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Stress state of workpieces during upsetting with additional shear

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A B S T R A C T

The article presents an analysis of the stress state of workpieces during upsetting of workpieces with an additional shear. For the analysis, the slip line method and the finite element method were used. A schematic diagram of upsetting in dies with “floating” elements, contributing to the implementation of additional shear, reduction of barreling, inhomogenous deformation and contour tensile stresses, is presented. The analysis of the research results showed that during upsetting of workpieces with additional shift forces, tensile stresses on the side surface of the workpieces decrease, which excludes the appearance of cracks on the side surface of the samples, especially when processing low-plastic alloy steels and alloys, and also reduces the barreling of the side surface.

1. Introduction

As it is known the upsetting of workpieces (with coefficient of friction μ > 0) between the upper and lower flat die (Lange et al. 1985; Tschätsch, 2006; Hosford & Caddell, 2011) is accompanied by extremely inhomogenous (non-uniform) deformation over the entire body volume as shown in Fig. 1 (Kajtoch, 2007).

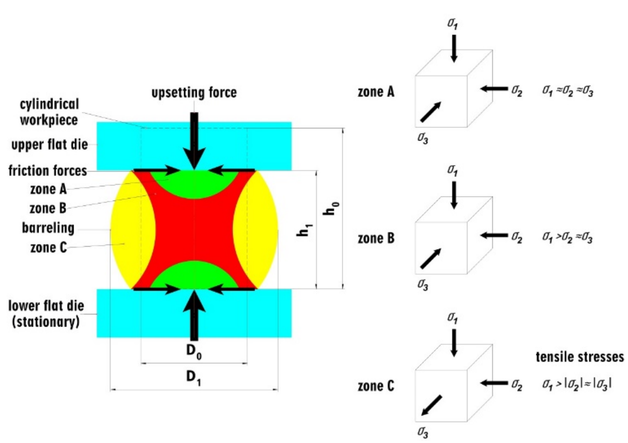

Fig. 1. Inhomogeneity of deformation and stress state scheme in an upsetting with friction: h_0 and D_0 – height and diameter of the workpiece before upsetting; h_1 and D_1 – height and diameter of the workpiece after upsetting; σ_1, σ_2 and σ_3 – main tensile stresses

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Fig. 1 shows that, in the general case, during the upsetting of a cylindrical body, three zones with different deformability can be distinguished: zone A - a zone where the difference between the stresses is insignificant and may not correspond to the plasticity condition, although the stresses themselves are large; zone B - a zone of intense deformation, where the most optimal compressive stresses act; zone C - a zone where the restraining effect of friction forces is the same as in zone B, but the stress state pattern is different (there is tensile stress), which reduces the plastic properties and worsens the deformability of the upset workpiece.

In this case, one of the main problems in the upsetting of workpieces between flat dies is the barreling of the lateral outer surface due to the presence of contact friction between the surfaces of the deforming strikers and the upsetting workpiece, which in turn leads to the appearance of dangerous contour tensile stresses. Tensile stresses at certain values can exceed the values of the material's yield point and lead to cracks on the lateral surface or destruction of materials in the direction of maximum tangential stresses (Komori, 2020). Also, an important factor is that during traditional upsetting of workpieces between flat dies, intense shear deformations, which make it possible to work out the metal structure more intensively and, as a result, to obtain the highest quality defect-free workpieces (Naizabekov et al. 1999; Najzabekov et al. 2004) are either absent or existing tools with flat working surfaces, realizing severe shear deformations, have a complex design and are difficult to manufacture and install. Therefore, it is of great interest to develop new methods of upsetting, one of which is upsetting with additional shear elements (Fig. 2).

