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Elastic-Plastic Thermomechanical Fatigue Analysis of Forging Dies

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Abstract. Abrasive wear and low cycle fatigue (LCF) have the greatest influence on the durability of dies. This paper presents a new criterion for estimation of the LCF of forging dies. The deformation model of Manson-Coffin is the classic model for the calculation of LCF. The pulsating cycle of loading dies and the phenomenon of cyclic thermal softening doesn't provide implementation of the full Manson-Coffin's model for the analysis of the tool life. At the same time the majority of researchers do not take into account the plastic strain component for estimating the fatigue durability of the dies and use only elastic component of the Manson-Coffin's law or model of Basquin that is based on the analysis of the stress cycle. The present work uses the strain-kinetic criterion to analyze the durability of the dies that allows taking into account the elastic-plastic strain components and thermos-cyclic softening. During loading in bulk forging the first cycle is to be with plastic deformation while all remaining cycles would have to remain within the elastic limit due to metal hardening. Moreover it has been shown that cyclic softening effect may also be observed in the thermomechanical fatigue. This approach has been implemented for LCF simulation of the die in hot forging in FE program QForm by introducing a special subroutine. The comparison of results of the die fatigue failure simulation has shown good correspondence with practice.

Introduction

Durability of dies is one of the most important factors affecting the cost of hot forging products and is in the range of 5 to 30% of the cost [1]. Work [1] describes four main causes of die failure in hot forging. If we exclude catastrophic die cracking due to overloading, then 70% of die failures are caused by wear and about 25% are related to mechanical fatigue. Plastic deformation of dies and thermal fatigue are a much less significant reason of die failure according to statistical data.

In most of finite element software packages intended for the simulation of forging processes, there are built-in tools for analysis of surface die wear [2]. However, a low cycle fatigue prediction feature is still not available routinely.

A significant feature of the loading of dies is the pulsating character where tool loading in each cycle changes from zero to maximum. Moreover, the maximum loadings could be considered as constant for the same die impression if we do not take into account deviations of the mass and temperature of the forgings in a batch that are relatively small.

Within such circumstances only the first cycle is to be with plastic deformation while all remaining cycles would have to remain within the elastic limit due to metal hardening. This phenomenon is known as an elastic shakedown in continuum mechanics. However, this conclusion is valid only if we assume isotropic hardening. Plastic deformations can be accumulated under kinematic or mixed hardening conditions.

In work [3] it is shown that steady state is usually achieved in the first 8-10 cycles. For a hardening material, it will correspond to the elastic cycle. The accumulation of plastic deformation goes down with each cycle.

In [4, 5] it is pointed out that the effect of cyclic softening depending on the temperature, frequency etc. may influence the thermomechanical fatigue in die steels. Efimov and others have shown in work [6] that the softening of die steels also exists under static loading. Moreover, the softening has the biggest effect in the initial stage but then the intensity of softening reduces.

In [4] a mathematical model is proposed that determines the change of flow stress during cyclic loading. The model is based on a generalized model of hardening by Lemaitre [7] for uniaxial stress state Eq. 1, Eq. 2:

$$|\sigma - X| - R - \sigma_Y = 0 \tag{1}$$

where X is the kinematic component of the hardening, R – isotropic component, σ_Y – yield stress.

$$R = Q_1 \cdot \varepsilon^p + Q_2\left(1 - \exp\left(-\beta \cdot \varepsilon^p\right)\right) \tag{2}$$

where ε^p is the accumulated plastic strain, Q1, Q2, β are the parameters dependent on the material and temperature.

Methods of calculating the low cycle fatigue

The process of the product life cycle can be divided into two stages: the nucleation of the crack and its growth. The initial dies are considered as crack free. Practice of calculations [8] shows that accounting for cracks propagation in the total life cycle of a die can be discard.

Manson-Coffin's strain model is the classical approach for low cycle fatigue analysis. According to this model the total strain in a cycle is the sum of elastic and plastic strains and each of them has a power dependence on number of cycles to failure [9]. Then Morrow proposed another formulation of the same law by introducing the amplitude of the total strain. This approach is widely used in current investigations. In earlier works Basquin proposed a power relationship between the amplitude of the stresses in a cycle and the number of cycles to failure. In the notation of Morrow, the laws of Manson-Coffin and Basquin may be considered as shown in Eq. 3 and Eq. 4:

$$\frac{\Delta\varepsilon}{2} = \left(\frac{\sigma'_f}{E}\right)\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c \tag{3}$$

$$\frac{\Delta\sigma}{2} = \sigma'_f\left(2N_f\right)^b \tag{4}$$

where $\Delta\varepsilon/2$, $\Delta\sigma/2$ are respectively the amplitudes of total deformation and stresses, $2N_f$ is the number of load reversals (two reversals for each cycle). ε'_f and σ'_f/E are the points of intersection of elastic and plastic lines of the axis at $2N_f$=1 (one reversal), c and b are the slopes of the elastic and plastic lines when using logarithmic scale of cycles.

