Effect of Residual Stress on Cracking of Hot Die-Forged Brass Fittings

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Abstract. Lead brasses, i.e. copper-based alloys with additions of zinc and lead, are widely used for production of specific components in the industry and commerce. Brass components are usually produced under hot conditions, i.e. via hot die forging (with the advantageous applications of induction heating), the semi-products for which are typically rods extruded from cast billets. Finally, the components are machined to their exact shapes. Nevertheless, such a complicated production process is prone to introduce defects in the structures of the final components. The herein presented paper deals with investigations of a brass component (pre-shaped gas valve, i.e. fitting) manufactured via hot die forging. The fitting exhibited cracking in a specific location after forging and the presented investigation attempts to characterize the factors, which could have possibly induced the occurring cracking, from the viewpoint of stress distribution. The experimental investigation focused on characterization of the structure in the vicinity of the cracked area with the particular focus on the occurrence of residual stress via scanning electron microscopy. This analysis was supported with the results of stress-strain distribution during forging acquired via numerical simulation of the die forging processing step (with implemented induction heating prior forging, in accordance with the real industrial conditions) performed using the finite element method (FEM). According to the acquired results, the cracking occurred in a location featuring local inhomogeneity of stress. The inhomogeneous distribution of stress in the particular location most probably developed as the result of the geometry of the forging die, which also introduced instabilities in the material plastic flow during forging.

1. Introduction
Regardless the exact composition and geometry of the final product, commercial purity (CP) copper, as well as alloys, compounds, and composites based on copper are widely used in the industry and commerce, primarily due to their superior properties (e.g. electric and thermal conductivities, non-magnetism, and corrosion resistance) [1,2]. Probably the most characteristic property of CP Cu is the high electric conductivity; given by this feature, CP Cu is widely used for conductors [3]. Innovative Cu-based composite materials are also typically fabricated with the aim to maintain high electric conductivity of the final composite, however, together with enhancing specific mechanical properties, such as strength and hardness [4–6]. On the other hand, the primary aim of the production of
numerous Cu-based alloys is to fabricate constructional materials with favourable properties suitable for various applications (such as for screws, bolts, nuts, valves, etc.) [7,8]. Cu-based alloys with probably the widest range of possible applications are brasses, which are compounds based on copper, zinc, and other selected elements. The selection and overall content of the alloying elements is the major factor influencing the phase composition of the final brass, and consequently its specific properties [1].

Lead brasses are created by combining Cu and Zn with the additions of Pb. Among the typical properties of Cu-based alloys is also their good machinability, which facilitates the production process of the final products, as most of the components are subjected to final machining. As regards the lead brasses, the most advantageous machining behaviour was documented for alloys containing less than 3 wt. % of Pb; García et al. [9] reported that the solubility of Pb in Cu is very low by the effect of which Pb forms fine precipitated particles in the structures, and Pantazopoulos and Vazdirvanidis [10] documented that the content of lead in the brass influences formation of chips during machining, since Pb forms discrete island of precipitated particles at the α/β interfaces. Despite the fact that Xiao et al. [11] reported the positive effects of heat treatment performed at temperatures between 400 °C and 600 °C followed by subsequent quenching on modification of structures of biphase brasses, based on the heretofore performed research, the Pb content in lead brasses should be kept under 3 wt. % to ensure facile finishing of the produced components. Lead brasses are used to produce medical gas valves. The production process of these components is quite complicated and consists of multiple technological steps: the procedure begins with casting, which is typically followed by extrusion performed to more or less homogenize the structure and properties of the cast billet, hot forging the primary aim of which is to transform the extruded semi-product into the pre-finished required shape and dimensions, and final machining performed to finish the shape and surface of the final brass gas valve. Each technological step is designed with the intention to enhance the performance of the final product. On the other hand, each step can result in the introduction of defects, such as segregations, cavities, pores, cracks, surface defects, etc., which can eventually decrease the lifetime of the gas valve.