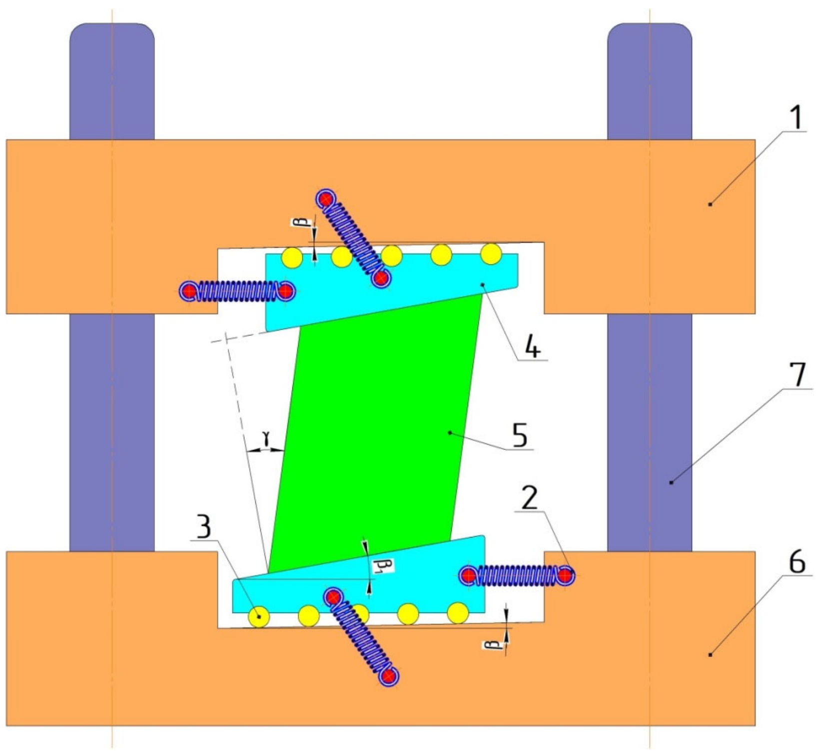

Fig. 2. Upsetting scheme in dies with "floating" elements: 1 – upper die; 2 – tightening springs; 3 – rollers; 4 - "floating" cone elements; 5 – workpiece; 6 – lower die, 7 – shafts

To align the upsetting and shearing of the workpiece (Doltsinis, 2001; Hosford, 2013; Chung & Lee, 2018; Dixit & Dixit, 2014), the dies are equipped with additional shear tapered or "floating" elements mounted on rollers 3, i.e. "Floating elements" 4. To prevent the “floating elements” from getting stuck and to successfully implement shear deformations, the dies are provided with slopes β и β_1. With small compressions, the inserts will slide relative to the fixed dies 1 and 6. To return the dies to their original position, tightening springs 2 are provided. To align the workpieces, it must be tilted 180°, and moved with upsetting in the opposite direction. In this case, the workpiece receives alternating strain (Wood & Davies, 1953; Zehetbauer & Valiev, 2004; Valiev et al. 2014; Bogatov & Nukhov, 2015), which has a positive effect on the quality of the processed workpieces.

In previous studies by Najzabekov et al. (2004), the kinematics of movement of the components of the forging dies, which provide settlement of the blanks with additional shear forces, are described in detail. The geometric relationship between horizontal and vertical movements of the elements of the component parts of the dies has been established. In addition, the influence of the spring stiffness of the dies on the displacement ratio is shown. The peculiarity of the known proposed design of forging dies is that by combining the upsetting with shear, the contour tensile stresses and barreling are reduced. However, how much these most dangerous tensile stresses are reduced is not given in this work. In addition, in the known forging dies, additional shear occurs due to the action of the maximum value of contact friction, which significantly distorts the shape of the workpiece.

Therefore, this work presents the results of the stress state during upsetting workpieces with additional shear, not only due to contact friction, but also due to the taper of the forging dies. For this purpose, a grid of slip lines (s.l.) was built during the upsetting of blanks with additional shear forces and the corresponding velocity field.

2. Study of the stress state

2.1 Study of the stress state by the slip line method

The slip line method, which is one of the classical methods in the theory of plastic deformation of materials and the basis of which was developed in the early 20s of the 20th century (Prandtl, 1920; Hencky, 1923), is used to determine the stress state from the volume of a deformed body at plane and axisymmetric deformation. The slip line and velocity field is constructed using the basic properties of the slip line method (Johnson et al., 1982; Hill, 1998; Yu et al., 2006; Bhaduri, 2006; Rees, 2006; Hosford & Caddell, 2011; Hosford, 2013; Abishkenov et al., 2020; Ashkeyev et al., 2021; Ashkeyev & Abishkenov, 2021)