The calculation of LCF of dies has been the subject of numerous studies. Authors of work [10] studied various models for predicting service life of hot dies. They have concluded that the best approach is using stresses because the stresses in forging dies are mostly in the elastic area. Authors of [11] studied the influence of process parameters and die design features on fatigue failure of dies for extrusion. They have neglected the plastic strain component according to recommendations of [3]. Amplitude value of the stress for the analysis was determined by the equivalent stress, and the amplitude value of the strain - at the maximum principal strain. The calculation results have shown that the approach based on stresses gives the durability more than an order of magnitude smaller than the analysis on the strains amplitude. The comparison with practical data shows the best approximation is observed when the amplitude of stresses is used. The results are stable under different temperatures, strain rates, radii of fillets and the value of the extrusion ratio.

Authors of [12] analyzed the influence of the position of the flash on the die tooling life in cold forging of rings. The calculation was carried out the amplitude of effective stresses based on an average stress in the cycle.

Work in [13] is dedicated to predicting of durability of die inserts made of steel X38CrMoV5-3 (1.2367) with a hardness of 54 HRC. Strains were calculated by simulation of the thermomechanical cycle by finite element method. It was based on an assumption that maximum principal stress and strain are to be used. Only elastic deformation component has been taken into account in the calculations of LCF and predicted number of cycles in the die was 1980. This result is close to reality although slightly overestimating experimental observation (1700 cycles).

Work in [14] showed a comparative analysis of two models: Basquin and Manson-Coffin. The latter one takes into account only the plastic component of strain. Calculations have shown that the Basquin's model works better in predicting the durability of dies from steel H11 in large-scale production while Manson-Coffin's model works better for dies from steel L6 for small-scale production. These results may be explained by different conditions of dies loading. Authors of work in [8] determined the influence of punch radius on the durability of the die for cold forging. The simulation was carried out in two stages of plastic and elastic deformation. Calculated durability was 782 cycles while the die life in industrial environment indicated 1000 cycles. Paris's formula was used to predict the number of cycles for the crack propagation. It was estimated that the additional time for crack growth was 82 cycles that is significantly smaller than the life of the tool.

Thus the majority of researchers in their calculations neglect the plastic strain component for the analysis of tool life. At the same time, neglecting of the plastic strain may lead to an exceeding of the predicted tool life.

The strain-kinetic criterion of low-cycle damage based on damage accumulation is described in works [15, 16]:

$$\int_0^{N_f} \frac{dN}{N_f(T,t)} + \int_0^{N_f} \frac{de}{\varepsilon_f(T,t)} = 1 \tag{5}$$

where $N_f(T,t)$ is the resource on the fatigue curve for hard loading with specified form cycles of thermomechanical loading, $\varepsilon_f(T,t)$ is the limit plastic deformation under sustained loading in specified conditions.

In Eq. 5 the first integral corresponds to damage from elastic strain, and the second term the damage from plastic strain. The criterion shows the process of damage accumulation for soft and mixed types of loading. In other words here the first term defines the fatigue fracture and the second term the quasi-static damage accumulated in the material during cyclic loading.

The proposed method of calculation

The proposed method is based on the following assumptions:

1. The process of dies cyclic loading is considered as a combination of two stages, i.e. firstly, the elastic-plastic loading accompanied by the accumulation of plastic deformations in areas of stress concentration, and then at the second stage a purely elastic loading.
2. The accumulation of damage caused by plastic and elastic deformations is summarized in accordance with the strain-kinetic failure criterion.
3. The plastic deformation damage is based on damage accumulation theory.
4. Damage caused by the elastic deformation is determined by the elastic component of the equation of Manson-Coffin-Basquin.
5. The maximum stresses in the locations of stress concentration are constant and determined by the load during the first cycle.
6. The process of plastic deformation accumulation is determined by the mechanism of thermos-cyclic softening.
7. The material is linear hardening. Softening reduces the yield stress. Hardening modulus remains constant.
8. The value of the yield stress reduction is proportional to the plastic deformation in a cycle

The model of plastic strain accumulation that is based on assumption of linear hardening in elastic-plastic material as shown in Fig. 1. As we see the plastic deformation in each cycle decreases and tends to zero while elastic strain remains invariable. This model agrees with literature data on the gradual reduction of the plastic strain of the dies during the first cycles.

