Prediction of the structural state in a wheel forging based on computer modeling

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Abstract. The landing gear of any flying vehicle is a unit of increased responsibility. The entire load during take-off and landing is perceived by the wheels of the landing gear. The reliability of aircraft wheels is determined, among other things, by the distribution uniformity of the structure and mechanical properties over their volume. This work represents a method for predicting the structural state in stamped forging of an aluminum alloy wheel included in the chassis of a small bomber. Based on the simulation results (deformation temperature and deformation rate), the cause of grain growth in the area of the wheel rim is determined. Using the structural state diagrams of Vainblat Yu M. It is shown that a region with coarse grains in the rim is formed due to local recrystallization during heating for quenching. Based on analysis of temperature-speed conditions in coarse-grained area, stamping modes are proposed with stepwise reduction of deformation rate at the final stage of the process, which excludes recrystallization.

1. Introduction

The life cycle of any reusable aircraft product includes numerous takeoffs and landings, during which the chassis carries the maximum load. A key component that ensures the reliability of the chassis is the wheel and its disk. In order to reduce flight weight, landing gear discs are made of aluminum thermally hardened alloys. The reliability of the disk is determined not only by the high level of its mechanical properties, but also by their uniform distribution over the volume of the part. This is ensured by the uniform desired micro- and macrostructure of the disc material.

The vast majority of metal products at various stages of production are hot formed. The conditions for hot deformation differ from cold deformation in a wide variety of temperature regimes, and the methods for obtaining a given structure are much more complicated.

The deformation of metals and alloys in a heated state is used to obtain products of complex shapes, at large reductions, in a wide range of temperatures and strain rates. It is characterized by a strong structural heterogeneity and a wide range of possible structures types.

The solution of the problem of obtaining a homogeneous given structure requires the selection of a small number of adjustable deformation parameters. Work in this direction for wrought aluminum alloys was initiated by a group of Russian researchers led by Yu M Vainblat in the 60-80s of the last century. In a number of their publications [1-4], it was shown that not only the modes of the final heat treatment...
of the deformed product, but also the temperature and rate parameters of the final stage of plastic deformation, take part in the formation of the final structural state.

For a driving force quantitative assessment of the metallophysical processes occurring in a deformed alloy during subsequent heating, Vaynblat adopted the well-known Zener-Hollomon parameter [3]:

\[ Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right), \]

were: \( \dot{\varepsilon} \) – strain rate; \( Q \) – activation energy; \( R \) – universal gas constant; \( T \) – temperature.

Experimental data on the structural state in the workpieces deformed under known conditions were superimposed on the graphs of the isolines of the parameter \( Z \) in the coordinates “\( \dot{\varepsilon} – T \)”. This allowed the authors to construct diagrams of the structural state for the majority of industrial wrought aluminum alloys (figure 1).

![Figure 1. Structural state diagram of the 1360 aluminum alloy after deformation and heating for quenching. Data from Yu M Vaynblat.](image-url)

The diagram shows three areas that are fundamentally different in the emerging structural state: area I - polygonized structure; II - recrystallized structure; III - mixed structure. Temperature-rate region III during subsequent heating for quenching is characterized by a very small number of recrystallization centers. Recrystallized grains have time to grow to significant sizes, which leads to the formation of a coarse-grained structure.

The described tool for predicting the structural state in deformed semi-finished products made of aluminum alloys made it possible to substantiate the appearance of a coarse-grained rim on pressed products [5], to obtain USSR copyright certificates on the method of manufacturing parts from pressed aluminum alloys [6] and the method of thermomechanical processing of aluminum alloys [7], to study the effect alloying elements for spontaneous recrystallization in aluminum alloys [8].

It should be noted that the above method for predicting the structural state, and hence the properties of semi-finished products from aluminum alloys, is not the only one. Since the beginning of the 21st century, methods [9] have become widespread that directly link various parameters of metal and alloy processing technologies with the mechanical properties of the resulting products. This became possible due to the development of methods of statistical data processing and the use of high-performance computers with specialized software for technological modeling.

