PRELIMINARY LOW CYCLE STUDIES OF 1.2344 HOT-WORK TOOL STEEL USED FOR FORGING TOOLS

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Abstract

This paper presents the results of preliminary low-cycle fatigue tests of 1.2344 tool steel, used to make forging tools for work in higher temperatures. Based on macro- and micro-structural studies and numerical simulation of industrial forging processes, the conditions for performing laboratory fatigue tests were determined. Samples were subjected to cyclic, uniaxial loading (under tensile-compressive conditions) at four levels of total strain amplitude (0.5; 0.8; 1.0; 2.0 %), at two temperatures: 20 and 600 °C. The results of fatigue tests were approximated using the Manson-Coffin-Basquin equation in a ε_a-$2N_f$ system and then used during verification of damage on a selected forging punch, which revealed high consistency between results. The comparative analysis of fatigue test results and numerical analyses, combined with microstructural studies, conducted in this work, demonstrated the possibility of using these tests, analyses and studies in the process of designing tools used in forging processes from the perspective of their durability and resistance to thermomechanical fatigue.

Keywords: Low cycle fatigue of 1.2344 steel, durability of forging tools, thermo-mechanical fatigue

1. INTRODUCTION

Determining the durability of tools subjected to cyclic thermal and mechanical loads is a significant problem in modern materials engineering. Fluctuating stresses significantly reduce the lifetime of parts, since destruction occurs at stresses lower than the material's static strength. Determining the durability of tools in processes in which thermal loads are present alongside mechanical loads poses particular difficulties. Such conditions are present in hot die forging processes, among other, in which the temperature of tools in the near-surface layer may reach from as low as 50 to 700 °C, and stresses may reach up to 1200 MPa. For this reason, numerous studies are being conducted in the field of materials engineering concerning both the development of new tool materials dedicated for such processes and advanced studies of the behavior of hot-work tool steels under similar operating conditions [1]. Based on analysis of the state-of-the-art, it can be stated that much valuable information about the durability of forging tools and behavior of tool material at elevated temperatures can be obtained on the basis of fatigue tests that are simple to perform [2-10].

The research problem undertaken in this paper is the experimental verification of the possibility of using the results of low-cycle fatigue tests conducted under laboratory conditions for advanced analysis of the durability of a selected forging tool.

2. LOW-CYCLE FATIGUE OF FORGING TOOLS

The extreme working conditions of forging tools may sometimes cause them to become damaged prematurely. As a result of cyclic thermal loads caused by alternating heating and cooling of a tool's surface, thermal stresses occur within it, finally leading to the formation of a network of microcracks. This form of damage is defined as thermal fatigue. This is why tool working temperature is a significant parameter of the forging process, in terms of both tool durability and the quality of the ready product. In addition, in die forging processes, the presence of cyclically variable mechanical loads causes the occurrence of fatigue processes defined as mechanical fatigue, the intensity of which increases due to the appearance of the microcrack network formed as a result of thermal fatigue, which ultimately forms macro-cracks. The codependency of thermal and mechanical fatigue mechanisms means that both of these mechanisms are considered together as thermomechanical fatigue (**Figure 1a** and **Figure 1b**) [1,11,12].

a) b)

Figure 1 The vief of: a) die after forging of 7900 face wheel forgings with a photograph of the surface, b) die (cut in half) after forging of 8371 CVJB forgings with a SEM photograph of the surface

Over the course of tool exploitation, as the number of performed forgings grows, the network of thermomechanical cracks develops and progresses (a secondary crack network forms), simultaneously intensifying abrasive wear. This leads to total tool destruction. Average lifetime (durability), defined as the number of manufactured forgings (without defects) ranges from 1000 forgings (dies for forging with stamps) to over ten thousand, depending on the tool (average lifetime for the insert in **Figure 1a** is 10000 forgings, for the die in **Figure 1b** - 16000 forgings), and sometimes this lifetime is as low as several dozen forgings (tools for upset forging/flattening). In the case of damage in forging tools, the decisive destructive mechanism is low-cycle thermomechanical fatigue (over ten thousand forgings - fatigue cycles), being the dominant destructive mechanism leading to reduction of their durability. Studies conducted by the authors employing numerical modeling of industrial forging processes allow for determination of characteristic parameters of the technological process than cannot be determined otherwise. **Figure 2a** presents examples of temperature distributions in the tool in the final phase of forging deformation (the forming-forging process itself lasts no more than 0.2 s), and **Figure 2b** shows distributions with total deformation for 2 tools used in the second operation of forging the face wheel [11].