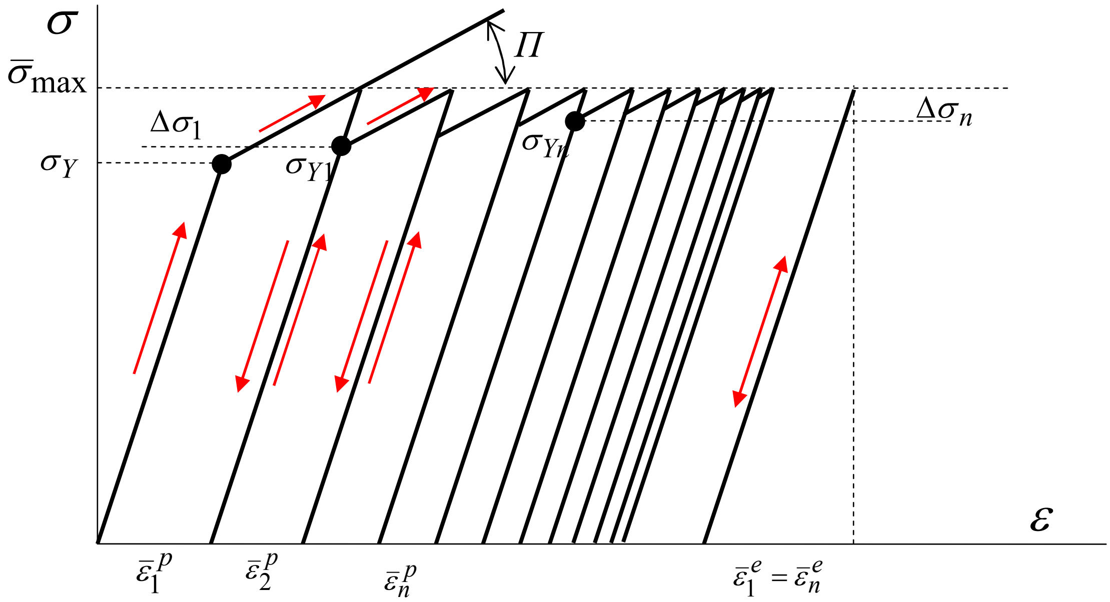

Fig. 1. The accumulation of plastic strain at cyclic loading of the dies when taking into account the softening of the material.

We assume that the softening occurs during technological pause that causes reduction of the yield stress in the next cycle by the value $\Delta\sigma_n$

$$\Delta\sigma_n = R_n - R_{n-1} \tag{6}$$

Here R_n and R_{n-1} are softening parameters after n and ($n-1$) cycles of loading.

In QForm it is used a piecewise linear approximation of the yield stress hardening in tools simulation. Plastic strain in an arbitrary cycle is calculated as:

$$\bar{\varepsilon}_n^p = \frac{\Delta\sigma_{n-1}}{\Pi} \tag{7}$$

where Π is the module of hardening.

The total plastic strain is defined by a recurrence formula:

$$\bar{\varepsilon}_\Sigma^p = \bar{\varepsilon}_\Sigma^p + \bar{\varepsilon}_n^p \tag{8}$$

Fracture due to plastic strain is possible to define using the equation of damage accumulation:

$$\omega = \int_0^{\varepsilon} \left(\frac{d\varepsilon}{\varepsilon_{cr}} \right)^a \tag{9}$$

Where:

$\varepsilon_{cr} = c \cdot \exp(-d \cdot k)$ is the critical strain,

$k = \frac{\sigma_m}{\tau_i}$ is the index of multi-axis stress state

σ_m, τ_i are the mean stress and intensity of shear stresses respectively,
d, c are the material constants that depend on the Lode-Nadai coefficient and temperature as follows

$$c = \frac{1}{\sqrt{3}}\left[c_0 - (c_{-1} - c_0)\mu_\sigma\right], \quad d = \left[-d_0 - (d_{-1} - d_0)\mu_\sigma\right]$$

$a = a_0 \cdot \exp(1 + 0.238 \cdot k)$ is the exponent that reflects the nonlinearity of the damage accumulation
a_0 is the material constant that depends on the temperature.