Researchers have been dealing with the possibility to eliminate the risk of formation of defects during hot processing of brasses. For example, annealing [12], and optimization of the production process [13] were implemented to modify the structures and grains’ morphologies of brasses in order to positively influence their final properties. Generally, the heretofore performed research has documented that the phase composition and grain size are the most important factors affecting the final performance and mechanical and utility properties of brass products. Based upon these findings, the application of severe plastic deformation (SPD) methods, based on imposing high amounts of shear strain into metallic materials in order to impart substantial grain refinement and consequently enhance their final performance and properties [14–18], has a great potential for production of high-quality brass products. This hypothesis has recently been proven by Naser Radhi et al. [19], who documented the positive effects of processing of a brass via the Equal Channel Angular Pressing (ECAP) SPD method on its final mechanical properties. Nevertheless, the presence of residual stress within the processed structure, or stress inhomogeneity during deformation processing, are of non-negligible importance for the lifetime and durability of the final products, too, as both these factors can contribute to possible nucleation and development of cracks [20–22].

According to the available literature, no study documenting the stress-strain relations within a brass gas valve (fitting) produced under real industrial conditions with the occurrence of defects (cracking) has been published. The aim of the presented study is thus to numerically predict the distribution of the effective strain and stress within the forged fitting, with a special focus on the area the cracking in which occurred. The stress-strain parameters are supplemented with evaluation of other important influencing factors, such as the material flow and distribution of temperature. The predicted results are supported by experimental data from microscopic analyses and microhardness measurements.
2. Materials and Methods

The presented study was performed to provide numerical and experimental characterization of selected factors within a lead brass (CuZn40Pb2) fitting, i.e. pre-shaped gas valve, produced by GCE company (Gas Control Equipment, Chotěboř, Czech Republic), which exhibited cracking during hot die forging (see Figure 1a for the axial longitudinal cut through the fitting the cracked area in which was highlighted). The fitting was manufactured from a cast and subsequently extruded semi-product (rod), which was subsequently subjected to induction heating to the processing temperature of 680 °C, followed by die forging. The chemical composition of the brass the fitting from which was produced, acquired via inductively coupled plasma atomic emission spectroscope, i.e. ICP-AES, was the following (in wt. %): Cu 58.10, Zn 39.6, Pb 1.75, Fe 0.27, Sn 0.20, Ni 0.07, Al 0.004, Si 0.003.

2.1. Numerical analyses

The first step performed to investigate the parameters of interest within the forged fitting during processing was assembling the FEM numerical simulation of die forging with the help of Forge NxT® commercial software. To be able to compare the predicted results with the experimentally acquired ones, the geometrical dimensions, as well as mechanical properties of the FEM assembly, were selected to be identical to the experimental conditions (see Figure 1b for the numerical model of the brass fitting). The dies were defined to be rigid, while the brass billet was defined to be a deformable body meshed with tetrahedral elements with activated re-meshing (intensive plastic deformation was expected to occur). According to the real processing conditions, the friction was defined via using a graphite lubricant, and the defined tools’ speed was 3 mm/s. The selected boundary conditions for the elevated processing temperature of 680 °C were the thermal conductivity of 120 W/(mK), thermal expansion coefficient of \(2.2 \times 10^{-5} \text{ (K}^{-1})\), specific heat of 380 J/kgK, Young’s modulus of 30 GPa, Poisson’s ratio of 0.35, emissivity of 0.7, and density of 8440 kg/m\(^3\). The simulation was defined via using an elastic-plastic model with implemented Newton–Raphson convergent algorithm and the mechanical properties of the used brass were acquired experimentally using SETARAM device (servo-hydraulic torsion plastometer), and subsequently imported to the material flow stress database of the Forge NxT software. The deformation behaviour of the brass semi-product was characterized with the help of the Haensel-Spittel equation (e.g. [23–25]), the values of the regression coefficients for which were \(A = 8039.59 \text{ MPa, } m_1, m_2, m_3, \text{ and } m_4 \text{ were } -0.00835, -0.00099, 0.1693, \text{ and } -0.00924, \text{ respectively, and } m_5, m_6, m_7, \text{ and } m_8 \text{ were } 0.\)

**Figure 1**: Axial longitudinal cut through die-forged brass fitting with highlighted cracked area (a); numerical model of fitting (b).
2.2. Experimental analyses

The mechanical properties were evaluated via Vickers microhardness measurements. These were performed in two significant locations (two perpendicular lines), in a line along the cracked surface, and in a line from the crack towards the internal volume of the die-forged fitting (for depiction of the measured locations see Figure 2). The loading time for each indent was 10 s, and the load for each was 200 gf. Finally, graphs from both the sets of measurements were drawn.