a) b)

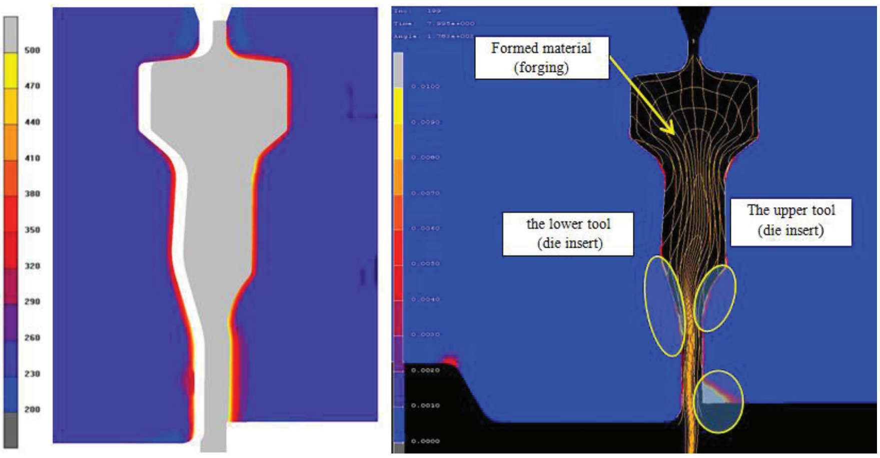

Figure 2 Distributions of: a) temperature and b) total deformation, obtained from MES (axisymmetrical model) for die inserts made of WCLV preliminarily heated to 250 °C, forging material QS19-20, preform heated to 1150 °C

The presented temperature and deformation distributions indicate that, in certain areas of the tool, particularly in the central part of both tools, temperatures above 600 °C occur on their surfaces, and deformations in these same areas range from 0.002 to above 0.01. Such high deformation values (at a level of 0.01) may constitute localized areas of plastic deformations, which is typical for low-cycle fatigue (thermomechanical) in hot die forging processes. Studies conducted using a thermovisual camera confirmed the results of numerical modeling (values and areas of occurrence). On one hand, the high temperature gradients will cause thermal fatigue phenomena, and in turn, the longtime of contact between the hot forging and the tool may result in local tempering, which could presumably lead to plastic deformations. On the other hand, the application of increasingly advanced measuring methods as well as temperature determination on the basis of e.g. numerical modeling is difficult, but definitely justified, since such information could serve for determination of critical points in the tool, which, in combination with microstructural studies and strength tests, would make it possible to obtain a complete characterization of the tool's work [4,1,11].

That is why interesting as well as valuable information on the occurrence and development of thermo-mechanical cracks can be provided by laboratory fatigue tests conducted under conditions similar to those present in industrial forging processes. The results presented by the authors of this work can be used to support numerical modeling and detailed analysis of the degradation mechanisms occurring in die forging processes, as well as in the selection of a better tool material, during tool designing and in the application of other methods of increasing the life of forging tools [12].

3. TEST DESCRIPTION AND METHODOLOGY

Cylindrical samples with threaded heads, with nominal size of the measuring part d = 8 mm and length of the measuring base γ = 15 mm, prepared according to standard PN-84/H-04334 and its equivalent, were used in static tensile tests as well as low-cycle fatigue tests [13]. Samples made of 1.2344 hot-work tool alloy steel underwent thermal treatment: quenching and two-fold tempering. After the thermal treatment, the hardness on the surface of all the samples was in the range of 50-50.5 HRC; similar hardness values are used for forging tools. For accurate determination and selection of the amplitude of total deformation under the conditions of strength tests, static tensile tests were first performed at 20 and 600 °C, corresponding to the conditions of the tools' work. The sample, fixed in the machine holders, was exposed to the action of increasing tensile force equaling 0.05 mm / s and loaded in the axial direction until the moment of its permanent separation in the measuring part area.