The Eq. 8 is based on concept that damage defines by accumulated plastic strain. Then the plastic component of the total damage in deformation-kinetic criteria is transformed to the following expression:

$$d_s = \int_0^{N_f} \frac{d\varepsilon}{\varepsilon_f(T,t)} = \left(\frac{\bar{\varepsilon}_\Sigma^p}{\varepsilon_{cr}}\right)^a \tag{10}$$

Material parameters as critical strain ε_{cr} and the exponent a define the nonlinearity of damage accumulation that depends on temperature, Lode-Nadai coefficient and stress state. For steel H13 (1.2344 DIN) these dependencies can be determined according to work [18]. Data for cyclic softening of H13 steel have been obtained by means of processing of experimental results reported in [19] as described in [5].

The material parameters considerably depend on temperature the Lode-Nadai's coefficient and stress state that in turn vary in the process of die loading. So it possible to identify them using average integral values over the cycle in accordance with the following expressions

$$\tilde{T} = \frac{\int_0^{t_c} T dt}{t_c}; \; \tilde{\mu}_\sigma = \frac{\int_0^{t_c} \mu_\sigma dt}{t_c}; \; \tilde{k} = \frac{\int_0^{t_c} k dt}{t_c} \tag{11}$$

Where $\tilde{T}$ is the average temperature during the cycle; $\tilde{\mu}_\sigma$ is the average Lode-Nadai coefficient during the cycle, $\tilde{k}$ is the average stress-state parameter during the cycle.

The formula for calculation of damage in the elastic strain that takes into account average stress of the cycle can be obtained from the general formula of Manson-Coffin-Basquin in notation of Morrow [9]

$$\sigma_{qa} = (\sigma'_f - \sigma_{qm})(2N_f)^b \tag{12}$$

Here σ_{qa}, σ_{qm} are equivalent values of the amplitude and average stress of the cycle.

To calculate equivalent amplitudes and average stress of the cycle in the case of 3D stress state it is possible to use the equivalent von Mises stress with regard to the sign of the first principal stress [10]:

$$\sigma_{eq} = \bar{\sigma}\frac{|\sigma_m|}{\sigma_m}, \; \sigma_{qa} = \frac{\sigma_{eq\max} - \sigma_{eq\min}}{2}, \; \sigma_{qm} = \frac{\sigma_{eq\max} + \sigma_{eq\min}}{2} \tag{13}$$

Parameters of the material such as coefficient of fatigue strength σ'_f and the exponent of fatigue strength (the slope of the elastic line of the law of Manson-Coffin-Basquin) b can be obtained from experimental data as described in book [9]. These parameters were defined for steel H13 based on the data of work [10]. Assuming that the load in each cycle is the same then it is possible to get the expression for fatigue failure that is based in stresses:

$$d_f = \int_0^{N_f} \frac{dN}{N_f(T,t)} = 2N_f \left(\frac{\sigma'_f - \sigma_{qm}}{\sigma_{qa}} \right)^{\frac{1}{b}} \tag{14}$$

Finally, the total number of cycles to crack formation is the following:

$$N_f = \frac{1 - \left(\frac{\bar{\varepsilon}_\Sigma^p}{\varepsilon_{cr}} \right)^a}{2\left(\frac{\sigma'_f - \sigma_{qm}}{\sigma_{qa}} \right)^{\frac{1}{b}}} \tag{15}$$

The formula is comprehensive and allows predicting the low cycle fatigue for cycles with elastic and plastic deformation. The Eq. 15 may be implemented as post processor function for one simulated cycle of the forging dies loading. The main drawback of such approach to tool life prediction is the need to get extensive experimental tool material.

Examples of fatigue failure prediction

To implement the proposed method we have created a subroutine for calculating of the low cycle fatigue failure to be used in QForm forming simulation software. The subroutine allows defining the following calculated fields for tools:

– Number of cycles till failure.
– Plastic strain is in the first cycle.
– Accumulated plastic strain till the failure.
– The number of cycles with plastic strain i.e. damage from the plastic strain.
– Equivalent amplitude of the cycle.
– Equivalent mean stress of the cycle.

The first example is the analysis of the dies for forging of a bevel gear in a mechanical press[1].

Fig. 2. The crack in the die appeared after 400-420 cycles

The upper die with fracture near the bottom of the die after forging about 400 parts is shown in Fig. 2. Fig. 3 shows the equivalent stress in the upper die at the final stage of forging when the load

[1] With permission Cramlington Precision Forge Ltd

and stresses reach a maximum value b. The die insert made from steel H13 is fitted in the die block with 0.05 mm shrinking. Stress analysis of the die insert shows that the maximum effective stress occurs at the fillet transition area where we observe the actual damage (see Fig. 2). These stresses exceed the die yield stress that leads to plastic strain.

