The issue of low resistance of punches when heading of sunk screw made of ferrite-pearlite steels

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Abstract. The causes are investigated and the types of punches wear during extrusion of a cruciform slot in screws with countersunk head from ferritic-pearlite class steels, in particular, 16KhSN steel, are evaluated. The research methodology included two simulations of the M5 screw landing process using the DEFORM-3D software package. In the first simulation, using a generalized curve of the hardening of the material of the deformable workpiece, its stress state on the contact surface with the punch is determined. The obtained values were set in the form of a load on the punch when determining its stress state. The second simulation was carried out using the hardening curve of the punch material. The information obtained on the magnitude and distribution of stresses in the forming profile of the punch made it possible to draw a conclusion about the types of wear that are defined as loss of profile geometry and fatigue failure.

In mechanical engineering, screws with a countersunk head (hereinafter referred to as screws) and a cross-shaped slot according to GOST 10753-86 from high-strength materials, in particular, ferritic-pearlite class steels (Figure 1), are widely used [1].

![Figure 1. Photograph of an M5 countersunk head screw and Phillips head a) and heading operating blanks b)](image_url)

The problem of their manufacture lies in the low resistance of the form-forming profile of the punch (hereinafter referred to as the punch), in the form of loss of its geometry during axial extrusion of the cross-shaped slot (hereinafter referred to as the slot), as well as, in some cases, its destruction [2]. The indicated problem requires an assessment of the magnitude and distribution of stresses in the punch [3],
which was the purpose of this study using the example of the landing of the M5 screw from steel 16XCH, the chemical composition of which is shown in the table 1.

**Table 1.** The chemical composition of steel 16HSN GOST 5632-2014.

|   | C     | Cr    | Ni    | Si    | Mn    | Cu    | P     | S     |
|---|-------|-------|-------|-------|-------|-------|-------|-------|
|   | 0.13-0.2 | 0.8-1.1 | 0.6-0.9 | 0.6-0.9 | 0.3-0.6 | up to 0.2 | up to 0.035 | up to 0.035 |

In accordance with the goal, two interrelated tasks are formulated. The first task is to assess the stress state of the material of the deformable workpiece on the contact surface with the punch (hereinafter referred to as the contact surface). In the second task, the obtained values are set in the form of a load on the punch when determining the magnitude and nature of its stress state.

The solution of the set tasks included two mathematical simulations of the M5 screw landing process, which was carried out using the DEFORM-3D software package and simplified solid-state models of the initial workpiece and tool developed in the PRO ENGINEER program.

In the first simulation, a generalized hardening curve of 16KhSN steel was used in the coordinates "stress intensity - degree of deformation" (Figure 2) [4]. The methodology for constructing generalized hardening curves involves combining the dependences “strain degree – hardness” and “stress intensity – hardness,” and using the hardening curve in compression at the initial stage [5].

![Figure 2. The generalized hardening curve of steel 16 HSN with the initial section (indicated by circles) corresponding to the hardening curve under compression](image)

The results of mathematical modeling are presented in the form of pictures of the stress-strain state (Figures 3 and 4) at two stages. At the first stage, the punch end face is introduced into the blank; on the second - a mated section having the shape of a truncated cone.

When pressed into the billet end conical section there is a non-uniformity of deformation. In the layers of the workpiece at a distance of ~ 0.1 mm from the surface of the punch, strain values \( \varepsilon_i = 0.982 \) and higher are realized. When removed in the radial direction, the degree of deformation decreases, reaching the value \( \varepsilon_i = 0.655 \) at a distance of ~ 0.3 mm, and then to \( \varepsilon_i = 0.329 \) at a distance of 1.4 mm. The stress state picture has a similar spatial heterogeneity with a deformed state. The stress intensity in the metal layers adjacent to the surface of the punch is \( \sigma_i = 1544 \) MPa. Further in the radial direction, the stress intensity decreases to 1230 MPa.
When a truncated cone is pressed into the workpiece, the deformed state of the material in the workpiece volume increases. It is possible to distinguish zones differing in the degree of deformation. Their location is equidistant to the contour of the slotted groove. On the contact surface in a layer with a thickness of ~ 0.1 mm, the strain has the highest values $\varepsilon_i = 3.9 \div 2.64$, and stresses reach 3730 MPa. Next is a layer with a thickness of 0.2 ... 0.6 mm with lower degrees of deformation in the range $\varepsilon_i = 2.64 \div 1.32$. The stress state in this zone decreases to 2500 MPa. In the rest of the head, the deformed state is significantly reduced, including in the intermediate zones between the grooves, and corresponds to the interval $\varepsilon_i = 1.32 \div 0.95$ with a stress of 1270 MPa.

