Numerical simulation and practical investigation of the thermal fatigue behaviour of hot work tool steels in die casting processes

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Abstract. *Fatigue due to thermal cycling is one of the main reasons for the damage of tools used in die casting processes. In order to investigate the thermal fatigue behaviour of tool steels a thermal fatigue testing facility was designed and built up. For better understanding of the mechanisms of thermal fatigue finite element-simulations were carried out. To specify the cyclic material behaviour push-pull-tests at different temperatures were performed. The Chaboche-model was used to describe the kinematic material response. Isotropic softening is also taken into account. Depending on the arising accumulated plastic strain stable cyclic deformation or continuous softening occurs. The results are consistent with the accomplished thermal fatigue tests on different hot work tool steels.*

1. INTRODUTION

The damage of industrial components is often caused by thermal cycling. Changing operating temperatures result in locally different thermal expansions which cause thermal stresses arises. Depending on the stress amplitude and the yield stress of the material periodic elastic and plastic strains occur, which are responsible for the thermal fatigue of the material [1].

Thermal cycling occurs in processes like hot forging, hot rolling, die casting, but also in large engineering structures like turbines or in power plants. Surface near zones of thermally cycled tools are not only subjected to mechanical loading, but also to thermo-mechanical loads induced by the repeated contact with the hot metal of the work piece [2].

In the case of manufacturing tools the maximum surface temperature which is achieved in the manufacturing process strongly depends on the process type and the parameters used. For aluminium pressure die-casting the maximum surface temperatures are in the range of about 500–650 °C [3]. Normally, the background temperature of dies is held constant at a temperature level of about 200-250 °C in order to reduce the thermal stresses [4].

The fatigue damage process occurs as a sequence of the following processes: (1) cyclic softening or hardening process, (2) stable cyclic deformation, (3) crack initiation and (4) crack growth and final fracture [5,6]. The typical material response in case of strain controlled cycling is shown in Fig. 1. Depending on the material the time to crack initiation or the time to crack growth are life time controlling processes.

Fatigue is in general related to irreversible plasticity which occurs on micro- or macroscale. At the beginning of fatigue loading irreversible plastic deformation causes fatigue hardening or softening, depending on the initial state of the material and the loading parameters like stress amplitude, mean stress, temperature and deformation rate.

Cyclic hardening is typical for annealed materials. Due to the plastic deformation the dislocation density increases with increasing number of cycles and special dislocation structures are built-up (veins, cells, etc.). This results in an increase of the strength of the material [7].

Cyclic softening is a fatigue phenomenon which is often found in strain-hardened and precipitation-hardened materials. It involves interaction between dislocations and precipitated particles as well as with other dislocations. The strength of the material decreases [7].

Both, cyclic hardening and softening ends, if a stable dislocation substructure is formed (stage 2).

If the magnitude of the strain amplitude exceeds a critical value, the specimen fails before reaching a stable material behaviour. Then the material response is a continuous decrease of stress in case of constant strain amplitudes, or a continuous increase of plastic strain in case of stress controlled tests. This material behaviour, presented in Figure 1, is called "continuous softening".

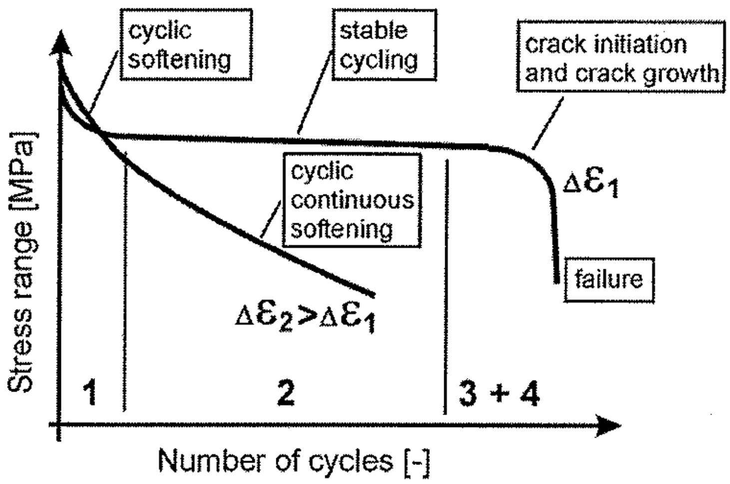


Figure 1. Material response in a cyclic softening test at constant total strain range (schematic)

The aims of the present work are:
- To calculate the temperature transients during cyclic thermal loading
- To characterise the kinematic and isotopic material behaviour of hot work tool steels for typical loading conditions
- To compare and interpret the results of the calculated thermal stresses and elastic and plastic strains with experimental data

2. EXPERIMENATAL

A special thermal fatigue testing facility was developed to study the thermal fatigue behaviour of tool steels, see Figure 2.

