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NUMERICAL MODELLING OF THE THERMAL FATIGUE OF STEEL WCLV USED FOR HOT FORGING DIES

MODELOWANIE NUMERYCZNE ZMĘCZENIA CIEPLNEGO STALI WCLV STOSOWANEJ NA MATRYCE W PROCESIE KUCIA NA GORĄCO*

The paper presents an analysis of a numerical simulation of the low-cycle thermal fatigue of steel WCLV (X40CrMoV511) used in hot forging. As part of experimental studies a special test rig based on the rotating disc method was built and tests were carried out. Their results showed that the method can be used to reproduce the thermal fatigue conditions prevailing in the industrial forging process. For the given experimental conditions the instant when fatigue cracks appear was determined. A numerical model was built and the obtained finite element analysis results were compared with the laboratory test results in order to determine the amplitude of plastic strains at which a crack appears. As part of further research in the future the Coffin-Manson low-cycle fatigue model will be verified for other conditions and a low-cycle fatigue curve for steel WCLV will be determined.

***Keywords**: low-cycle thermal fatigue, the rotating disc method,numerical modelling, die life, hot forging.*

W pracy przedstawiono analizę symulacji numerycznej niskocyklowego zmęczenia cieplnego stali WCLV stosowanej podczas kucia na gorąco. W ramach badań doświadczalnych zostało zbudowane specjalne stanowisko bazujące na metodzie "wirującego krążka" [13], przeprowadzone zostały próby, które potwierdziły możliwość stosowania tej metody do odwzorowania warunków zmęczenia cieplnego panujących w przemysłowym procesie kucia. Dla danych warunków eksperymentu określono moment pojawienia się pęknięć zmęczeniowych. Następnie zbudowano model numeryczny, po czym porównano uzyskane wyniki z MES i prób laboratoryjnych w celu określenia amplitudy odkształceń plastycznych, przy których pojawia się pęknięcie. Dalsze prace pozwolą w przyszłości na weryfikację niskocyklowego modelu zmęczenia Coffina-Mansona dla innych warunków oraz pozwolą stworzyć krzywą niskocyklowego zmęczenia stali WClV.

***Słowa kluczowe**: niskocyklowe zmęczenie cieplne, metoda "wirującego krążka", modelowanie numeryczne, trwałość matryc, kucie matrycowe na gorąco.*

1. Introduction

Because of the extreme operating conditions the dies used in hot forging are exposed to many degrading phenomena. Forging dies are impacted by heavy mechanical and thermal loads and their surface is repeatedly intensively heated up, abraded and oxidized [8, 2, 3, 16]. Thermal fatigue is a major factor contributing to the wear of the tools. Thermal fatigue results from the large temperature gradient due to the changing contact with the preheated material. Because of the tool material's limited thermal conductivity there are large differences in temperature between the core and the surface. As a result, high stresses arise, especially in the die's surface layer. As the consequence of the cyclical variation in temperature the material is alternately tensioned and compressed. Also the dynamic loads exert a considerable impact, introducing additional stresses, which combined with the thermal stresses intensify fatigue leading to tool surface cracking. As a result, a network of fatigue cracks forms and an oxide film appears on the die's surface. As the number of forgings increases, a secondary network of cracks develops, the oxides separate from the surface and acting as an abrasive contribute to the abrasive wear of the tool. The network of cracks has an adverse effect on the quality of the finished product, by imprinting itself on its surface. A fatigue crack may also become the focus of a brittle fracture resulting in the total failure of the tool [5, 6, 1, 17]. Die life is a significant factor in the forging process costs. It is estimated that 10% of the price of a forging constitute tool expenses. Therefore research aimed at effective predicting, extending and optimizing the service life of forging tools is vital [14]. In recent years, not only ordinary nitriding, but also thermal endurance enhancing hybrid coatings have been increasingly often used [12, 10, 19, 7, 9]. Because of the large number and variety of factors having a bearing on forging tool life, this problem is very difficult to analyze. For this reason, increasingly often software tools, such as CAD, CAM and CAE, based on the finite element method (FEM), are employed to design, analyze and optimize forging processes [21, 15]. Information obtained from the FEM is very useful for building the fatigue models which can be used to predict the durability of tools in the real processes. It requires not only suitable experiments but also correct FEM models. There are a lot of research methods into thermal fatigue well described in literature where the thin-walled, discs and cylindrical samples heated by electric induction, the stream of the hot air etc. are applied [11, 13, 14, 19, 20]. Authors in position [4] describe the most popular research method of the thermal fatigue. The processes of thermal fatigue are very difficult to model by FEM regarding the rapid changes of the setting temperature. However, it permits to get the information indispensable to build the fatigue models.

