Stress-Strain Distribution Within Rotary Swaged Tungsten Heavy Alloy

Ludmila Krátká, Rudolf Petrmichl
Faculty of Materials Science and Technology, VŠB-Technical University of Ostrava, 17. listopadu 15, 70833, Ostrava 8, Czech republic
ludmila.kratka@vsb.cz

Abstract. This study deals with thorough investigation of stress-strain parameters within an innovatively processed tungsten heavy alloy (THA). THAs are challenging materials featuring exceptional mechanical and physical properties and they are applicable in various demanding industrial fields, such as in the aeronautics, medicine, or military. The herein studied material is a WNiCo alloy prepared from original powders via powder metallurgy. The pre-sintered material was processed via plastic deformation, in particular hot rotary swaging with the usage of induction heating directly before a swaging pass. The experimental study was supplemented with numerical simulation of the deformation process, which was performed via the finite element method (FEM). The simulation was primarily focused on prediction of the development of effective imposed strain during the swaging process performed in multiple steps, and its correlation with stress distribution during swaging. The numerically predicted effective imposed strain development was subsequently verified via Vickers microhardness measurements, whereas the predicted results of stress distribution were validated via experimental observation of residual stress distribution performed via analysing scans acquired by scanning electron microscopy (SEM, electron backscatter diffraction analysis). The results showed that the deformation technology consisting of induction heating and hot rotary swaging was well optimized as the swaged billets featured satisfactory surface roughness and no surface cracks. Also, the tungsten agglomerates within the structure exhibited deformation in the direction of the main acting swaging force, especially in the locations the effective imposed strain in which was the highest. The values of predicted effective imposed strain and microhardness correlated reliably with the experimentally acquired and predicted results of residual stress distribution. In other words, the locations the effective strain in which was the highest also exhibited a more significant presence of residual stress.

1. Introduction
Tungsten heavy alloys (THA), in our case W-Ni-Co, consist of the majority of tungsten (approx. 90% by weight), which is supplemented with a softer NiCo matrix [1,2]. Tungsten guarantees high strength (maximum strength around 1900 MPa) of the material, whereas the matrix in the material ensures plastic properties. THAs are used primarily as protection against harmful radiation or to block kinetic energy [3,4]. Given by the high density of THAs (≈16 g / cm³), the advantageous use of tungsten heavy alloys is, for example, as shielding in the manufacture of therapeutic devices in oncology, counterweights in aeronautics, or for the manufacture of kinetic penetrators used by the military.
Powder metallurgy is in most cases used for the production of THA alloys \[5,6\]. Mixed metal powders are usually isostatically pressed into rods. The bars are then sintered in a protective atmosphere (H, Ar, vacuum), in the temperature range between 1000 and 1500 °C. Other alloying elements with a lower melting point (Ni, Co, Mo, Re) are also added to the powder mixture with a tungsten content above 90% by weight to form the softer matrix around the tungsten agglomerates during sintering. In this way, a homogeneous material is formed \[7,8\]. The elements contained in the THA matrix ensure the plasticity of the material, however, their negative effect is a certain decrease in strength. For optimal strength and plastic properties, for example, modification of the chemical composition, or improvement of the properties via plastic deformation, can be used \[9,10\].

THAs can be processed via conventional processing technologies, such as rolling, forging, extrusion, etc. \[11,12\]. Nevertheless, techniques of intensive plastic deformation, such as the severe plastic deformation (SPD) methods \[13–17\] could also be applied for their favourable effects on structure homogenization and improvement of mechanical properties. The most suitable technologies are, however, those that are continuous, such as ECAP-conform \[18\] or rotary swaging (RS) \[19,20\]. These processes take place continuously and are therefore suitable for large-scale production. Due to its great variability, the RS technology is suitable for various branches of industry. The RS technology is characterized by high-frequency hits of dies that rotate around the blank being deformed. This process can be realized under both, cold and hot conditions \[21\], but induction heating can advantageously be used to heat the material before processing. It is suitable for the production of solid semi-finished products, and hollow shaped parts, too. RS is an advantageous technology for processing of difficult-to-process materials (Ti, THA) and composites (Al/Cu) due to the advantageous distribution of forces during processing \[22–25\].