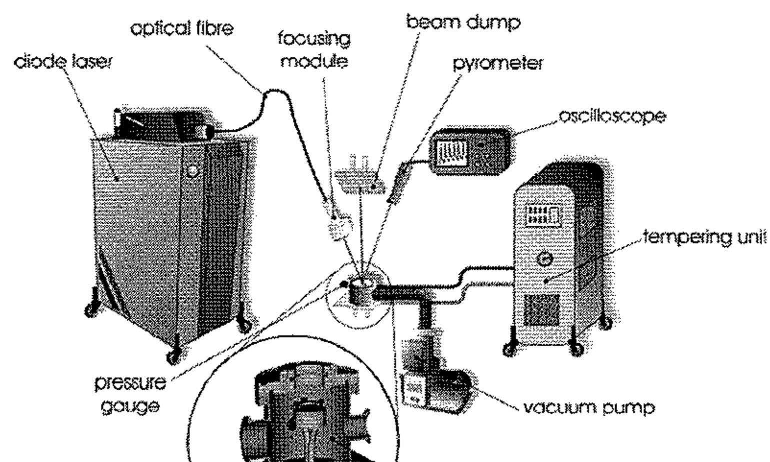


Figure 2. Thermal fatigue testing facility

A disk shaped specimen is tested in a vacuum chamber to prevent oxidation of the heated surface. All tests were carried out under vacuum at a pressure lower than $3*10^{-6}$ mbar. No significant oxidation is observed even for the longest testing time of seven days. The sample is mechanically fixed on a temperature-controlled copper mounting system, which is held at a constant temperature of 200°C for all tests. Cyclic surface heating is done by using a pulsed diode laser beam with a maximum power of about 1.8 kW. All tests are performed at a frequency of 1 Hertz and a pulse duration of 250 ms. Variations of the pulse energy are used to vary the maximum surface temperature. The laser radiation is guided via an optical fibre, a focussing unit and a transparent window onto the specimen. A circular area with a diameter of about 6 mm is irradiated. The reflected laser radiation is absorbed in a water-cooled beam dump. The temperature in the interaction zone is controlled with a pyrometer with an operating range from 250 to 1300 °C and a response time of 15 μs. A spectral filter in the optical system of the pyrometer prevents effects from the reflected and scattered laser radiation. An oscilloscope is used to display the thermal cycles and to provide an interface to a PC [2].

For the thermal fatigue damage simulation eight different pulse energies have been chosen in order to achieve maximum surface temperatures of about 575, 600, 625, 650, 680, 710, 740 and 770 °C.

All tests were performed at the hot work tool steel DIN X 38 CrMoV 5-1, its nominal chemical composition is given in Table 1. The specimens were tested in a quenched and tempered condition (austenitising: 990 °C - 50 min, tempering: 550 °C - 1h and 575 °C - 2 h) at a hardness level of 502 HV1.

	C	Cr	W	Mo	V
X 38 CrMoV 5-1	0.38	5	-	1.3	0.65

Table 1 Nominal chemical compositions of the X 38 CrMoV 5-1 in wt.%

1.1 Process simulation

The path of the process simulation is presented in Figure 3.