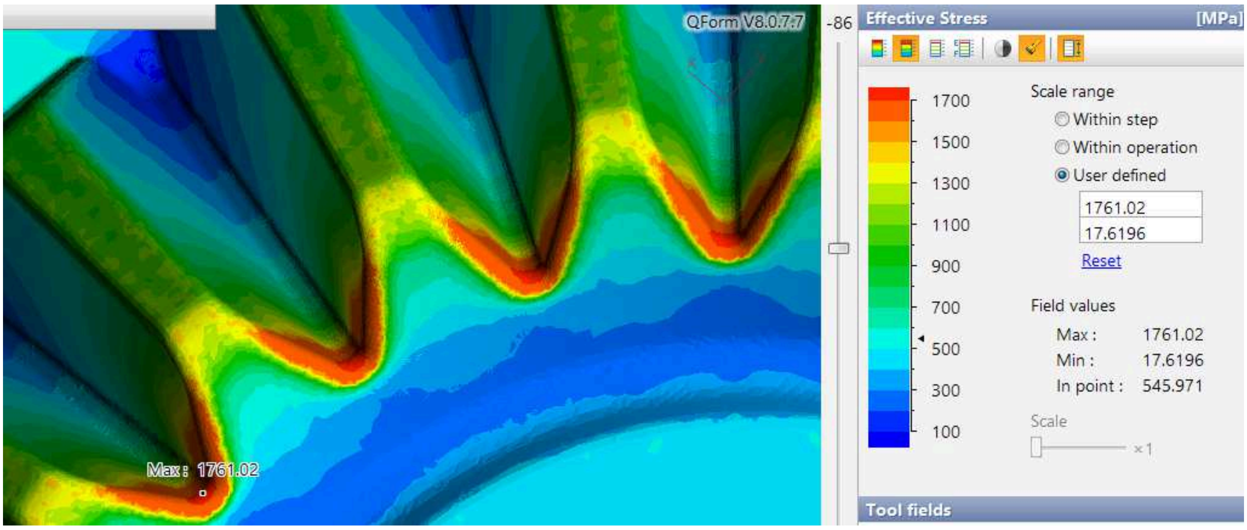

Fig. 3. Distribution of equivalent von Mises stresses (in MPa) in the upper die at the end of forging

Analysis of the loading cycle of the dies shows that the stress state of triaxial compression (all three principal stresses are negative) is realized at the initial stage of loading in the fillet area. At the final stage of forging during the flash formation the stress state is close to uniaxial tension with an equivalent stresses equal to 1600-1800 MPa. Thus in the fillet area it is realized an alternating cycle with a positive value of the average stress of the cycle.

The calculation of the temperature of die is performed simultaneously with the simulation of metal flow and stress-strain state in the die (coupled modelling). The simulation shows that the temperature in the fillet area varies in the range of 200 - 400°C.

Having the stress-strain parameters and temperature distributions in the die we have implemented the presented model of LCF prediction within the QForm software. The results are shown in Fig. 4. The minimum number of cycles to failure is 398 which are very close to experimental observations as well as being located in the same area as in reality.