The already published studies devoted to stress-strain characteristics of THAs report differing results. For example, work by \[2,20,21\] characterizes the differences in the material plastic flows in cases of cold and hot rotary swaging. It is obvious that the temperature thus plays an important role not only in the case of plastic flow of material, but also in the related stress distribution. Residual stress is thus a very important indicator of the performed forming, which subsequently affects not only the mechanical characteristics of THA products \[2,21\]. It should be noted, however, that publications with this focus are relatively scarce. A more detailed study devoted to the currently widely studied THA (WNiCo) is thus in great demand, as so far only partial attention has been paid to this problem.

The aim of this study is to predict stress states during rotary swaging of a THA material from original WNiCo pseudo-alloy. In the first part, the study is focused on FEM simulation of hot rotary swaging of the material. Numerical modelling was for this purpose performed using Forge NxT software. The second part of the work is focused on experimental verification of the predicted internal stress distribution in the rotary swaged pseudo-alloy.

2. Material and methods
This study is divided into two main parts. In the first part of the paper, the proposed forming process of hot rotary swaging is simulated by FEM analysis. The simulation is focused on predicting the stress state after rotary swaging. The second part of the work is devoted to practical verification of the numerically predicted stress state results using a real application of rotary swaging (Figure 1) with induction pre-heating. For these purposes, the self-developed KOMAFU S 600 forging force detection system was used. The forging itself took place on a rotary swaging machine by HMP company.
The rotary swaging simulation was designed to predict the behaviour of the WNiCo tungsten heavy alloy. For this purpose, an elastic-viscoplastic model created by the software based on the THA tensile stress-strain curve was used. The model was determined by the Haensel - Spittel relation (equation 1), where $X$ is the equivalent strain rate, $\varepsilon$ is the equivalent strain, $T$ is the temperature and $A$, $m_1$, $m_2$, $m_3$, $m_4$, $m_5$, $m_7$, $m_8$, $m_9$ are regression coefficients the values of which were as follows: $A = 1447.002738$, $m_1 = -0.009$, $m_2 = 0.0895$, $m_3 = 0.0044$, $m_4 = -0.0069$, $m_5$, $m_7$, $m_8$, $m_9$ are 0.

$$
\sigma = A \exp(m_1 T) T^{m_9} \varepsilon^{m_2} \exp \left( \frac{m_4}{\varepsilon} \right) (1 + \varepsilon)^{m_5} T \exp(m_7 \varepsilon) \varepsilon^{m_3} \varepsilon^{m_8} T
$$

For real experimental verification of the results, 93W7Ni3Co pseudo-alloy with the chemical composition of 90 wt.% W, 7 wt.% Ni, 3 wt.% Co. was selected. This alloy was prepared by powder metallurgy from powders with the mean grain size of 2.78 µm, by ÚJP Praha a.s. The preparation process involved mixing the powders, cold isostatic pressing at 400 MPa, and then sintering in H2 atmosphere-protected oven at 1525 °C for 20 minutes, followed by rapid cooling in water. The minimum temperature for forming (900 °C) was chosen based on previous experimental studies [4,21]. The mentioned works reported massive surface oxidation after exceeding the temperature of 1100 °C. Temperature control during induction heating was provided by an optical pyrometer. The WNiCo blank was gradually reduced from the original diameter of 30 mm to the final diameter of 20 mm.

Structural analysis of the experimentally processed work-piece is performed on its cross-sectional sections, focusing primarily on the analysis of residual stress, and the development of structure. Observations were made using scanning electron microscopy. The samples were mechanically ground on SiC papers and subsequently polished with Eposil F substance. EBSD analyses were performed in the subsurface sample area, 1 mm from the outer edge of the rod, with the scanning step of 0.5 µm. Scanning was evaluated using ATEX software [26].