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

2. Research aim and range

The aim of this research was to build an accurate numerical model of the rotating disc method, enabling one to determine the amplitude of the plastic strain resulting from a temperature gradient. As part of the further research the Coffin-Manson low-cycle fatigue will be verified on the basis of the number of cycles after which first cracks appear at the strain amplitude determined for the given conditions by FEM. The Coffina-Manson fatigue model should be correct for thermal and mechanical loads because both kinds of loads result in deformations, which lead to destruction of material.

3. Description of industrial forging of spur gear

The considered industrial process of forging the spur gear in the Jawor Forge PLC consists of three operations performed on a crank press with a load of 25MN (Fig. 1). The first forging operation consists in the upsetting of the cylindrical preform. The second operation is die roughing. In this operation that the greatest forging pressures and material deformations occur. In the third operation, i.e. finishing die forging, the forging assumes a shape close to that of the finished product. A detailed analysis of the process showed that abrasive wear, thermal fatigue and thermal-mechanical fatigue are the dominant material degrading phenomena. Figure 2 shows photographs of the die inserts after a different number of forgings, in which the impacts of the above phenomena are visible.

Fig. 1. Die inserts used in industrial hot forging.

a) b) c)

Fig. 2. Die insert wear after forging: a) 550, b) 1900 and c) 4300 pieces.

4. Thermal fatigue investigations by rotating disc method

In real conditions it is often impossible (and if possible, it takes much time and money) to test the thermal endurance of a material. Then numerical simulations can be run, but they do not always accurately represent the operating conditions of the components or the behaviour of the material. A special test rig is the right tool for the physical modelling of this phenomenon. Having carried out a survey of the literature [5, 11, 13, 20] on the resistance to high temperature gradients and on the peculiarities of the spur gear forging process, the authors designed and built a test rig based on the rotating disc method [18], as well as proposed a test methodology and carried out tests. The arguments for the choice of this method were that thermal fatigue tests are carried out on geometrically simple specimens in easily controllable conditions and that a numerical model reproducing the experiment can be built. The idea of the investigations consists in combining the physical and numerical modelling of the thermal fatigue phenomenon. During testing the material is heated up in its surface layer, similarly as in the hot forging process. A specimen, in the shape of a disc with a hole, was made from tool steel WCLV (the die material). It was subjected to the same thermal treatment as the forging tools, i.e. quenching and double tempering at a temperature of 540°C. The test rig is shown in fig. 3. The disc (8), immersed in water flowing through a tank (8), rotates at constant speed and is superficially (to a depth of about 1-2 mm) heated up by a high-frequency inductor (6) with temperature smoothly adjustable in a range of 100-900°C.

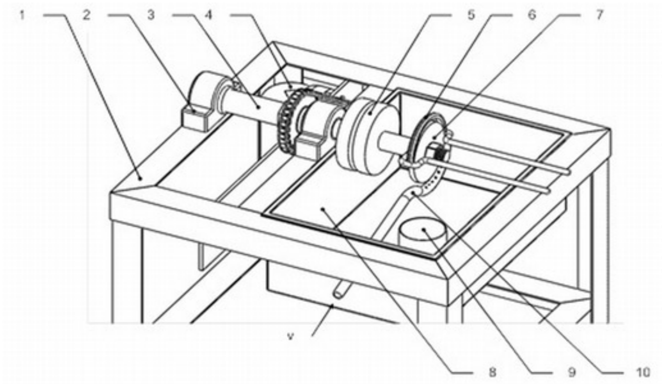

Fig. 3. Scheme of thermal fatigue test rig; 1- steel frame, 2- support with plain bearing, 3- shaft drive, 4- DC motor 5- cooling rings, 6- inductor, 7 - test specimen, 8 - water tank, 9 - water outflow, 10 - adjustable water supply.

