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# SOME CONSIDERATIONS ABOUT NON-ISOTHERMAL FATIGUE WEAR OF THE FORGING DIE STEEL

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***Abstract:*** *Frequently the durability of the forging dies is firstly determined by the non-isothermal fatigue wear, which causes the cracks appearance on their internal surfaces, much more before their abrasion wear to reach the limit value. In these conditions it is necessary to design the forging dies firstly by the point of view of the non-isothermal fatigue wear. For a correctly choosing and using of metallic material, it is necessary to determine their intrinsic characteristics regarding its cyclic non-isothermal stresses durability. The experimental determination of these characteristics implies a lot of experiments, which are done in specific conditions, different from those used for isothermal mechanical fatigue durability determination. The paper presents the experimental results concerning intrinsic characteristic determination of the forging dies steel. Based on these results there were determined specific equations which characterize this kind of stresses, and the diagrams that represent their graphic image. These data can be used both in designing and exploitation of the forging dies.*

***Keywords:*** *non-isothermal fatigue wear, forging die steel, non-isothermal fatigue characteristics, durability, middle alloy steel*

## 1. INTRODUCTION

Non-isothermal fatigue wear is a kind of degradation, which characterizes the metallic element friction surface of some couples, like forging dies, fire guns, heavy-duty mechanical brakes etc. In case of forging dies the thermal stresses and strains, which appear in the friction surface adjacent zone of these couples, have high values, which are higher than the yield limits of the metallic materials used at their construction [1, 2].

During the drop forging process the die surfaces are heated. Because this heating has a variable or almost cyclic character, the thermal stresses and strains effects are similar to that, which characterize the low cycle, fatigue. These effects consist in the cracks appearance on the friction surface. In time, the number and the size of these cracks increase, and the result is the attaining of the fatigue fracture state.

Frequently the durability of the forging dies is firstly determined by the non-isothermal fatigue wear, which causes the cracks appearance on their internal surfaces, much more before their abrasion wear to reach the limit value. In these conditions it is necessary to design the forging dies firstly from the point of view of the non-isothermal fatigue wear.

For a correctly choosing and using of metallic material, it is necessary to determine its intrinsic characteristics regarding its cyclic non-isothermal stresses durability. The experimental determination of these characteristics implies a lot of experiments, which are done in specific conditions, different from those used for isothermal mechanical fatigue durability determination [3, 4, 5].

It has to be mentioned, that up to present, most of the researches in the thermal and non-isothermal fatigue field were done for the metallic materials like heat-resisting alloys and steels used for the construction of steam-turbines, turbo-jet engines, nuclear equipments, chemical reactors a.s.o. [2].

Also, there are many structures non-isothermal stressed where there are used for construction middle alloy steels. The non-isothermal fatigue durability of these sorts of steels has been relatively little studied till now [4, 6, 7].

## 2. EXPERIMENTAL CONDITIONS

### 2.1 Testing methodology

Usually, both isothermal and non-isothermal fatigues of the metallic materials characterize their durability in oligocyclic range (low durability)[1,8]. The isothermal durability determination in this range presumes the cyclic axial stress in an elastoplastic regime when the maximum and minimum temperature values are maintained constants.

Unlike the isothermal fatigue experiments, which are developed under constant amplitude, the non-isothermal fatigue tests present the strain amplitude variation in time. In the first part of the test, the total elastoplastic strain varies until the hysteresis cycle stabilization, and finally it decreases because of the material hardening state appearance. The cylindrical test pieces are recommended for tests with the strain amplitude up to 2 %. Over this value there are recommended the toroidal test pieces [1, 4, 5].

The experiments were developed on a testing stand, specially built for non-isothermal fatigue of the metallic materials (Figure 1) [4].

**Figure 1.** Non-isothermal fatigue testing stand

The sample pieces heating on this stand is carried out through thermal effect of electric current. The testing stand can be used for determining the durability characteristics for the metallic materials tested in the following conditions:

- thermal cycles with the test piece strained with tensile stresses at the maximum temperature of the cycle;
- thermal cycles with the test piece strained with compression stresses at the maximum temperature of the cycle (by its fastening in a frame with determined rigidity).

The concrete conditions of the tests were the following:

- test pieces were tested in non-isothermal regime between a minimum and a maximum temperature values;
- test pieces were fastened by enclosure and they were stressed to compression at the maximum temperature of the cycle;
- elastoplastic strain variation was limited using three rigidity steps of the test piece fastened system (12, 28, 55 MN/m);
- maximum cycle temperature values were 700°C respectively 800°C in accordance with the maximum temperature values which are reached during the forging process;
- minimum cycle temperature value was 100°C;
- average heating speeds of the test piece were in the range of 35…80 °C/s;
- average cooling speeds of the test piece were in the range of 5.5…7.0 °C/s;
- absence of the keeping time at the maximum temperature of the cycle;
- the using of the full test pieces with 4 mm diameter and 30 mm length of the calibrated part (Figure 2);
- the criterion of the testing break was the decrease of the initial strain amplitude value with 10 %.