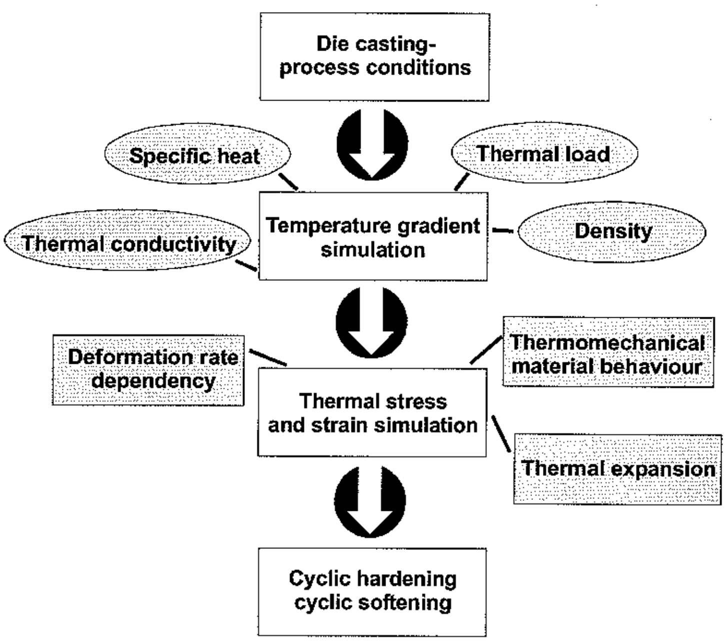


Figure 3. Process simulation path

The thermal loading conditions used in the test are typical for die casting in which maximum surface temperatures up to 650 °C can arise. To investigate the mechanisms taking place a wide range of laser pulse energies were chosen to vary the heat fluxes and to achieve maximum temperatures of 575 to 770 °C.

The resulting temperature gradient is affected by the thermal conductivity, the specific heat and the density of the material. The temperature distribution which is achieved at the end of an absorbed laser pulse of 66,6 J is shown in Figure 4.

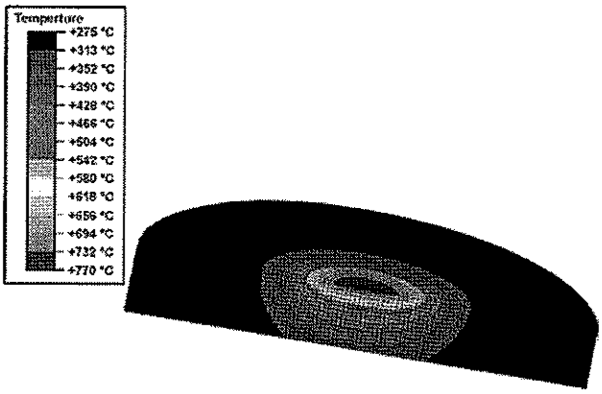


Figure 4. Temperature distribution at the end of a laser pulse of 66,6 J

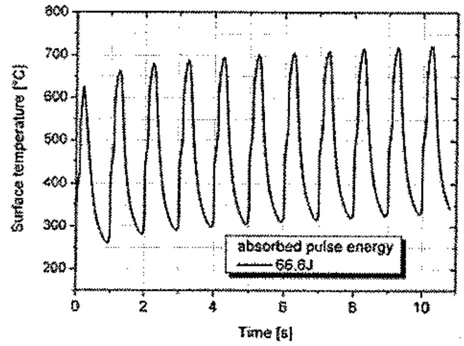


Figure 5. Variation of the surface temperature during pulsed laser irradiation

For the chosen testing set-up a minimum number of cycles has to be considered to get stable results for the temperature cycles. Fig. 5 shows the variation of the surface temperature for a absorbed pulse laser energy of 66,6 J within the first cycles indicating that the maximum temperature stabilises after about ten cycles.

Results of the FEM simulation of the temperature cycles are compared in Table 2 with pyrometrically measured temperatures. The results indicate an excellent accordance between measured and calculated surface temperatures for various absorbed pulse energies. The absorbed laser energy was estimated from the laser pulse energy assuming an absorption of 37%. The interaction time was 0,25 s and the total cycle time was 1 s.

Absorbed pulse energy [J]	Measured maximum surface temperature [°C]	Calculated max. surface temperature [°C]
43,0 J	575 °C	575 °C
48,5 J	600 °C	605 °C
50,0 J	625 °C	621 °C
54,6 J	650 °C	654 °C
57,1 J	680 °C	678 °C
61,1 J	710 °C	707 °C
63,6 J	740 °C	736 °C
66,6 J	770 °C	771 °C

Table 2. Measured and calculated maximum surface temperatures for different pulse energies

A simple parameter H based on Skelton [5] was used to characterise the softening / hardening behaviour of the irradiated material:

$$H = \frac{\Delta\sigma_{INIT} - \Delta\sigma_N}{\Delta\sigma_{INIT}} = \frac{H_{INIT} - H_N}{H_{INIT}} \qquad (1)$$

$\Delta\sigma_{INIT}$; H_{INIT} ..... Initial stress range; Hardness before thermal cycling

$\Delta\sigma_N$; H_N ..... Stress range; Hardness after a defined number of cycles

Cyclic softening gives a positive and cyclic hardening gives a negative softening- hardening parameter H.