In the course of heating the near-surface layer locally very quickly expands while during rapid cooling it undergoes rapid compression.

Figure 4 shows a photograph of the industrial forging process with temperature distributions on the particular dies, taken by a thermovision camera. On this basis proper thermal parameters (the cycle upper temperature T_g=650÷800°C), corresponding to the real process, were selected. Figure 5 shows a thermogram with temperature distributions on the tested specimen. The thermogram was the basis for building a numerical model. Two cycle lengths: 15 s – the actual cycle and 4 s – the shortened cycle were used in the investigations. To make the analysis complete, the average maximum depth of cracks, the density of the cracks and their maximum depth were adopted as the criteria for evaluating the fatigue resistance of the material. Temperature was measured by a thermovision camera and a pyrometer. The cycle length was determined by the motor's rotational speed which could be changed by changing the current intensity and voltage.

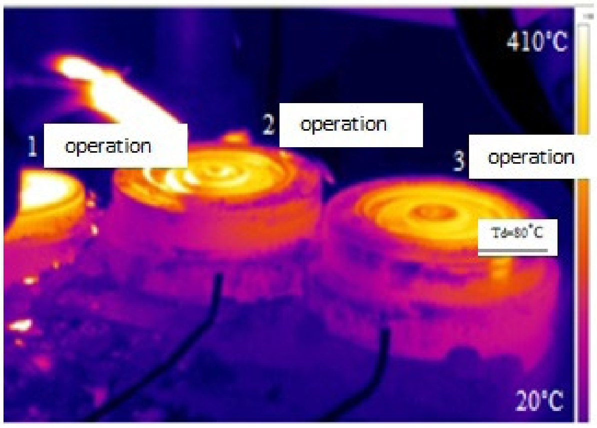

Fig. 4. Thermogram of surfaces of die inserts.

A decision was made to carry out several tests for different cycle lengths and different cycle upper temperatures. In the course of the test the condition of the surface was being documented by a camera. It was critical to determine the instant at which the first cracks appear on

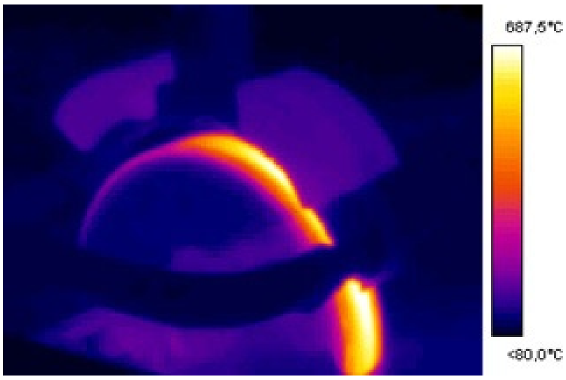

Fig. 5. Thermogram of specimen surface.

the surface of the specimen (observation under optical microscope). Figure 6 shows a typical network of cracks on the specimen's surface at temperature Tg=700°C at which fine cracks appeared already after 50 fatigue cycles. The direction of the cracks was consistent with that of the specimen axis from the middle of the heated path towards the edge. The network had an open character and it expanded with the number of cycles.

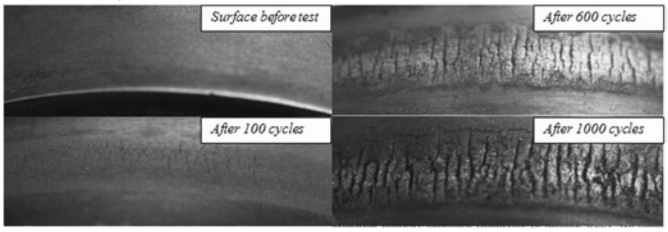

Fig. 6. Network of cracks after successive thermal fatigue cycles in test conditions: cycle length- 5 s, upper cycle temperature 700°C.