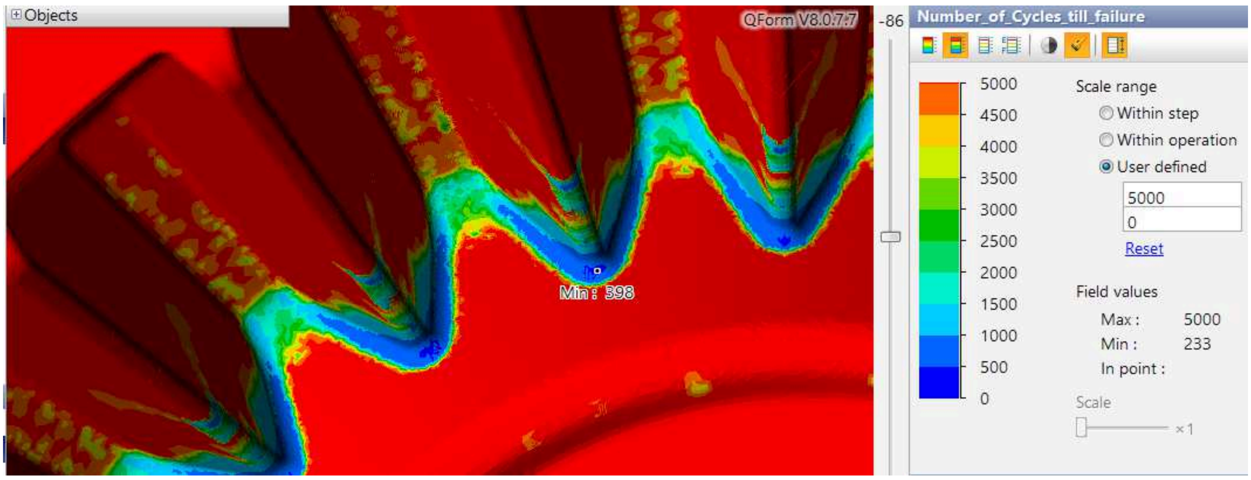

Fig. 4. Location of the crack predicted using proposed model with indication of the number of cycles till failure as 398.

In the next example we consider the hammer forging of a steel part. The sequence of the action is shown in the Fig. 5. The basic technological parameters are the following: A two ton drop hammer has been used, the workpiece is made of carbon steel AISI 1020, the billet temperature is 1200 oC, initial tool temperature 30^{o}C and tool material H13. The production of this part requires one blow for every action, i.e. upsetting, preforming and finishing. The lubricant is graphite with water.

Existing technology doesn't provide acceptable tool life. In practice it is about 200 forged parts and then the die crack appears. The photo of the die with this characteristic failure is shown in the Fig. 6.

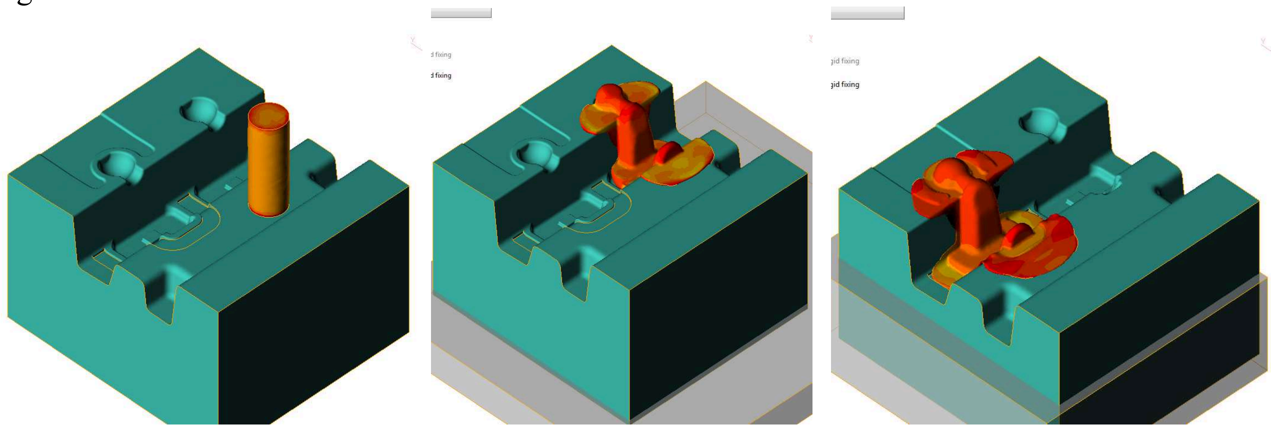

Fig. 5. The billet in the first, second and third blows of hot steel forging sequence.

Fig. 6. The crack after about 200 forged parts in the third cavity of the die block in hot hammer forging.

Simulation of the tool was performed in coupled mode simultaneously with simulation of the material flow. The critical operation from the point of view of the tool life is the last action. Analysis of the loading cycle of the die in the third action shows the tensile stress state in the problem zone as indicated by red color in Fig. 7. The calculation of the die temperature has shown that it may reach up to 250°C in the first cycle.