In accordance with the flow patterns of the metal (Figure 3 c), a conclusion is drawn on the realizable mechanical deformation scheme. The predominant metal flow occurs in the radial direction and coincides with the direction of normal compressive stresses acting on the contact surface. The axial flow is determined by the shear stresses due to the friction forces on the contact surface. The free flow corresponds to the tangential direction, while the material of the end part of the workpiece undergoes the greatest elongation.

In the second simulation, in determining the magnitude and nature of the stress state of the punch, the data on the stress state of the material along the contact surface obtained in solving the first problem are used. Similar to the previous step in studies, the stress state of the punch was evaluated in two stages: at the first stage, when the end conical section of the punch was introduced into the billet, and at the second, the conjugated section in the form of a truncated cone (Figure 4). In the simulation, a hardening
curve was used for the punch material—H12M tool wear-resistant steel, with a compressive yield strength $\sigma_{0.2} = 2200–2300$ MPa (HRC 60–62).

The stress state of the material of the forming element of the punch at two stages of indentation into the workpiece is shown in the form of its paintings (Figure 5) and fields of the stress state (Figure 6).

Figure 5. Pictures of the stress state of the workpiece material and the forming punch when pressing sections into the workpiece: a) - end conical; b) - truncated cone

Figure 6. Fields of stress state of the forming element of the punch when pressed into the workpiece sections: a) - end conical; b) - truncated cone
When indenting the end conical section of the punch, the zone of greatest stresses is located above its base, while the stresses in the radial direction increase from 2000 MPa to 2400 MPa. The voltage across the contact surface is also not constant. It increases with the transition from the top to the beginning of the spline elements from 800 MPa to 2100 MPa. At this stage of indentation, the main load is created by normal stresses.

With the further introduction of a section of a punch in the form of a truncated cone into the billet, the main load transfers to its spline elements. The greatest stresses are in the middle of their length. Their value is 3500–6000 MPa, which exceeds the yield strength of the punch material and indicates that the material of the spline elements during cold heading works under conditions of low-cycle fatigue. In this case, the ratio of normal and tangential stresses along the contact surface changes in favor of the latter, as evidenced by the loss of profile geometry of the spline elements of the punch. In general, this indicates two types of wear when extruding a crosswise slot: fatigue strength and abrasion.

Conclusions
1. The causes are investigated and the types of punches wear during extrusion of a cruciform slot in screws with countersunk head from martensitic-ferritic steel, in particular, 16HSN steel, are evaluated. The magnitude and nature of the stress distribution in the forming profile of the punch are determined. The maximum stresses exceed the yield strength of the punch material and occur in the middle of the length of its spline elements. The information obtained on the stress state of the punch material made it possible to draw a conclusion about the types of wear that are defined as loss of profile geometry and fatigue failure, which corresponds to the actual production data.

2. A methodology for assessing stresses in the forming element of a tool is proposed, based on two simulations of the screw landing process using the DEFORM-3D software package. At the first simulation using a generalized curve of the hardening of the workpiece material, its stress state on the contact surface is determined. The obtained values are set in the second simulation in the form of a load on the punch to determine its stress state, using the hardening curve of the material of the punch.

References
[1] Bunatyan G V and Kutyaykin V G 2012 Standardization and technical fundamentals of quality management of threaded fasteners in mechanical engineering (Nizhny Novgorod: NSTU)
Levinson R E, Khokhlov E N, Timerbaev V G and Kutyaykin V G 1990 Die forging fasteners. Constructive and technological calculations (Gorky: KTIavtomatiz)
Vladimirov Yu V and Gerasimov V Ya 1984 Technological fundamentals of cold heading of rod fasteners (Moscow: Mechanical Engineering)
[2] Galkin V V, Ivanov S A, Bratukhin A V and Gavrilov G N 2017 Procurement in engineering 12 6 – 12
[3] Storozhev M V and Popov E A 1971 Theory of metal forming (Moscow: Mechanical Engineering)
Gromov N P 1978 Theory of metal forming (Moscow: Metallurgy)
Kutyaykin V G 2007 Metrological and structural-physical aspects of steel deformation (Moscow: ASMS)
[4] Del G D 1971 Determination of stresses in the plastic field by the distribution of hardness (Moscow: Mechanical Engineering)
Smirnov-Alyaev G A 1978 Resistance of metals to plastic deformation (Leningrad: Mechanical Engineering)
Galkin V V, Kudryaytsev S A, Tereshchenko E G and Derbenev A A 2013 Procurement in engineering 11 23-27
Galkin V V, Gavrilov G N, Derbenev A A and Bratukhin A V 2019 Engineering solutions for assessing the mechanical properties of cold-deformed metal materials in multi-stage processing conditions (Nizhny Novgorod: NSTU)
[5] Kroha V A 1980 Hardening of metals during cold plastic deformation (Moscow: Mechanical Engineering)