3.1. Description of the industrial forging process for verification of results

In order to verify the results, analysis of the durability of the selected forging tool was carried out in the forging process performed on a P-1800T press, nominal force 18 MN, in three forging operations: upsetting, roughing and finishing forging. The elements were forged from C45 steel. The temperature of the charge material equaled 1150 °C. All tools are made from 1.2344 hot-work steel. The research concentrated on the tools assigned for the second operation (roughing), which exhibited the lowest durability (about 5400 forgings), and a detailed analysis was performed on the stamp of the upper die (**Figure 3**).

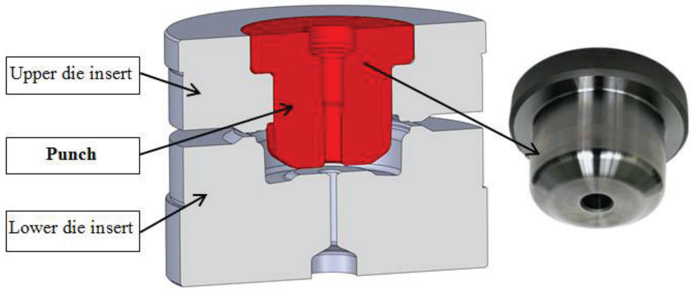

Figure 3 Tool set in 2nd operation of roughing (preliminary forging)

Numerical modeling of the second forging operation was also performed to determine characteristic areas on the tool and to determine temperature distributions and normal pressures.

4. RESULTS

The results of static tensile tests of WCLV (1.2344) steel at three temperatures (T_1 = 20 °C, T_2 = 600 °C) are presented in **Figure 4** in the form of tensile charts in the coordinate system: sample elongation ε - stress σ. Stress in the sample during static and fatigue tests was calculated by dividing instant load values registered during the tests by the sample's initial cross-sectional area. Basic mechanical properties of the tested steel are given in **Table 1**.

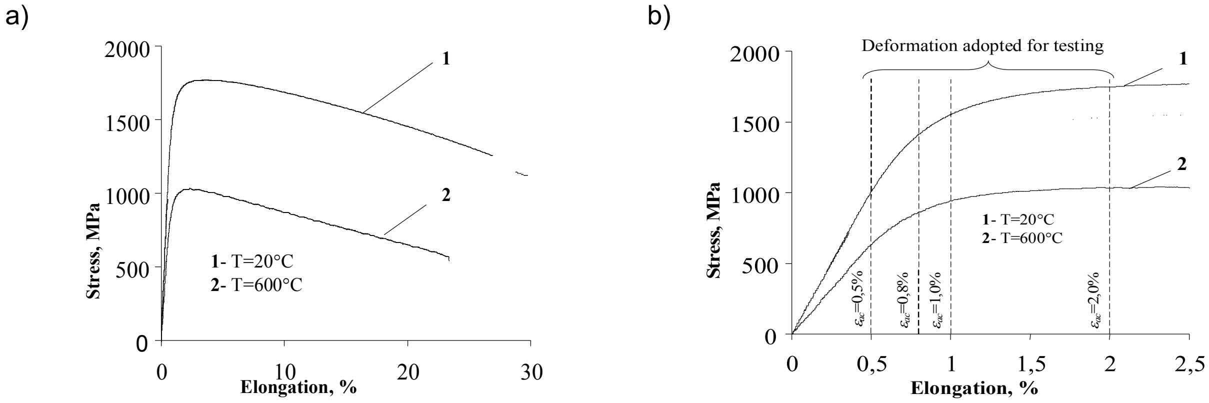

Figure 4 Results of static tests: a) tensile charts, b) initial area of the chart to selection of strain amplitude

Table 1 Strength parameters of WCLV steel at different temperatures of tensile testing

Parameter name	Temperature	
	20 °C	600 °C
R_m [MPa]	1778	1041
$R_{p0,2}$ [MPa]	1528	913.6
$A_{12,5}$ [%]	26.9	23.4
Z [%]	49.8	52.1
R_u [MPa]	2513	1137
E [MPa]	207020	126910

Cyclic weakening of samples was observed during low-cycle fatigue tests. This manifested as continuous reduction of the maximum load on the sample at a constant amplitude of total deformation ε_{ac}. The testing temperature has an effect on the degree of weakening. **Figure 5** shows examples of stress σ_a charts as a function of the number of loading cycles at two temperatures (T = 20 °C and T = 600 °C). Based on comparative analysis of the charts presented in **Figures 6a** and **6b**, it can be stated that temperature and deformation level have an impact on the degree of change of the analyzed parameter (ε_a). Stress changes at a single strain level increase as temperature and deformation ε_{ac} increase.