The construction of the slip line mesh for the considered upsetting with shear process begins with determining the s.l. exit angles out onto the contact surface and the slope of s.l. to the main x and y-axes. S.l. exit angle on the contact surface, depending on the magnitude of the shear stresses τ_k on the contact surface, can be expressed from the following ratio:

$$\tau_k = \frac{\cos 2\varphi}{2}\sigma_n \tag{1}$$

where the ratio (cos2φ)/2 expresses the value of the contact friction coefficien μ on the contact surface, i.e. μ=(cos2φ)/2; φ – is the outlet angle of HP on the contact surface, which can be determined through the value of μ and vice versa; σ_n – normal stress on the contact surface, which is equal to the yield strength of the processed material.

For the case under consideration, the average value of the contact friction coefficient is taken, i.e. within μ≈0.25÷0.20, because the shift is mainly carried out due to the action of the taper of the forging die inserts. Then, from relation (1), the angle of exit of the s.l. on the contact surface will be φ=30°. From geometric considerations, it is easy to see that the tilt angle of the s.l. to the y-axis at the nodal point 1.2 is 45 °, i.e. $\theta_{1.2}$=45°. The tilt angles at the remaining nodal points are determined by taking the step of changing the s.l. equal to Δθ=10°. Hence, the values of the angles of inclination of the s.l. at the adjacent nodal points of the s.l. will be:

- at the nodal point 0.1: $\theta_{0.1} = \theta_{1.2} + \Delta\theta = 55°$,
- at the nodal point 1.1: $\theta_{1.1} = \theta_{1.2} - \Delta\theta = 35°$,
- at the central, axial nodal point 0.0: $\theta_{0.1} = [\theta_{1.1} + \theta_{0.1}]/2 = [35°+ 55°]/2 = 45°$.

The intersection of the s.l. of the main x, y-axes at an angle of 45° indicates the correctness of the mesh of the slip line (Fig. 3, a), since the maximum shear stresses intersect with the main stresses at an angle of 45 °. In addition, the correctness is confirmed by the kinematic potential field of velocities (Fig. 3, b), where from the condition of incompressibility it is possible to write:

$$\upsilon_0 \cdot D_0 = \upsilon_1 \cdot h_1 \ \text{ or } [\upsilon_0/\upsilon_1] = [h_1/D_0] \approx 1{,}45 \tag{2}$$

where υ_0 – the velocities of the workpiece points along the x-axis, υ_1 – the velocities of the workpiece points along the y-axis, D_0 – the workpiece diameter, h_1 – the workpiece height at the considered upsetting moment.

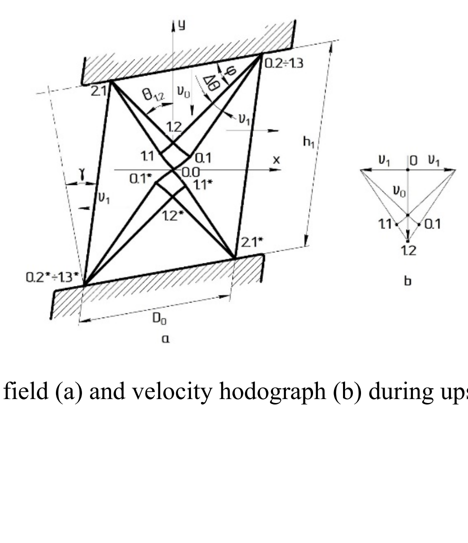

Fig. 3. Slip line field (a) and velocity hodograph (b) during upsetting with shear

Further, the stress state at the axial nodal point 0.0 is determined from the constructed field of slip lines. From the condition of equilibrium of forces applied to the plastic region on the right, taking into account the signs relative to the y-axis, we can write the following:

$$\int_{0,0}^{0,1} \sigma dy + kx_{0,2} + \sigma_{0,1}\left(y_{0,2} - y_{0,1}\right) + \int_{0,1^*}^{0,0} \sigma^* dy + \sigma_{0,1^*}\left(y_{0,1^*} - y_{0,2^*}\right) + kx_{0,2^*}) = 0 \tag{3}$$

where $y_{0.1}$, $y_{1.1}$, $y_{0.2}$, $y_{0.2*}$, $x_{0.2}$, $x_{0.2*}$ – the coordinates of the nodal points along the y and x axes at the corresponding nodal points indicated in the indices; σ – average normal stress along slip lines 0.0–0.1; $\sigma_{0.1}$ – average normal stress at the nodal point 0.1; σ^* – average normal stress along sliding lines 0.0–0.1*; $\sigma_{0.1*}$ – average normal stress at the nodal point 0.1*; k – is the shear stress of the material or the plastic constant.