5. Numerical modelling

A numerical model was built for the test carried out at T_g=700°C for 5 s. Fifty cycles were simulated since after this number of cycles cracks would appear during the physical test. Rotating disc method simulations were run using the MARC software package. A full (3D) model of the process (fig. 7) was built and the symmetry plane was used to shorten the computing time. The model is made up of 28590 hexa elements. Less thick elements and a denser mesh were used on the face of the disc in order to more accurately reproduce plastic deformations. In the model the heating part (simulating induction heating) and the cooling part (simulating cooling in water) rotate around the stationary disc. The heating part supplies thermal energy

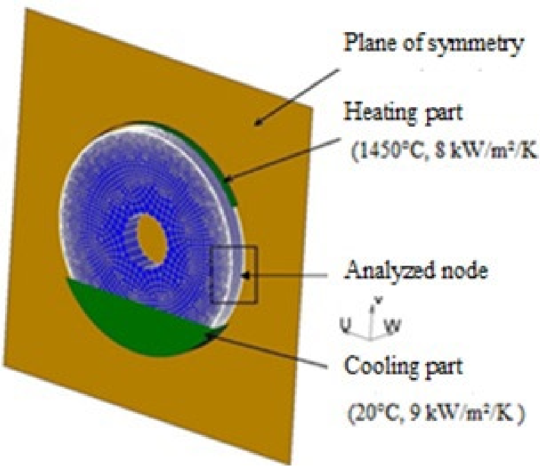

Fig. 7. General view of model

to the disc while the cooling part removes this energy by means of the NEAR CONTACT function. The complete rotation takes about 5 seconds (200 simulation steps). The material specifications were taken from the MATYLDA material database and from dialatometric studies. 20°C and 50°C were adopted as respectively the ambient temperature and the initial temperature of the disc.The temperature of the heating part and that of the cooling part was respectively 1450°C and 20°C. The thermal conductivity coefficients in the contact between the heating and cooling parts and the disc were assumed to be respectively 8 kW/m²/K and 9 kW/m²/K. The thermal conductivity coefficient (selected from material databases) between the disc and the surroundings amounted to 0.35 kW/m²/K.

6. Simulation results

Figure 8 shows the temperature distribution after 50 fatigue cycles (1 cycle=5s) in the symmetry plane where the largest variation in temperature occurred. A diagram of temperature variation in the course of 50 cycles for a selected node is shown in Fig. 9. The results are consistent with the laboratory test results as regards both the temperature variation and distribution (as revealed by the thermogram) on the surface of the specimen.

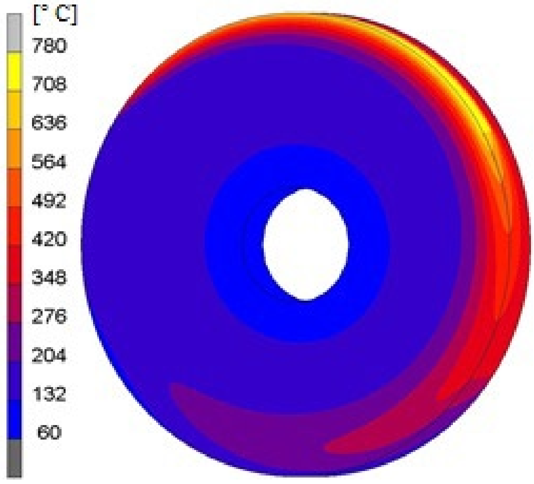

Fig. 8. Temperature distribution after50 cycles.

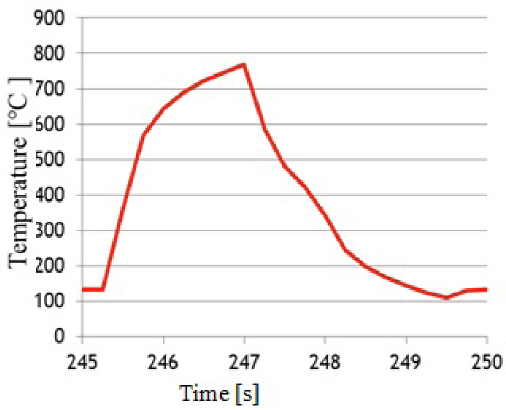

Fig. 9. Distribution of temperature over time (50th cycle).Temperature

Figure10 shows distributions of circumferential strain after 50 cycles since in the case of this method it is these strain components which are mainly responsible for the development of cracks on the side surface of the tested specimen. In the close-up one can see the distribution of strain in the symmetry plane – the place where the