Subsequent experimental analyses were performed on a sample acquired from a longitudinal axial cut through the fitting (see Figure 1a) via optical microscopy using Olympus DSX100 digital optical microscope, and scanning electron microscopy, Tescan Lyra 3 XMU FEG/SEMxFIB device equipped with Ultim Max EDS detector and Symmetry EBSD detector for which was used. The optical microscopy was used to observe the material flow and compare the real flow of grains with the precipitated material flow vectors. The EDS observation was performed to detect possible presence of precipitates and/or oxides.

3. Results and discussions

3.1. Material flow

The first predicted parameter was the material flow, since inhomogeneities in material flow are among the possible factors which could have imparted the generation of cracks. This parameter was assessed via depicting the material flow vectors. Figure 3a shows the vectors of material flow on the axial longitudinal cut through the simulated fitting at the end of forging. As can be seen in the figure, the volume of the material had a strong tendency to flow towards the upper neck of the fitting (i.e. in the horizontal direction in Figure 3a), which is in accordance with the tendency of the material to flow in the line of least resistance. The simulation of material flow thus revealed that this parameter featured significant inhomogeneities, as presupposed. The area the cracking in which subsequently occurred (depicted with arrow in Figure 3a) featured evident aggravation of material flow, as there are almost no flow vectors evident in this location.

The predicted material flow was experimentally confirmed by optical microscopy analysis (Figure 3b), which also revealed the tendency of the material volume of the brass rod to flow towards the neck of the forged component. The cracked area evidently corresponds to the area the predicted material flow in which was aggravated (the area of crack is in Figure 3b depicted by an arrow).
3.2. Temperature distribution

The inhomogeneous material flow goes hand in hand with changes in the distribution of temperature throughout the forged component. Before forging, the brass rod was homogeneously pre-heated via induction to the processing temperature of 680 °C. Nevertheless, the temperature and its distribution during forging was influenced by mutual effects of several factors. The first important factor is that the pre-heated brass rod was inserted into a die pre-heated to a lower temperature, which instantaneously imparted heat transfer from the hotter brass to the cooler die. The second important factor affecting the temperature is friction between the brass and the die. Friction is generally known to affect the processed material by influencing its (surface) temperature [27]. Nevertheless, as the material flow of the brass was inhomogeneous, the temperature of the forged product was inhomogeneously affected by friction, too, and thus local decreases in temperature occurred.

This is documented by Figure 4, the temperature distribution throughout the forged brass product in which is depicted. The figure shows that the temperature was the highest in the neck area of the fitting, i.e. in the area the material flow in which was the most intense. On the other hand, the temperature
was the lowest in the peripheral areas of the conical part of the fitting, including the area in which the crack occurred, which exhibited temperature drop to approx. 650 °C.

3.3. Stress-strain parameters
The inhomogeneous temperature distribution, together with the inhomogeneous material flow, non-negligibly affects the stress-strain relations within the forged fitting.

Figure 5a shows a detail of the area of crack with predicted stress distribution during forging. As can be seen, this particular location featured evident stress inhomogeneity, areas exhibiting tensile and compressive stresses in which fade into one another. Such stress distribution was most probably imparted by the mutual effect of the geometry of the die, which introduced the aggravated material flow in this location, resulting in the observed local temperature drop. These factors most probably imparted increased friction, and consequently the development of residual stress, which could not further be relaxed. The inhomogeneous stress state was a significant contributor to the cracking.

The predicted effective imposed strain along the axial longitudinal cut through the fitting is depicted in Figure 5b. The figure shows that the effective strain was the highest in the shaped areas of the forged fitting (depicted by red colour). Nevertheless, the majority of the conical part of the fitting, together with certain locations in its shaped part, including the area the material flow in which was aggravated, featured lower effective strain values (compared to the shaped areas). As can be seen, the area of the crack is located in the region featuring effective imposed strain inhomogeneity; the blue colour depicting the effective strain of around 1 changes rapidly into the green colour, i.e. the effective strain increases rapidly to the values of around (and more than) 2 in this location.

![Figure 5: Predicted stress distribution along cracked area, detail from axial longitudinal cut through the fitting (a); predicted effective imposed strain along axial longitudinal cut through the fitting (b).](image)

3.4. Structure analysis and Microhardness
The predicted parameters were subsequently verified experimentally via structure analyses and microhardness measurements.