In Figure 6 the property change caused by thermal cycling is indicated by the evolution of the softening-hardening parameter H. Two types of material response were found. For high maximum surface temperatures which cause high elastic and plastic strains continuous softening is observed. This softening accelerates the fatigue damage. For thermal cycling with lower maximum surface temperatures up to 650°C the material behaviour stabilises after an initial softening phase.

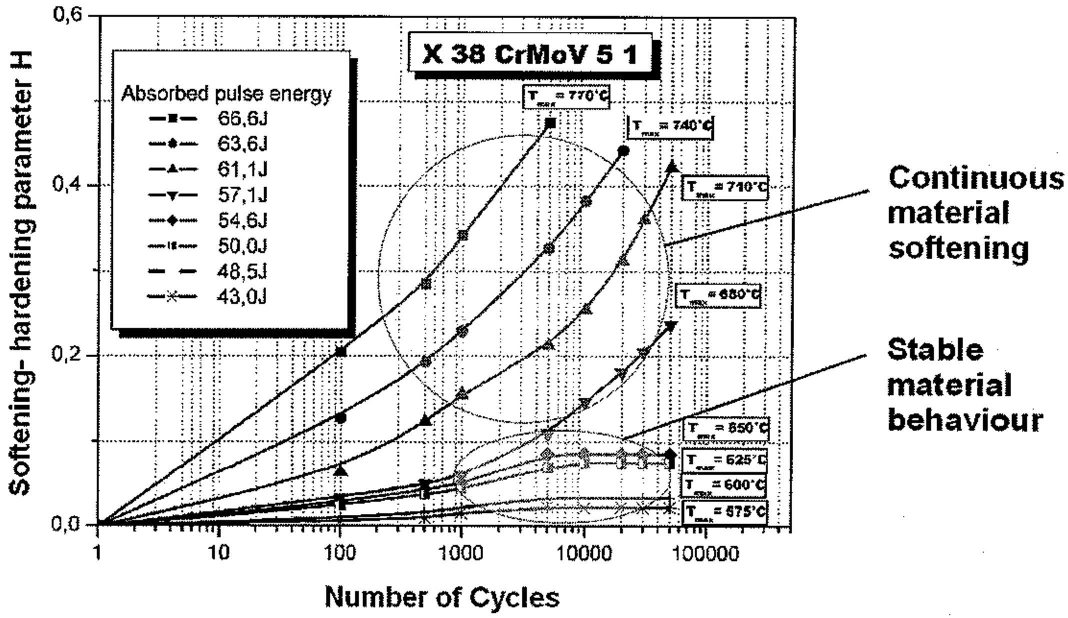
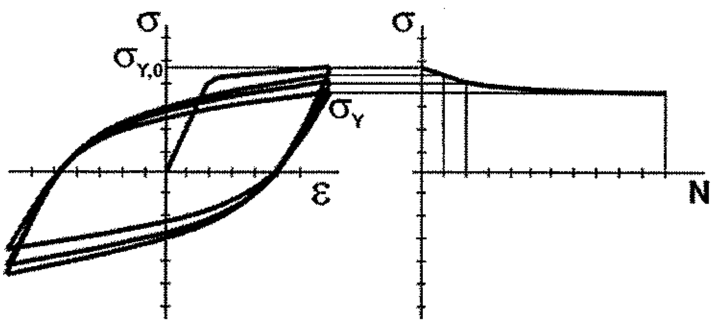


Figure 6. Softening for different maximum surface temperatures

The kinematic and isotropic material behaviour was investigated in order to determine material data to simulate the stresses and elastic and plastic strains due to thermal cycling. Combined push-pull and torsion tests at different temperatures and deformation rates were performed to characterise the kinematic and isotropic material parameters.

1.1.1 Isotropic material behaviour

Depending on the initial material conditions a change in the yield surface radius occurs under cyclic plastic deformation. Caused by dislocation interaction and rearrangement the yield strength increases or decreases. The magnitude and the rate of the increase resp. decrease of the strength depends on the plastic strain range. The hardening or softening is described as a change of the yield surface due to cyclic plastic deformation. The cyclic hardening law used is shown in Figure 7 [8].