According to [14], fatigue charts in a bilogarithmic system were approximated using the Manson-Coffin-Basquin equation [15] in the form of:

$$\frac{\Delta\varepsilon_{ac}}{2} = \frac{\Delta\varepsilon_{ae}}{2} + \frac{\Delta\varepsilon_{ap}}{2} = \frac{\sigma_f'}{E}\left(2N_f\right)^b + \varepsilon_f'\left(2N_f\right)^c \qquad (1)$$

where: b - fatigue strength exponent, c - cyclic deformation exponent, ε_f' - coefficient of fatigue strength in MPa, ε_f' - coefficient of cyclic plastic deformation, E - Young's modulus in MPa.

Due to the absence of the stabilization period in equation (1), coefficients and exponents were determined for hysteresis loop parameters at half of fatigue strength (n / N = 0.5). Fatigue charts obtained as a result of approximation of fatigue test results using equation (1), for two temperatures, are shown in **Figure 6a**.

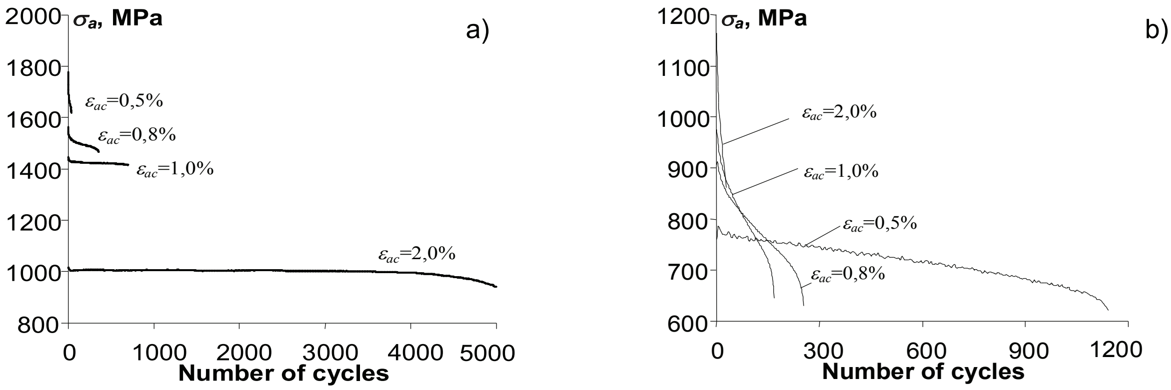

Figure 5 Changes of stress ε_a as a function of the number of loading cycles: a) T = 20 °C, b) T = 600 °C

4.1. Verification of the results

Figure 6 presents results obtained for selected areas in the tool based on determined fatigue strength charts (**Figure 6a**) from the perspective of deformation, distributions of total deformation determined by the FEM (**Figure 6b**) and SEM photographs of selected areas (**Figure 6c**).