3. Results and discussion

3.1 FEM of rotary swaging

Figure 2a) shows the material flow with the projected temperature field during hot rotary swaging. The simulation shows that the material flow during rotary swaging is very complex. It can be seen that the material flows in both the directions from the neutral plane located in the reduction zone of the dies. In
addition, a component of tangential plastic flow, the amplitude of which is variable during rotary swaging, is evident in the surface layers of the material. At the beginning of the work-piece, we observe that the material flows significantly in the direction of material movement during swaging. Since the material volume has the possibility to flow plastically in both the directions along the axis of the work-piece during swaging, it is necessary to determine the position of the neutral plane. Thus, the neutral plane is the location along the length of the work-piece in which the material changes the orientations of the flow vectors. From the beginning of the work-piece towards the neutral plane, the material flow gradually slows down. At both the ends of the rotary swaged work-piece, the influence of the rigid ends, which significantly affect the plastic flow of the material, can be detected. At the rear end, the rigid end is manifested by the presence of a manipulator. From the direction of the vectors can be seen that the rigid end, i.e. the presence of the manipulator, results in a deflection of the direction of the plastic flow vectors. This suggests that, during rotary swaging, the end of the work-piece tends to bend in the direction of the dominant direction resulting from these vectors.

Figure 2. Temperature field in the longitudinal direction a); transverse direction b)

Figure b) shows the temperature field during rotary swaging. From the figure ensues that the material cools evenly from the surface towards the axis and the temperature field visibly creates three areas; cold surface area, warmer subsurface area, and hot axial area.
Figure 3. Stress state in the cross section of hot swaged material: stress tensor a); 1st principal stress b); 3rd principal stress c); 2nd principal stress

Figure 3a) shows the stress tensor considering both the normal and shear stresses in the material during rotary swaging, where compressive stress predominate in the surface layers. This phenomenon is mainly caused by friction between the dies and the material, when during rotary swaging, the material flow in the surface layer is aggravated. Thus, this region acts more as a transmitter of plastic deformation towards the axial region of the material, by the effect of which the formation of compressive stress occurs. In subsurface areas, on the other hand, the material plastic flow is less aggravated, which is manifested by the occurrence of tensile stress. This stress point to the occurrence of significant movement of material in these locations. In the axial area, the compressive stress occurs again, this stress arises from the nature of the material flow during rotary swaging; the strain in the axial region of the work-piece is lower than in its (sub)surface regions and thus the material in this area does not have sufficient energy to flow. At the same time, significant part of the plastic flow is realized in the subsurface layers, therefore, the axial regions of the material are characterized by the compressive stress.

Figure 3b) shows the main normal tensile stress. The figure shows that the tensile stress is concentrated in the subsurface, and slightly in the surface areas. Figure 3c) shows the main normal compressive stress. This figure demonstrates the effect of compression in the middle and surface areas of the material. The resulting figure 3d) is the intersection of figure 3b) and 3c), it shows that the compressive stress is strongly suppressed in the axial region by the prevailing tensile stress.
From this distribution of tensile stress is evident that the stress state during rotary swaging is significantly influenced by the flow of the material, as well as the distribution of the temperature field within the material.

3.2 Structural analysis
Figure 4 a) shows the structure state after sintering. During sintering, the tungsten powder agglomerates together and agglomerated particles of tungsten are formed. This leads to the formation of agglomerates the shapes of which are very close to the shape of a sphere. Figure 4a shows large spherical agglomerates of hard tungsten surrounded by the softer NiCo matrix. The matrix ensures the cohesion of the material, as well as plastic properties. Figures 4b) and 4c) show the structural state of the work-piece after hot rotary swaging. Figure 4b) shows the subsurface area which exhibits high penetration of plastic strain. This phenomenon is evident from the pronounced deformation of the matrix and the visible deformation of the tungsten agglomerates. In many areas, the deformation of the matrix is so evident that the tungsten agglomerates developed larger contact surfaces. In Figure 4c), the structure in the axial area of the sample is shown. It is obvious that the deformation in this region is not as significant as in the subsurface area. At this point, the deformation is concentrated in the NiCo matrix. Therefore, almost no deformed tungsten grains can be seen in this location and the structural state in the axial region of the swaged material is similar to the state after sintering.

