the upper die moves according to the planetary motion scheme. Due to the nature of this die movement, which can be regarded as a particular type of straight line motion scheme, the distributions of parameters studied in two specific moments of orbital forging are analysed – when the upper die inclination angle increases and reaches

its maximum (Fig. 12a) and when this angle decreases and its instantaneous value is $\gamma = 1.6^\circ$. These are two extreme cases for which the upper die-workpiece contact surface is respectively the largest (ca. 90%) and lowest (ca. 64%) than the whole volume of the material.

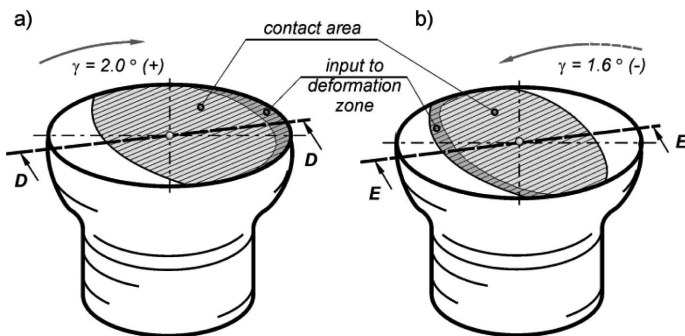


Fig. 12. The top surface of the workpiece with the upper die-workpiece contact area marked and the cross section orientation; it is shown for typical stages of orbital forging process when is applied the planetary or straight line scheme of motion: a) progress is 56.4% and current angle $\gamma = 2.0^\circ$, b) progress is 61.3% and current angle $\gamma = 1.6^\circ$; (+) means the angle γ is in increasing phase, (-) means the angle γ is in decreasing phase

The following Figs 13 and 14 show a typical stress and strain rate distribution for the orbital forging process in the conditions on the PXW press, when the planetary motion scheme has been applied. When the upper die-workpiece contact area is the largest, the vast majority of the workpiece cross section D-D (Fig. 13a) area is characterized by a favourable, isotropic compressive stress state (1). At the free surface of the workpiece there are zones of the material in which at least one normal stress is tensile. In the right part of the cross section, i.e. the side where the upper die directly affects the material, there is a zone (3) in which only the tangential stress σ_θ is tensile. But on the opposite side of the workpiece axis, where the upper die is not in contact with the top surface of the material, the zone (3) is surrounded by three different material zones, which are adjacent to the free surface of the workpiece. On the border between the top and lateral surface (5) there is the most unfavourable, isotropic tensile stress state. The calculation results showed that with increasing lower die velocity v_m the zone narrows – this is caused mainly by the increase of upper die-workpiece contact area.

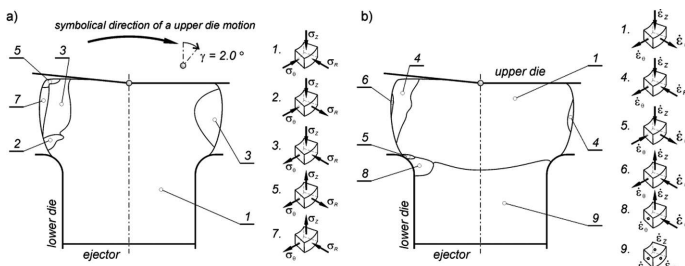


Fig. 13. Stress (a) and strain rate (b) fields in cross section D-D – according to Figure 12a

Analysis of the strain rate (Figure 13b) determined in cross section D-D allows distinguishing four main zones of the material. The workpiece centre (9) does not experience plastic deformation. However, the central part of the forged

flange (1) is characterized by such a strain state in which compressive strain occurs in the axial direction, while in the remaining two directions the strain is tensile. Thus, such a state of deformation causes an increase of the axial cross section at the expense of reducing the flange height. However, the change of flange dimensions is uneven, because close to the free surfaces of the workpiece some specific material zones exist in which the strain negatively affects the forging process stability. On the right side of the workpiece axis, where the upper die affects the material directly, there is a zone (4) where the radial strain is compressive – it causes local inhibition of uniform diameter increase during the process. On the other side of the workpiece axis the material zone is much larger. In addition, there are zones in which the strain is unfavourable at least in one direction. In zone (6) the material is additionally stretched in axial direction and in zone (5) there occurs excess material flow in a radial direction. This happens because in the remaining two directions the strain is compressive. If the lower die velocity v_m is too small, the relative intensity of material flow in the zone (5) is so large that it results in local flange diameter increase right by the lower die. As a result a cold shut may appear – avoiding it is possible if the lower die rounding radius surrounding this zone is sufficiently large. Furthermore, it was observed that at the border of zones (1) and (9) in the vicinity of zone (5) there is a small material zone (8) which is characterized by a flat deformation state. Unlike the adjacent zone (5), radial strain is compressive and in axial direction the strain is tensile.

Let us now examine the stress-strain distribution determined in the workpiece (cross section E-E) when the upper die-workpiece contact area is the smallest (Fig. 14). In this case, the vast majority of workpiece cross-sectional area is still characterized by a favourable, isotropic compressive stress state (1). At the free surface of the workpiece there are material zones in which at least one normal stress is tensile. An increase in the lower die velocity v_m results in reducing the unfavourable stress state area. The relatively small upper die-workpiece contact area makes the stress-strain state more complex.