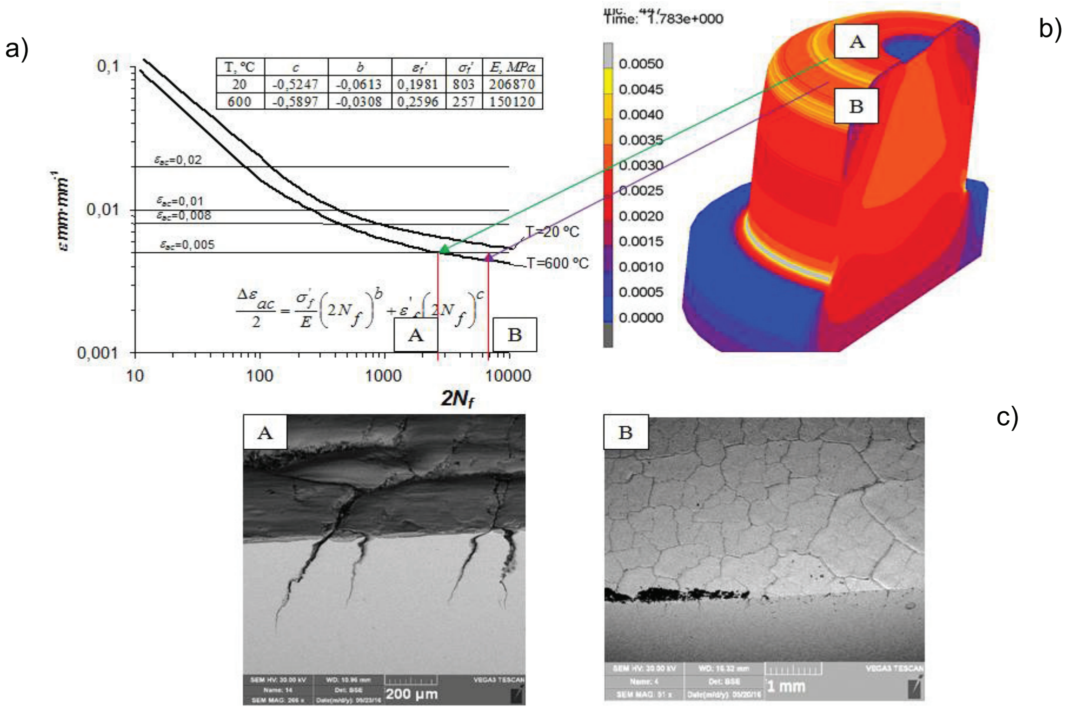

Figure 6 The view of: a) fatigue charts from a deformation perspective, b) results of FEM simulation - distributions of total deformation, c) photographs of microstructure in selected areas of a tool after 4000 forgings: A - 0.005 deformation - visible network of thermomechanical fatigue cracks along with deep cracks, B - 0.003 deformation - visible mild crack network of thermal origin

Based on the presented charts, it can be stated that the testing temperature significantly affects fatigue strength. Its impact depends on the amplitude of total deformation. This impact is low in the area of the greatest deformations (ε_{ac} = 2.0 %) and increases as the deformation level is reduced. The decidedly greater influence of elevated temperature on fatigue strength at the lowest levels of deformation can be justified by the significantly greater increase of the range of plastic deformation at these levels at a temperature of 600ºC compared to the increase of the plastic deformation range at the highest levels (**Figure 6a**).

The presented verification tests (**Figures 6b** and **6c**) showed that for the defined operating conditions, defined on the basis of both FEM (deformation and temperature distributions) and results of microstructural studies of selected areas of the forging tool, the determine low-cycle fatigue curves are reliable. Based on the SEM photographs presented in **Figure 6c** for area A, a "large" network of thermomechanical fatigue cracks is visible on the tool's surface, and there are clear, deep and partially curved cracks in the cross-section indicating the presence of plastic deformations. In this area, the deformation distribution determining by FEM is at a level of 0.005, which gives a value of approx. $4000 \cdot 2N_f$, corresponding to approx. 4000 forgings, on the fatigue curve for a temperature of 600 °C. In area B, a characteristic network of cracks typical for thermal (potentially thermomechanical) fatigue is visible, and there are no cracks in the cross-section. It should be emphasized that slightly higher temperatures and normal pressure values are present in area A (**Figure 6**) in comparison to area B, thus a slightly different proportion of destructive mechanisms is possible. It should also be emphasized that it is difficult to distinguish the proportions of individual destructive mechanisms occurring in selected areas of a forging tool since the wear process is very complex, as confirmed by numerous studies. Nevertheless, the determined fatigue curve (particularly for 600 °C) obtained on the basis of laboratory fatigue tests and applied conversion methods have been positively verified on the example of analysis of the selected forging tool.