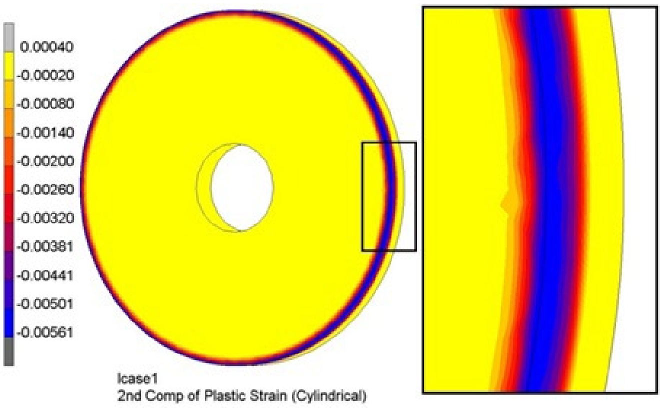

Fig. 10. Distribution of circumferential strain E2 after 50 cycles.

highest strains occur. During the experiments the initiation and propagation of cracks were observed in the specimen surface directions. Figure 11 shows a diagram of circumferential strain over 50 fatigue cycles for a selected node. Positive and negative changes in strain in the course of the whole process are visible. The decrease in circumferential strain amplitude is due to the strain hardening of the material

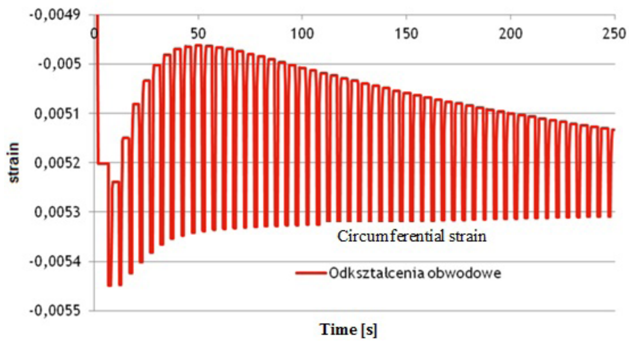

Fig. 11. Circumferential strain-time diagram for selected node.(Strain)

in the successive cycles.

Then the average strain amplitudes and the instant at which cracks appear after a given number of cycles were determined and it will be used to verify the Coffin-Manson low-cycle fatigue model (1).

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f'(2N)^c \qquad (1)$$

where:

- $\Delta\varepsilon_p/2$ – the plastic strain amplitude,
- ε_f' – a coefficient of fatigue ductility
- N – the number of cycles until fatigue,
- c – a fatigue ductility exponent.

ε_f' is approximately equal to the real elongation under monotonic tension and c for most materials changes in a range from −0.7 to −0.5.

Then by changing the test conditions (T_g or the cycle length) and determining the instant when a crack appears during the rotating disc fatigue test one can obtain another circumferential plastic strain amplitude and thereby determine the next points on the low-cycle thermal fatigue characteristic curve. For the diagram obtained in this way it is possible to determine the limit number of cycles for the given tool material in the industrial forging process, after which one can expect fatigue cracks to appear on the surface of the dies. In the case of forging processes, one should also take into account the possibility of cracking as a result of mechanical deformations.

7. Conclusion

The authors using a test rig based on the rotating disc method have created a numerical model of the rotating disc method. Physical tests were carried out to determine the instant when a crack would appear in the specimen's side surface in the given test conditions. The numerical modelling highly accurately reproduced the rotating disc method, and so the course of the real process (but with regard to only thermal loads). In order to reveal very small plastic strains, a denser mesh was applied to the disc face (the finite element thickness was reduced to about 0.1 mm). Thanks to the adopted boundary conditions the stresses and strains occurring in the disc in the course of the process, which could not be physically measured,were determined. The amplitude of the plastic strains needed to determine the limit number of cycles until a crack appears was determined for the forging tools through numerical modelling.

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