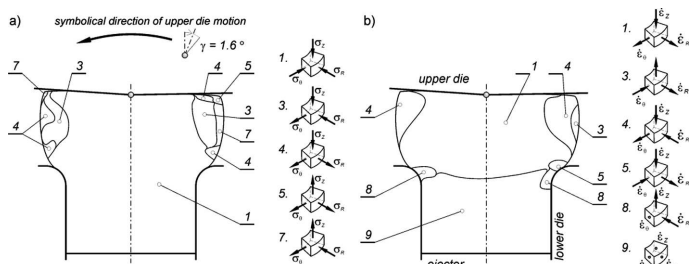


Fig. 14. Stress (a) and strain rate (b) fields in cross section E-E – according to Figure 12b

At relatively low lower die velocities the stress state scheme in the characteristic plane usually has a symmetrical distribution in relation to the workpiece axis. Increasing this velocity contributes to a more favourable stress distribution, especially occurring in the left part of the cross section E-E (Fig. 14a). Zone (3) borders with a small zone (4), which is located only at the free surface of the workpiece. The unfavourable zone (7) can be considered as negligibly small.

Analysis of the strain rate which occurs in the cross section E-E (Fig. 14b) allows distinguishing two dominant material zones. These are: rigid zone (9) and plastic zone (1), in which the material flow manner is considered to be proper – that is, the axial cross section of the flange increases at the expense of reducing its height. Between these zones, as a result of the lower die impact on the shaped part of the workpiece, a small transitional zone (8) appears, which is characterized by a flat strain state – in the tangential direction the material does not undergo deformation.

In addition, the plasticized zone (1) is limited by zone (4), which on the left side of the cross section is directly adjacent to the free surface of the workpiece. In this zone, the material is stretched only in the tangential direction and in the other directions the strain is compressive. The occurrence of this scheme of material deformation at the free surface of the workpiece is determined by the direct impact of the upper die on the forged material. However, on the other side of the analysed cross section of the workpiece (Fig. 14b), zone (4) turns into zone (3), which is directly adjacent to the lateral free surface of the workpiece. In this zone there is the least favourable scheme of material flow. The reason for this is the transition of the material from this zone to the relief phase. There appear zones in which the axial strain is tensile and there even appears a small dead zone. In the material zone (3) cracks usually begin to develop.

4. Summary

The article discussed the issue of stress-strain state which occurs in the flange pin type of workpiece during the orbital forging process using the PXW-100A press, when the different schemes of wobble-die motion have been used. The results of study have been presented for a typical stage of an orbital forging process. That is to say this stage is dominant during shaping a workpiece and determines the behaviour of workpiece material. Therefore, based on the presented results obtained by the author, the following major conclusions were formulated:

- in the process of orbital forging according to the circular and spiral schemes of upper die motion, the general deformation patterns of the material are very similar, moreover the flange is formed through a uniform increase of the axial cross section at the expense of reducing its height;
- the patterns of workpiece deformation during the orbital forging, when the planetary and rocking schemes has been used, are similar and its flange is formed as a result of cyclic radial flow of the material;
- the orbital forging with the incremental angle γ greater than 2.0° is not recommended, because it increases the dominance the material zones of unfavourable stress-strain state;
- while decreasing incremental angle γ value below 0.5° will reduce the orbital forging process to the traditional upset forging process, but than the pattern of stress-strain state is the most favourable.

REFERENCES

- [1] R. Shivpuri, *J. Mater. Shaping Technol.* **6**, 55 (1988).
- [2] J. Nowak, L. Madej, S. Ziólkiewicz, A. Plewiński, F. Grosman, M. Pietrzyk, *Int J Mater Form Suppl* **1**, 387 (2008).
- [3] G. Samołyk, *Steel Res Int* **83**, 175 (2012).
- [4] G. Samołyk, J. Tomczak, J. Bartnicki, *Arch Metall Mater* **57**, 205 (2012).
- [5] S. Ziólkiewicz, Z. Garczyński, *Obróbka Plastyczna Metali* **19**(3), 55 (2008).
- [6] H.K. Oh, S. Choi, *J Mater Process Tech* **66**, 101 (1997).
- [7] S. Choi, K.H. Na, J.H. Kim, *J Mater Process Tech* **67**, 78 (1997).
- [8] T. Canta, D. Frunza, D. Sabadus, *J Mater Process Tech* **80-81**, 195 (1998).
- [9] J.J. Sheu, C.H. Yu, *J Mater Process Tech* **201**, 9 (2008).
- [10] J. Bartnicki, *Arch Metall Mater* **57**, 1137 (2012).
- [11] A. Gontarz, Z. Pater, K. Drozdowski, *Arch Metall Mater* **57**, 1239 (2012).
- [12] G. Liu, S.J. Yuan, Z.R. Wang, D.C. Zhou, *J Mater Process Tech* **151**, 178 (2004).
- [13] Z. Decheng, Y. Shijian, Z.R. Wang, *J Mater Process Tech* **32**, 471 (1992).
- [14] Z.G. Yu, Q. Ma, Z.G. Lin, *J. Shanghai Jiaotong Univ.* **13**, 721 (2008).
- [15] W. Guangchun, G. Jing, Z. Guoqun, *J Mater Process Tech* **169**, 108 (2005).
- [16] X. Han, L. Hua, *Materials and Design* **30**, 2802 (2009).
- [17] X. Han, L. Hua, *J Mater Process Tech* **209**, 5353 (2009).
- [18] X. Han, L. Hua, *Tribol Int* **44**, 1742 (2011).
- [19] S. Rusz, H. Dyja, *J Mater Process Tech* **157-158**, 604 (2004).
- [20] J.T. Maximov, T.V. Kuzmanov, A.P. Anchev, M.D. Ichkova, *J Mater Process Tech* **171**, 459 (2006).
- [21] Z. Pater, J. Tomczak, *Arch Metall Mater* **57**, 919 (2012).