Figure 6a depicts a SEM-SE image of the cracked area; given by the aggravated material flow and decreased (sub)surface temperature in this location, the material evidently relaxed the developed residual stress via “stemmed” cracking. The following analyses were focused on mapping of the chemical composition in the cracked area in order to evaluate possible presence of oxides. Figure 6b shows the maps of the substantial elements resulting from the EDS analyses. The crack most probably
originated during forging since the stems of the crack evidently contained oxygen. The cracked area also exhibited depletion of copper, however, higher contents of zincs. The analyses thus point to the presence of zinc oxides in the crack.

![Figure 6: SEM-SE image of cracked area (a); SEM-EDS maps of elements present in cracked area (b).](image)

Last but not least, Vickers microhardness analyses were performed. Figure 7a shows the distribution of microhardness along the cracked surface of the forged fitting, while Figure 7b shows the profile of microhardness in the direction perpendicular to the cracked surface, i.e. towards the internal volume of the fitting (see Figure 2 for the depiction of the measured locations).

The surface of the forged product evidently featured the highest measured HV values, although sudden drops of microhardness can be observed in the exact locations of the “stems” of the crack. These finding corresponds to the structure observations, i.e. to the presence of hard and brittle oxides. The location of the most prominent crack (point at the distance of 5.5 mm in Figure 7a) was then the starting point for the second (perpendicular) line of measurement. Figure 7b depicts that the HV values decreased already in 1 mm distance from the surface of the forged component and remained more or less constant towards its internal volume; the average microhardness value in the internal volume of the forged fitting was 102.3 HV.

![Figure 7: Microhardness along the cracked surface of forged fitting (a); microhardness profile perpendicular to the cracked surface towards axial region of forged fitting (b).](image)

4. Conclusions
The aim of the herein presented study was to numerically and experimentally analyse the stress-strain relations within a brass fitting exhibiting cracking during hot die forging, including selected important influencing factors. The investigations revealed that the critical location the cracking in which occurred exhibited significant aggravation of the material flow, which resulted in accelerated heat transfer from the heated brass billet to the cooler die and imparted temperature drop in this location.
These factors were the most important phenomena behind the development of inhomogeneous stress state in the critical location and subsequent occurrence of “stemmed” cracking. Supplementary experimental analyses documented that the crack contained hard and brittle zinc oxides, which also resulted in local increase in (sub)surface Vickers microhardness values.

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**References**

[1] A. Russell, K.L. Lee, "Structure-Property Relations in Nonferrous Metals," 1st ed., John Wiley & Sons, Inc., New Jersey, 2005.

[2] M. Kreuzeder, M.-D. Abad, M.-M. Primorac, P. Hosemann, V. Maier, D. Kiener, "Fabrication and thermo-mechanical behavior of ultra-fine porous copper," *J. Mater. Sci.* vol. 50, pp. 634–643, 2014.

[3] X.H. Chen, L. Lu, K. Lu, "Electrical resistivity of ultrafine-grained copper with nanoscale growth twins," *J. Appl. Phys.* vol. 102, p. 083708, 2007.

[4] L. Kunčíčková, R. Kocich, Dvořák, A. Macháčková, "Rotary swaged laminated Cu-Al composites: Effect of structure on residual stress and mechanical and electric properties," *Mater. Sci. Eng. A.* vol. 742, pp. 743-750, 2019.

[5] T. Sapanathan, S. Khoddam, S.H. Zahiri, A. Zarei-Hanzaki, "Strength changes and bonded interface investigations in a spiral extruded aluminum/copper composite," *Mater. Des.* vol. 57, pp. 306–314, 2014.

[6] L. Kunčíčková, R. Kocich, "Deformation behaviour of Cu-Al clad composites produced by rotary swaging," *IOP Conf. Ser. Mater. Sci. Eng.* 369, p. 012029, 2018.

[7] I. Hamidah, A. Solehuddin, A. Hamdani, L. Hasanah, K. Khairurrijal, T. Kurniawan, R. Mamat, M. Kreuzeder, M. Primorac, P. Hosemann, V. Maier, D. Kiener, "Corrosion of copper alloys in KOH, NaOH, NaCl, and HCl electrolyte solutions and its impact to the mechanical properties," *Alexandria Eng. J.* vol. 60, pp. 2235–2243, 2021.

[8] Y. Geng, Y. Ban, B. Wang, X. Li, K. Song, Y. Zhang, Y. Jia, B. Tian, Y. Liu, A.A. Volinsky, "A review of microstructure and texture evolution with nanoscale precipitates for copper alloys," *J. Mater. Res. Technol.* vol. 9, pp. 11918–11934, 2020. https://doi.org/10.1016/j.jmrt.2020.08.055.