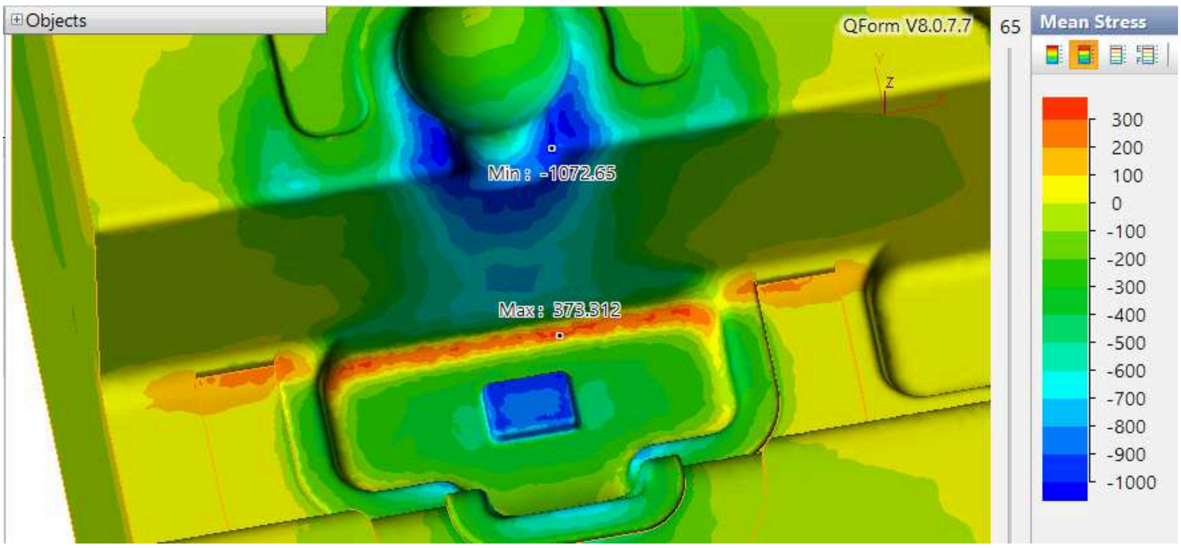

Fig. 7. The mean stress distribution and its extreme values are in the critical zone of the die during the third forging action.

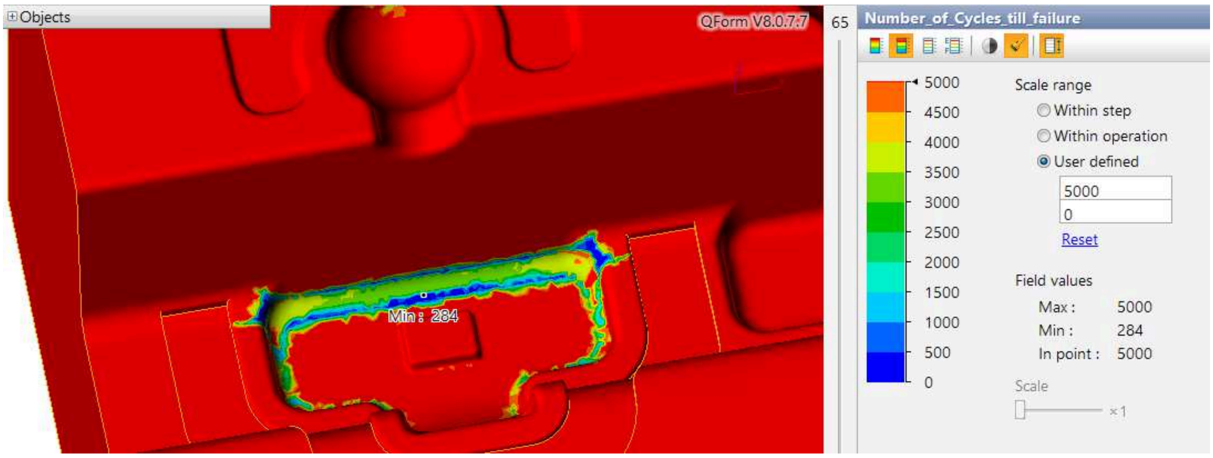

Fig. 8. Number of the cycles till the die failure because of LCF: minimum amount 284.

The tool life evaluation has been done using the same mechanical properties of the steel H13 as in the first example of bevel gear forging. Again, here we have got good correspondence between predicted and actual number of cycles before cracking as shown in Fig. 8.

The elastic properties during cyclic loading for steel H13 are published in work [10] and critical plastic strain is approximated using the results of investigation in [18]. For other widely used tool materials such as M2, L6 and H11, it is necessary to determine the material parameters be used in Eq. 14 and Eq. 15. In other words it is necessary to make the same investigation as was done for H13 and include in the database of the tool materials properties the following parameters:

– Young module, Poisson's coefficient and hardening parameter those are dependent on temperature;

– Dependence of the critical strain ε_{cr} on the temperature and parameter of stress state;

– Dependence of the parameters of cyclic softening Q_1, Q_2, β on the temperature

– Dependence of the coefficient of fatigue strength σ'_f and the exponent of fatigue strength b on the temperature.

The most difficult task is to determine the plastic critical strain that is included in Eq. 9 and Eq. 15. Meanwhile despite of limited amount of important experimental information regarding properties of the tool steel, the approach for quantitative estimation the tool life of the dies in hot and cold forging is possible as shown in this paper.