3.3 Residual stress
Figure 5 shows the internal misorientation of the grains in the scale from 0° to 15 ° in the axial region of the material. These misorientation point to the distribution of residual stress. The places with the least
misorientations are shown in blue in the picture. These areas largely correspond to the matrix, or to the areas with identical grains orientations. The least residual stress is manifested in these areas. This is ensured by the fact that the softer matrix allows the tension stress to relax. In the areas marked in red, there is a high concentration of grains misorientations; these are the areas with the minimum presence of matrix surrounding the tungsten agglomerates. In the red areas, the tungsten agglomerates mostly touch each other and therefore have no possibility to relax possible accumulated stress. This results into the greatest presence of residual stress. This stress development results from the deformation behaviour of the material during rotary swaging. During deformation, the orientation of the randomly arranged grains of material is changed so that the orientation of the grains is as favourable as possible. In areas in which a low volume of matrix is present, this phenomenon becomes problematic. Therefore, residual stress is most common in these places.

Figure 5. Internal grains orientations in axial region of swaged material

3.4 Force ratios during rotary swaging
Figure 6 shows a real record of the development of forces acting during rotary swaging in comparison with the predicted values from FEM (smooth curve). In the Figure we see the individual strokes of the dies, which reach different peaks. According to the record, it is clear that the force required to strike increases as the material continuously fills the dies. The force reaches the maximum values as soon as the working space of the dies is filled. Then follows a section in which the force remains more or less constant. In the last section of the graph, the force decreases as the material starts to empty the working space of the dies. At the end of swaging, an increase in the forces is evident. This increase is caused by cooling of the material and consequent increase in its flow stress. This trend is not significant in the predicted curve.

Figure 6. Force ratios acting on die
Figure 6 (smooth curve) shows that the real course differs from the predicted behaviour. The predicted curve has an upward trend up to the maximum, after the achievement of which a downward trend is evident. The predicted curve differs mainly in the last part, where the cold end of the material is swaged (in real rotary swaging). This is due to the inhomogeneity of the swaging process. The speed of feeding the material into the dies and its temperature have the major influence. The flow stress is also dependent on the temperature, i.e. it increases with decreasing temperature.

4. Conclusions
In rotary swaging, the material flow is characterized by its complexity. To characterize the material flow, it is essential to determine the neutral plane, which determines the direction of the material flow. Last but not least, the existence of rigid ends, which causes the material to bend during real forging, is also a significant phenomenon.

The stress in the material during hot forging is influenced by the temperature distribution along the cross section, and the material flow. The temperature distribution and flow of the material, according to the results from FEM, have effect on the location of tensile and compressive stress in the material. Shear stress, which occur mainly in the surface and subsurface material layers, play a considerable role in this type of forming. In general, hot forming is not characterized by high values of stress within the material due to the decreased flow stress of the material (i.e. higher plasticity).

Structural analyses confirm the effect of shear stress in the surface and subsurface layers of the material; the structure is significantly deformed in these locations. There is not such a significant deformation in the axial area; the deformation concentrates in the matrix in this location. The most significant presence of residual stress can be found in areas where there is low volume of matrix surrounding the tungsten agglomerates, and, in many cases, the agglomerates touch each other. Agglomerates with a contact surface are forced to adjust their orientations; in this way residual stress arises in the material.

The acting swaging forces acquired from the numerical simulation and experiment differed slightly. The real measurements show that the maximum experimental force acting on the dies is lower than the predicted maximum force. This fact is the effect of the inhomogeneity of the rotary forging process and is influenced by the feed rate into the dies and the temperature of the material (flow stress).

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