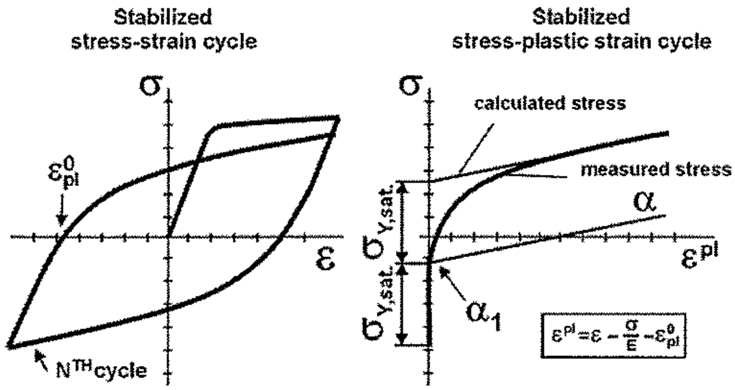
$$\sigma_Y = \sigma_{Y,0} + Q(1 - e^{-b\cdot\bar{\varepsilon}^p}) \qquad (2)$$

$\sigma_{y,0}$	...	Initial yield strength
σ_y	...	Yield strength
b, Q	...	Isotropic material parameters
$\bar{\varepsilon}^p$	...	Accumulated plastic strain

Figure 7. Isotropic material behaviour

1.1.2 Kinematic material behaviour

Another phenomenon of cyclic plastic deformation is the kinematic material behaviour, which is indicated by translation of the yield surface in the stress space. The material law from Chaboche describes this effect through the backstress α as shown in Figure 8 [8]. The materials parameter C, γ and α_1 were calibrated from cyclic test data for different temperatures and deformation rates.



$$\sigma = \sigma_{Y,sat.} + \alpha \tag{3}$$

$$\alpha = \frac{C}{\gamma}(1-e^{-\gamma\cdot\varepsilon^{pl}}) + \alpha_1 \cdot e^{-\gamma\cdot\varepsilon^{pl}} \tag{4}$$

σ ... Stress
$\sigma_{Y,sat}$ ... Elastic yield stress in the stabilised cycle
α ... Back stress
α_1 ... Initial back stress
C ... Kinematic hardening modulus
γ ... Material parameter
ε^{pl} ... Plastic strain

Figure 8. Kinematic material behaviour

The kinematic hardening law takes also the Bauschinger effect into consideration, an effect which is observed in most metals. The material yields in case of plastic deformation in one direction at a higher load then in a subsequent loading (deformation) in the opposite direction.

To carry out the finite element simulation the program ABAQUS (Version 5.8) was used. ABAQUS supports Chaboche´s model with one backstress component.

To evaluate the kinematic and isotropic material model combined push-pull-torsion tests were performed and simulated. The results presented in Figure 9 indicates a good correlation between the measured (a) and simulated (b) deformation cycles.

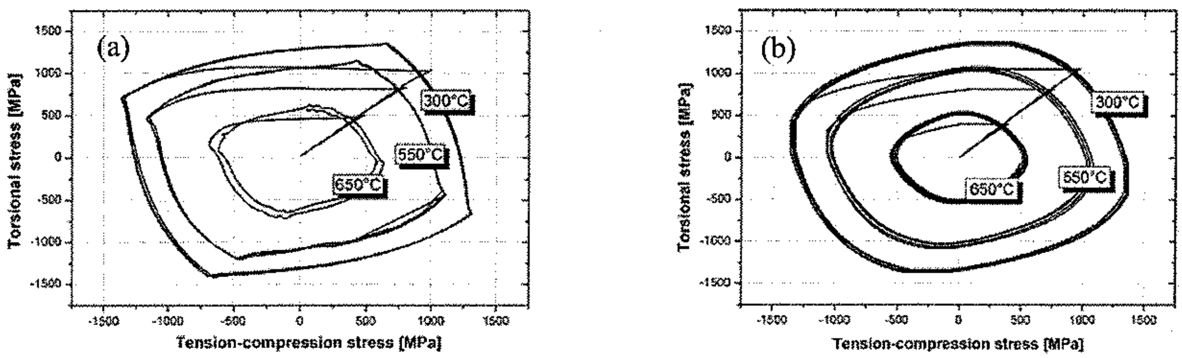


Figure 9. Measured (a) and calculated (b) material behaviour in tension-compression-torsion tests at a temperature of 300, 550 and 650 °C

3. RESULTS

In order to investigate the softening behaviour of the pulsed-laser irradiated hot work tool steel specimens experiments up to 50.000 cycles and simulations up to 100 cycles were performed. Results of the numerical simulation are shown in Figure 10 for the lowest and the highest absorbed pulse energy. After about 10 cycles the maximum surface temperature in the centre of the specimen changes for 43 J pulses from 293 to 575 °C resulting in cyclic radial thermal stresses varying from 72 to –332 MPa. The calculated stress range doesn't change significantly from temperature cycle number 10 to number 100 which indicates light softening of the material (Fig. 10a).