Conclusions

1. The proposed method for predicting low cycle fatigue failure of dies takes into consideration both elastic and plastic components of deformation and the influence of temperature.
2. The model and programmed subroutine have been used for predicting the low cycle fatigue dies failure during hot forging and have shown good correspondence with practical observations.
3. The developed method can be successfully applied in industry to predict tool life and optimize die design.
4. Additional experimental research is required to find out data for other tool materials that are essential for the proposed model.

References

[1] K.Lange, L.Cser, M.Geiger, J. Kals, Tool life and tool quality in bulk metal forming, CIRP Annals-Manufacturing Technology. V.41 No. 2 (1992) 667-675.

[2] B.A.Behrens, F.Schäfer, Service Life Predictions for Hot Bulk Forming Tools, Steel Res Int 80 (2009) 887-891.

[3] B.Falk, U.Engel, M.Geiger, Estimation of tool life in bulk metal forming based on different failure concepts, J. Mater. Process. Tech. 80 (1998) 602-607.

[4] G.Bernhart, G.Moulinier, O.Brucelle, D.Delagnes, High temperature low cycle fatigue behaviour of a martensitic forging tool steel, Int. J. Fatigue. 21 (1999) 179-186.

[5] D.Delagnes, F.Rezai-Aria, C.Levaillant, Influence of testing and tempering temperatures on fatigue behavior, life and crack initiation mechanisms in a 5% Cr martensitic steel, Procedia Engineering. 2 Issue 1 (2010) 427–439

[6] V.N Efimov, L.N.Sokolov, V.V. Savitsky, M.L. Zadkevich, High temperature hardening and softing metals and alloys, Naukova dumka, Kiev, 1992.

[7] J. Lemaitre, J.L. Chaboche, Mechanics of solid materials, Cambridge University Press, Cambridge, 1990.

[8] P.Skov-Hansen, N.Bay, J.Grønbæk, P.Brøndsted, Fatigue in cold-forging dies: tool life analysis, J. Mater. Process. Tech. 95 (1999) 40-48.

[9] S.S.Manson, G.R. Halford, Fatigue and durability of structural materials, ASM International, 2006.

[10] Y. J.Kim, C. H. Choi, A study on life estimation of hot forging die, Int. J. Precis. Eng. Man. 10 (2009) 105-113.

[11] S. S.Akhtar, A. F. Arif, Fatigue Failure of Extrusion Dies: Effect of Process Parameters and Design Features on Die Life , Journal of failure analysis and prevention. V. 10. No. 1 (2010) 38-49.

[12] M. W.Fu, J.Lu, W. L. Chan, Die fatigue life improvement through the rational design of metal-forming system, J. Mater. Process. Tech. 209 (2009) 1074-1084.

[13] B. A. Behrens, A. Bouguecha, F. Schäfer, T. Hadifi, FEA Based Tool Life. Quantity Estimation of Hot Forging Dies Under Cyclic Thermo-Mechanical Loads, International Conference On Advances In Materials And Processing Technologies (AMPT2010). AIP Publishing V. 1315. No. 1 (2011) 303-308.

[14] K.Mocellin, M.Ferraro, V.Velay, R.Logé, F.Rézaï-Aria, Numerical life prediction of mechanical fatigue for hot forging tools, Int. J. Mater. Form. 2 (2009) 129-132.

[15] R.M.Shneiderovich, A. P.Gusenkov, V. V.Zatsarinnyi, A strain-kinetic criterion for long term cyclic strength, in: Low-Cycle Strength Studies at Elevated Temperature [in Russian], Nauka, Moscow (1975), pp. 39-61.

[16] D.N. Reshetov, A.P. Gusenkov, Yu.P. Drozdov, Machinery bulding. Encyclopedia. Machines and mechanism. Structural strength. Friction, wearing, lubricants. in Russian, Mashinarybuilding, Moscow, 1995.

[17] A.V.Bogatov, O.I.Migiricky, S.V.Smirnov, Resource plasticity of metals in metal forming. in Russian, Metallurgy, Moscow, 1984.

[18] R.Lapovok, S.Smirnov, V.Shveykin, Damage mechanics for the fracture prediction of metal forming tools , Int. J. Fracture. 103 No.2 (2000) 111-126.

[19] J. Sjostrom, J.Bergstrom, Thermal fatigue in hot-working tools, Scandinavian Journal of Metallurgy. 34 (2005) 221–231.

[20] R. I.Stephens, A.Fatemi, R. R. Stephens and H.O. Fuchs, Metal fatigue in engineering, John Wiley & Sons, 2000.