Using Hencky equations (Hill, 1998; Yu et al. 2006; Rees, 2006; Dixit & Dixit, 2014):

$$\begin{Bmatrix} \sigma = \sigma_{0,0} - 2k\left(\theta - \frac{\pi}{4}\right) \\ \sigma_{0,1} = \sigma_{0,0} - 2k\left(\theta_{0,1} - \frac{\pi}{4}\right) \\ \sigma^* = \sigma_{0,0} + 2k\left(\theta^* - \frac{\pi}{4}\right) \\ \sigma_{0,1^*} = \sigma_{0,0} + 2k\left(\theta_{0,1^*} - \frac{\pi}{4}\right) \end{Bmatrix} \tag{4}$$

Substituting relations (4) into Eq. (3) and solving for $\sigma_{0.0}$:

$$\frac{\sigma_{0,0}}{2k} = \frac{\theta y_{0,1} + \theta_{0,1}\left(y_{0,2} - y_{0,1}\right) - \frac{\pi}{4}\left(y_{0,2} + y_{0,2^*}\right) + \theta^* y_{0,1^*} - \theta_{0,1^*}\left(y_{0,1^*} - y_{0,2^*}\right) - 0{,}5\left(x_{0,2} + x_{0,2^*}\right)}{y_{0,2} - y_{0,2^*}},$$

After substituting the corresponding values into the resulting equation directly from Fig. 3, and the average voltage at the nodal point 0.0 will be:

$$\frac{\sigma_{0,0}}{2k} = -1{,}10,$$

Hence, with $\sigma_{0.0} = -2k \cdot 1{,}10$ the stress components at the nodal point 0.0 can be determined using the following formulas:

$$\sigma_{x_{0.0}} = \sigma_{0,0} + k \sin 2 \cdot \theta_{0,0} = -2k(1{,}135 - 0{,}5) = -2k \cdot 0{,}60 \tag{5a}$$

$$\sigma_{y_{0.0}} = \sigma_{0,0} - k \sin 2 \cdot \theta_{0,0} = -2k(1{,}135 + 0{,}5) = -2k \cdot 1{,}60 \tag{5b}$$

$$\tau_{xy} = -k \cos 2 \cdot \theta_{0,0} = 0, \tag{5c}$$

2.2 Study of the stress state by the finite element method

The finite element method (FEM) is one of the most effective methods for solving technological problems of metal forming, which is based on solving boundary value problems of mathematical physics (Kobayashi et al., 1989; Rachakonda, & Dwivedi, 1991; Valberg, 2010; Fu, 2017). The mathematical basis for solving FEM problems is the mechanics of deformation of a body divided into parallelepipeds with their further division into tetrahedrons with nodes at their vertices. In plane problems, the area is divided into quadrangular or triangular two-dimensional elements.

When choosing a specific software package for FEM analysis, it is necessary to take into account the effectiveness of the mathematical calculation procedure, as well as the ability of the program to provide an adequate level of control over the calculation and verification (test) tests. One of the software packages that meets these requirements is the DEFORM software package for FEM analysis, which is the world leader in this area. The DEFORM software package allows solving the problems of deformation, heat transfer, heating and heat treatment of various materials by the finite element method.

For the FEM analysis of the upsetting process, 5140 steel with the corresponding rheological properties was taken as the material of the deformable workpiece. The analysis results are shown in Fig. 4.