The authors of [10] propose to solve the problem of obtaining the required mechanical properties in deformed semi-finished products from high-strength aluminum alloy 7075 already at the stage of casting billets for deformation. The electromagnetic field (EMF) method they use during the casting process provides a fine-grained structure in castings. The selection of the correct temperature and speed modes of forging and stamping is carried out using numerical simulation of the forging process with well-known specialized software Simufact. Forging 11.
Direct relationship between structure, structural state and mechanical properties of deformed semi-finished products is investigated in numerous works of different authors without application of computer technological modeling [11,12], and with its use [13]. The approach used in these studies makes it possible to solve the problems of achieving not only the required strength and plasticity, but also service characteristics, for example, fracture toughness. The solutions obtained provide the specified properties of not only aluminum, but also steel forgings [14].

Elucidation of the relationship between the structure and properties of a material is important not only for structural, but also for technological use. Computer modeling of plastic deformation processes is successfully used for the development and validation of new methods of workability technological testing [15].

The authors of [16], based on the results of computer simulation of the process of stamping a disk, proposed a model for the evolution of the microstructure of the Ti-6Al-4V alloy, taking into account the local deformational softening of the material.

The use of special software based on the finite element method (FEM) for calculating temperature and strain rate fields in a deformable workpiece requires a sufficiently high adequacy of the finite element model of the process. A team of researchers led by M Janjić compared the physical modeling of forging of a composite model of an aluminum disk with the operation of a virtual process model based on DEFORM-2D [17]. The obtained comparative results indicate the permissible (15-20%) deviation of the virtual values of stresses and strains from the actual ones.

The method proposed above for predicting the structural state in a deformed semi-finished product from an aluminum alloy was tested by us in the development of a technological process for multi-pass stamping of an automobile wheel from an aluminum alloy AV [18]. This made it possible to avoid coarsening of the structure in stamped forgings.

The purpose of this work is to determine the reason for the formation of a local region with very large grain in the already existing stamping technology on the hydraulic press of the heavy bomber chassis disk from an alloy 1360. The coarsening of the macro- and microstructure periodically appeared at the end point of the disc rim after finishing heat treatment (figure 2a) and was not compensated for by an allowance for machining (figure 2b).

![Figure 2](image_url). The coarse-grained area in the disc macro-template (a) and the intersection of the coarse-grained area with the outline of the finished part (b).
2. Materials and methods
Alloy 1360 is an original Russian alloy of the Al-Cu-Mg-Si-Mn system. Alloy is intended for production of stamped forging of parts of aviation application with high level of strength. The chemical composition of the alloy is shown in table 1. The alloy is thermally hardened according to the usual “hardening + aging” scheme. Heat treatment modes and typical mechanical properties of 1360 alloy forgings are shown in table 2.

| Alloy component | Content, % |
|-----------------|------------|
| Al              | Base       |
| Cu              | 1.8 – 2.6  |
| Mg              | 0.4 – 0.8  |
| Si              | 0.7 – 1.2  |
| Mn              | 0.4 – 0.8  |

| Treatment / Properties | Value         |
|------------------------|---------------|
| Heating temperature for quenching, °C | 505 – 525     |
| Aging temperature, °C     | 150 – 165     |
| Yield point, MPa          | 314           |
| Tensile strength, MPa     | 412           |
| Elongation, %              | 13            |

Computer simulation of the current technology of disk stamping was carried out in the Russian system for analyzing plastic deformation processes QForm, developed by QuantorForm LLC. The system provides information about the temperature, degree and rate of deformation at any place in the cross-section of the workpiece by using the built-in function of traced points. For each point, the system unloads an MS Excel file containing arrays of parameter values with a step of 0.5 - 0.05 mm of the press stroke.

Since the above defect of the forging is clearly structural in nature, the structural state diagram of the 1360 alloy (SSD) was used to analyze the causes of its occurrence. Two-dimensional arrays of temperature and strain rate data were applied to the DSS of the alloy. The analysis of the structural state in a given traced point was carried out according to the location of its array in a particular region of the SSD.

3. Results and discussion

3.1. Analysis of the current technology
The analyzed technology included the following basic transitions: heating the workpiece to 420-470 °C; upsetting the workpiece to a given height; final stamping without heating (figure 3). The temperature of the die heating is 250-300 °C. A model of a hydraulic press with a capacity of 100 MN and an idle speed of 150 mm/s was used as a virtual equipment.
Figure 3. (a) The main technological stages of the existing stamping: initial blank, (b) upsetting and (c) final stamping.