[9] P. García, S. Rivera, M. Palacios, J. Belzunce, "Comparative study of the parameters influencing the machinability of leaded brasses," *Eng. Fail. Anal.* vol. 17, pp. 771–776, 2010.

[10] G. Pantazopoulos, A. Vazdirvanidis, "Characterization of the microstructural aspects of machinable alpha-beta phase brass" - 2013 - Wiley Analytical Science, 2006.

[11] Y.H. Xiao, C. Guo, X.Y. Guo, " Constitutive modeling of hot deformation behavior of H62 brass," *Mater. Sci. Eng. A.* vol. 528, pp. 6510–6518, 2011.

[12] J. Matsumoto, H. Anada, M. Furui, "The effect of grain size and amount of β phase on the properties of back-torsion working in 60/40 brass," *Adv. Mater. Res.* pp. 661-666, 2007.

[13] G. Pantazopoulos, "Ledged brass rods C 38500 for automatic machining operations: A technical report," *J. Mater. Eng. Perform.* vol. 11, pp. 402–407, 2002.

[14] A.B. Naizabekov, V.A. Andreyachshenko, R. Kocich, "Study of deformation behavior, structure and mechanical properties of the AlSiMnFe alloy during ECAP-PBP," *Micron* vol. 44, pp. 210–217, 2013.

[15] R. Kocich, A. Macháčková, L. Kunčíčková, "Twist channel multi-angular pressing (TCMAP) as a new SPD process: Numerical and experimental study," *Mater. Sci. Eng. A.* vol. 612, pp. 445–455, 2014.

[16] L. Kunčíčková, R. Kocich, P. Král, M. Pohludka, M. Marek, "Effect of strain path on severely deformed aluminium," *Mater. Lett.* vol. 180, 280–283, 2016.
[17] U.M. Iqbal, S. Muralidharan, "Optimization of die design parameters and experimental validation on twist channel angular pressing process of AA6061-T6 aluminium alloy," *Mater. Res. Express.* vol. 6, p. 086512, 2019.

[18] L. Kunčická, R. Kocich, V. Ryukhtin, J.C.T. Cullen, N.P. Lavery, "Study of structure of naturally aged aluminium after twist channel angular pressing," *Mater. Charact.* vol. 152, pp. 94–100, 2019.

[19] H. Naser Radhi, M. Talib Mohammed, A.M.H. Aljassani, "Influence of ECAP processing on mechanical and wear properties of brass alloy," *Mater. Today Proc.* vol. 44, pp. 2399–2402, 2021.

[20] L. Kunčická, R. Kocich, C. Hervoches, A. Macháčková, "Study of structure and residual stresses in cold rotary swaged tungsten heavy alloy," *Mater. Sci. Eng. A.* vol. 704, pp. 25–31, 2017.

[21] N. van den Berg, H. Xin, M. Veljkovic, "Effects of residual stresses on fatigue crack propagation of an orthotropic steel bridge deck," *Mater. Des.* vol. 198, p. 109294, 2021.

[22] L. Kunčická, R. Kocich, P. Strunz, A. Macháčková, "Texture and residual stress within rotary swaged Cu/Al clad composites," *Mater. Lett.* vol. 230, pp. 88–91, 2018.

[23] R. Kocich, "Effects of twist channel angular pressing on structure and properties of bimetallic Al/Cu clad composites," *Mater. Des.* vol. 196, p. 109255, 2020.

[24] R. Kocich, L. Kunčická, A. Macháčková, "Twist Channel Multi-Angular Pressing (TCMAP) as a method for increasing the efficiency of SPD," *IOP Conf. Ser. Mater. Sci. Eng.* vol. 63, p. 012006, 2014.

[25] L. Kunčická, A. Macháčková, N.P. Lavery, R. Kocich, J.C.T. Cullen, L.M. Hlaváč, "Effect of thermomechanical processing via rotary swaging on properties and residual stress within tungsten heavy alloy," *Int. J. Refract. Met. Hard Mater.* vol. 87, pp. 1–15, 2020.

[26] B. Beausir, J.J. Fundenberger, "Analysis Tools for Electron and X-ray diffraction," *ATEX software*, www.atex-software.eu, (2017).

[27] R. Kocich, M. Kursa, A. Macháčková, "FEA of Plastic Flow in AZ63 Alloy during ECAP Process," *Acta Phys. Pol. A.* vol. 122, pp. 581–587, 2012.