5. SUMMARY

This paper presents the results of low-cycle fatigue tests of 1.2344 tool steel, used to make forging tools for work at elevated temperatures. Based on analysis of the results of fatigue tests conducted on samples and the results of computer simulations, additionally confirmed by studies of microstructure, it was stated that it is possible to use the results of experimental tests (material samples) in the process of designing tools used in industrial forging processes from the perspective of their durability and resistance to thermal and thermomechanical fatigue. The results of low-cycle fatigue tests can also be used for numerical modeling of die deformations in order to implement a thermomechanical fatigue model for modeling the wear process of forging tools. It seems that conducting further studies concerning fatigue strength for tool steels, particularly under different operating conditions determined on the basis of analysis of tool work, is highly justified. It would also be valuable to convert the results of fatigue tests and to present and identify the tool areas subjected to the greatest mechanical load from a stress perspective σ_a - N_f.

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REFERENCES

[1] HAWRYLUK, M., ZWIERZCHOWSKI, M., MARCINIAK M., SADOWSKI P. Phenomena and degradation mechanisms in the surface layer of die inserts used in the hot forging processes. *Engineering Failure Analysis,* 2017, vol.*79*, pp. 313-329.

[2] MROZIŃSKI, S., GOLAŃSKI, G., Low cycle fatigue and cyclic softening behaviour of martensitic cast steel, *Engineering Failure Analysis, 2013, vol. 2086*, pp. 692-702.

[3] NAGESHA, A., et al. Influence of temperature on the low cycle fatigue behaviour of a modified 9Cr-1Mo ferritic steel. *International Journal of Fatigue*, 2002, vol. 24, pp. 1285-1293.

[4] ANDERS, P., HOGMARK, S., BERGSTRÖM, J. Simulation and evaluation of thermal fatigue cracking of hot work tool steels. *International Journal of Fatigue*, 2004, vol. 10, pp.1095-1107.

[5] LAPOVOK, R., SMIRNOV, S., SHVEYKIN, V. Damage mechanics for the fracture prediction of metal forming tools. *International Journal of Fracture*, 2000, vol. 103 (2), pp. 111 - 126.

[6] LAVTAR, L., MUHIC, T., KUGLER, G., TERCELJ, M. Analysis of the main types of damage on a pair of industrial dies for hot forging car steering mechanisms. *Engineering Failure Analysis*, 2011, vol. 18 (10), pp. 1143-1152.

[7] PERSSONA, A., HOGMARKB, S., BERGSTROMA, J. Thermal fatigue cracking of surface engineered hot work tool steels*, Surface & Coatings Technology*, 2005, vol. 191, pp. 216- 227.

[8] BERTI, G. A., MONTI, M. Thermo-mechanical fatigue life assessment of hot forging die steel, *Fatigue & Fracture of Engineering Materials & Structures*, 2005, vol. 28 (11), pp. 1025-1034.

[9] SHIOZAWA, K., TOMOSAWA, T., HAN L., MOTOBAYASHI K. Effect of flows in coating film on fatigue strength of steel coated with titanium nitride. *JSME international Journal, series A,* 1996, vol. 39(1), pp. 142-150.

[10] KOCAŃDA, A. Określenie trwałości narzędzia w obróbce plastycznej metali, rozdział w monografii pt. Informatyka w Technologii Metali, red. A. Piela, F. Grosman, J. Kusiak i M. Pietrzyk, Wyd.Politechniki Śląskiej, Gliwice, 2003, pp. 213-256.

[11] GRONOSTAJSKI, Z, et al. Application of the reverse 3d scanning method to evaluate the wear of forging tools divided on two selected areas, *International Journal of Automotive Technology*, 2017, vol. 18 (4), pp. 653−662.

[12] Hawryluk, M. Review of selected methods of increasing the life of forging tools in hot die forging processes, *Archives of Civil and Mechanical Engineering*, 2016, vol. 16, pp. 845-866.

[13] ASTM E 606 - 04 Standard Practice for Strain-Controlled Fatigue Testing.

[14] MANSON S.S. Behaviour of materials under conditions of thermal stress. NACA TN - 2933 1953.

[15] RAMBERG W, OSGOOD W.R. Description of stress-strain curves by three parameters. NACA, Tech. Note 402. 1943.