For 66,6 J pulses (Fig. 10b) the maximum surface temperature varies between 346 and 770 °C after 10 cycles. Due to the high maximum temperature and plastic strain range the radial thermal stress range decreases significantly from the 10^{th} to the 100^{th} cycle. This cause a significantly higher softening of the material which is indicated by the reduction in the stress range.

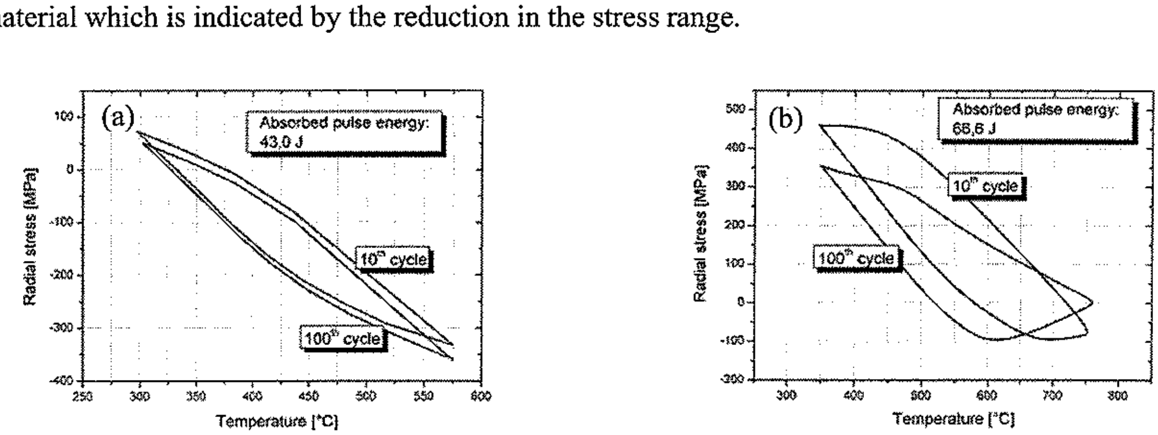


Figure 10. Calculated stress-temperature cycle for absorbed pulse energies of 43,0 (a) and 66,6 J (b)

The calculated and measured softening of the tool steel X 38 CrMoV 5-1 for the maximum surface temperatures between 575 and 770 °C is indicated by the softening- hardening parameter H in Figure 11. The results for higher maximum surface temperatures indicate a very good correlation between the measured and calculated softening. The larger differences between the calculated and measured parameter H for maximum surface temperatures between 575 and 680 °C are mainly caused by uncertainties in the determination of the yield stress from the performed push-pull-tests. The results indicate, that micro plastic deformation obviously occurs at lower stresses than it was expected in the calculations.

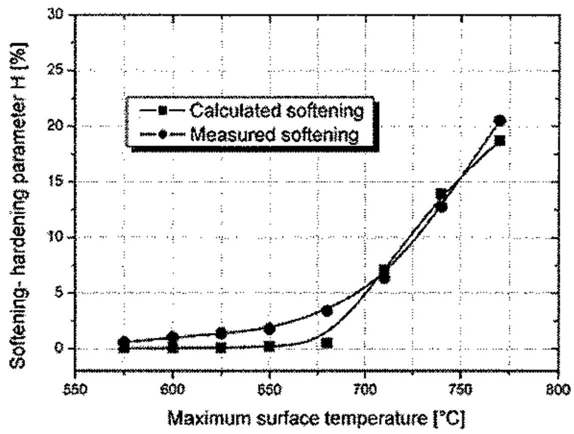


Figure 11. Softening behaviour for the different maximum surface temperatures after 100 Cycles

4. CONCLUSION

Thermal cycling experiments and finite element simulation were performed to investigate the cyclic softening behaviour of hot work tool steels under die casting conditions. Kinematic and isotropic material parameters were determined by performing push-pull tests at different temperatures and deformation rates.

The results indicate a good correlation between the calculated and measured softening behaviour.

The experiments and the simulations show, that the material response drastically changes at a maximum surface temperature of about 680 °C. If the maximum temperature exceeds 680 °C, significant cyclic softening occurs. It is expected, that cyclic softening has an important influence on the life time.

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