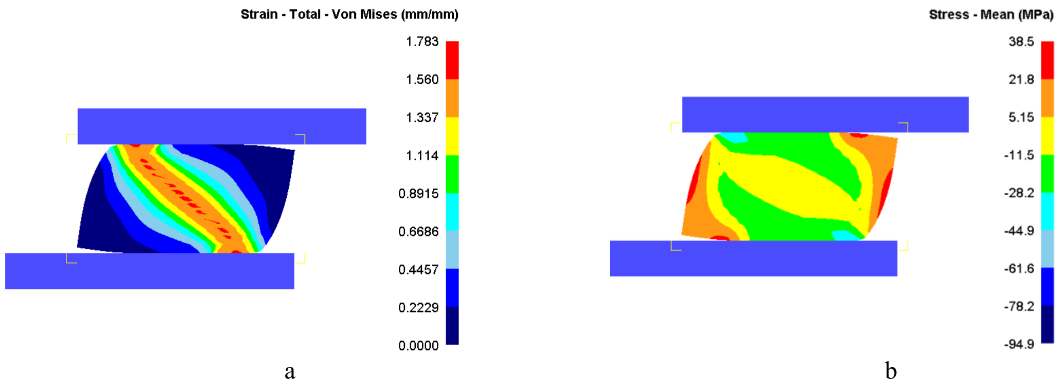

Fig. 4. Localization of the intensity of deformations (a) and stresses (b) along the direction of the small diagonal of the workpiece during upsetting with additional shear

3. Results and discussion

The results of calculating the stress state by the slip line method show that compressive stresses act at the nodal point 0.0, which prevent the destruction of the metal along the x axis and reduce barrelling. In this case, compressive stresses arise due to the action of the taper of the die inserts, which create compressive stresses mainly along the small diagonal of the workpiece. In this case, the greater the taper, the greater the values of the compressive stresses. It should be noted that due to the action of the taper of the die inserts, which, during upsetting, the strips are displaced opposite to each other, lead to an additional shear, and by reducing the tensile stresses on the lateral surface, they will make it possible to upset the workpiece with large degrees of reduction, which is impossible with ordinary upsetting, especially when processing low plastic materials. When upsetting the workpieces without shear, tensile stresses arise in the axial central zone, which, when the ultimate strength of the material is reached, can lead to cracking.

The danger in this is the localization of stress along the small diagonal of the workpiece, where the value of the shear stresses along the small diagonal is $\tau_{xy1.1} = -k\cos 2\cdot\theta_{1.1} = -k\cos 2\cdot 35° = -0.342\cdot k$, which, when the maximum value of shear stresses is reached, can lead to chipping in this direction. A completely different picture is observed along the large diagonal of the workpiece, where the values of the shear stresses are equal to $\tau_{xy0.1} = -k\cos 2\cdot\theta_{0.1} = 0.342\cdot k$, and is tensile, which can also lead to fracture at high values.

The foregoing is also confirmed by the results of the FEM analysis of shear settlement (Fig. 4). Figure 4 shows that the shear deformation is concentrated along the small diagonal of the workpiece, the same can be seen along the slip lines 2.1-1.1- 0.0 и 0.0–0.1* -2.1* (fig.3, a), where at high degrees of deformation can occur cleavage of the workpiece in this direction. Hence, the recommended shear angle γ should not exceed 20 °, because with a further increase, the compressive and shear forces will increase, which can lead to shearing in this direction, and the workpiece will also be significantly distorted.

Thus, the analysis of the results of the study of the stress state, under the combined effects of compressive and shear forces on the workpiece, shows that in the central zone of the specimen it shows the occurrence of mainly compressive stresses, which excludes cracking on the side surface of the workpiece and reduces barreling of the workpiece. When upsetting similar specimens with flat dies, tensile stresses arise in the indicated zones, which, at sufficiently high degrees of deformation and loads, can exceed the yield stress of the material and lead to cracks. Therefore, the deformation of the upset under the influence of shear forces excludes the possibility of cracks appearing on the lateral surface of the samples, especially when processing low-plastic alloy steels and alloys

4. Conclusions

The use of special composite forging dies that combine the upsetting and shear processes will make it possible to significantly reduce barreling and the most dangerous contour tensile stresses, which eliminates the likelihood of cracking on the lateral surface of the samples. The design feature of the proposed tool is that it, in principle, does not lose its versatility, i.e. the surface of the dies remains flat with a small taper and can be used in the manufacture of various forgings, but with the effect of additional shear.

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