The analysis of the temperature-rate parameters of deformation was carried out according to the traced points (Figure 4). The main analyzed point $A$ is located in the problem area with a coarse-grained structure. Additional traced points $B, C, D, E, F, G$ were selected for correct analysis results.

Figure 4. Layout of the traced points on the vertical section of the forging. The main point $A$ is highlighted in yellow.

The deformation trajectory of each point in the stamping process is quite complex and can include different ratios of temperature and strain rate. However, the formation of an energy reserve initiating
recrystallization upon heating for quenching occurs at the final stage of stamping. In this case, the analysis was carried out for the last 12 mm of the 205 mm full press stroke during final stamping.

In the process of modeling, the heating temperatures of the workpiece and dies were taken as nominal in accordance with the current technology, i.e. 450 and 300 °C. However, to take into account the influence of the permissible downward deviations of the workpiece temperature, the option with a minimum temperature of 420 °C was also tested. The variant of the process with the nominal billet temperature is conventionally named “Hot”, with the minimum – “Cold” (figure 5).

Figure 5. Location of investigated points on DSS of 1360 alloy.

The results of the structural state analysis at the points under consideration indicate that even at the nominal temperatures of the workpiece and dies (Hot), only point A partially falls into the unfavorable region III of the SSD. The location of the group of points A Hot on the boundary of regions I and III indicates the instability of the states. The A Cold point group is completely located in the region III of the SSD. This explains the periodicity of the appearance of a coarse-grained area in the forging. That is, only with a noticeable decrease in the heating temperature of the workpiece and dies, the problem area of the forging is guaranteed to be recrystallized.

It should be noted that all three nearby points (B, C and D) are also at risk of structure coarsening (figure 5). However, if the nominal heating temperature of the workpiece and dies is precisely maintained, this risk is reduced to zero. The structural state at the rest of the studied points (E, F and G), even with an average subcooling of the workpiece, is guaranteed to be polygonized after quenching.
3.2. Ways to exclude the coarse-grained area formation

To ensure the exclusion of the coarse-grained area formation, it is necessary to move the group of points \( A \text{ Hot} \) as far as possible from the border between areas \( I \) and \( III \). This is achievable by implementing two options for changing the technology: increasing the heating temperature of the workpiece and dies, or reducing the speed of the upper die.

The first option seems to be the simplest. The billet was heated up to 470, and the stamp up to 400 °C. Indeed, with such an increase in temperatures, the problem group of points noticeably moves upward from the dangerous boundary (figure 6, \( A \text{ Max} \)). However, due to the deformation thermal effect, the temperature in the vicinity of point \( A \) exceeds 500 °C and there is a risk of grain growth already during the stamping process. Of course, this is unacceptable.

The second option with a decrease in the strain rate also has a disadvantage. The considered technology is industrial, therefore, a decrease in the speed of the upper die will lead to a decrease in the productivity of the stamping process. This is also highly undesirable. However, for the formation of the final structural state, the final stage of shaping is critical. Accordingly, the speed can only be reduced at the end of stamping. Modern control systems for hydraulic presses allow you to control the speed of the traverse over a wide range.

To study the effectiveness of the second option, a virtual press with a stepped speed was created in the QForm system. In the course of the process, the speed is stabilized at 150 mm / s, and at the last 30 mm of the stroke, it decreases to 10 mm / s. Such a technological technique allows to shift the group of points on the SSD to the left and move away from the border between regions \( I \) and \( III \) without the risk of metal overheating (figure 6, \( A \text{ Rate} \)).

4. Conclusion

Research verification FEM - simulation of the current technology of forging a disc made of 1360 alloy on a hydraulic press was carried out. A joint analysis of the results on temperature and strain rate and SSD of the 1360 alloy made it possible to reveal the cause of the appearance of a coarse-grained region in the disk after heating for quenching.
Grain growth in the problem area of the forging is caused by an unfortunate combination of temperature and strain rate at that location. The deformation conditions correspond to the region of mixed structure on the 1360 alloy SSD. Here, the recrystallization grain growth during subsequent heating is weakly limited due to the small number of recrystallization centers.

The effectiveness of two options for combating grain coarsening is estimated: an increase in the heating temperature of the workpiece and a decrease in the stamping speed. Taking into account the advantages and disadvantages of these options, a compromise is proposed: a stepwise decrease in heating temperature and a decrease in the stamping speed. Taking into account the conditions of deformation in region III of the SSD.

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