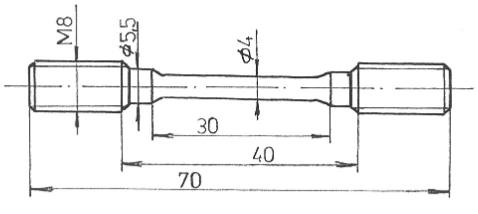

**Figure 2.** The sample piece

### 2.2 Experimental tested steel

Experimental determinations were carried out on middle alloyed steel which is frequently used for forging dies construction. Two kinds of sample pieces were used: one type made from normalized steel and the other made from temper hardening steel. Chemical composition and main mechanical characteristics of tested steel are presented in Table 1 respectively in Table 2.

**Table 1.** Chemical composition of tested steel

| Chemical alloying elements [wt. %] | | | | |
|---|---|---|---|---|
| C | Mn | Cr | Ni | Mo |
| 0.34 | 0.55 | 1.55 | 1.60 | 0.23 |

**Table 2.** Mechanical characteristics of tested steel

| Mechanical characteristic | Values | |
|---|---|---|
| | Normalized steel | Temper hardening steel |
| Tensile strength [MPa] | 900…1100 | 1200…1400 |
| Yield limit [MPa] | 700 | 1000 |
| Elongation [%] | 12 | 9 |
| Reduction of area [%] | 48 | 40 |
| Hardness, HB | 225 | 248 |

## 3. RESULTS AND DISSCUSIONS

A primary evaluation with comparative character of non-isothermal cyclic durability can be done using the following dependence [1]:

$$t_{\max} = A - b \cdot \ln(N) \qquad (1)$$

where $N$ is the durability, expressed like the number of cycles until testing break; $t_{\max}$ - the maximum temperature of the cycle; $A$ and $b$ – material constants.

The dependence expressed by relation (1) is in accordance with experimental results presented in Figure 3. The $A$ and $b$ constants were determined as a result of a regression analysis based on experimental data, and their values are shown in Table 3.

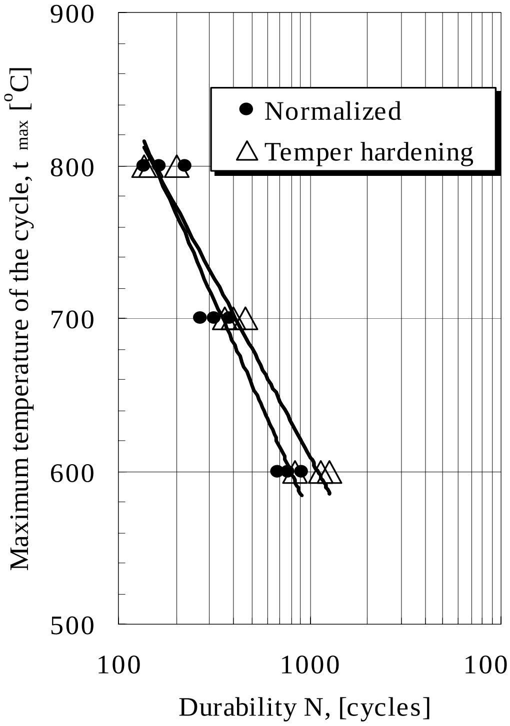

**Figure 3.** Maximum temperature of the cycle vs. durability for tested steel

**Table 3.** The results of the regression analysis (1)

| Regression characteristics | Values | |
|---|---|---|
| | Normalized steel | Temper hardening steel |
| Coefficient $A$ | 1415.5 | 1308.7 |
| Coeficient $b$ | 122.12 | 101.18 |
| Determination coefficient $R^2$ | 0.9309 | 0.9635 |

It has to be remarked that equation (1) can be used only for comparative calculus of non-isothermal fatigue durability because it does not contain total elastoplastic strain variation.

In Figure 4 and Figure 5, the influence of the total relative strain variation respectively stress variation on the durability are presented.

The total strain and the stress variation influence on the durability can be evidenced using dependence relations between the number of cycles until the crack appearance and the strain or stress, like Coffin-Manson type:

$$\Delta\varepsilon = C \cdot N^{k_1} \qquad (2)$$

$$\Delta\sigma = B \cdot N^{k_2} \qquad (3)$$

where: $\Delta\varepsilon$ is the total relative elastoplastic strain variation, %; $N$ – the durability, expressed like the number of cycles until the testing break; $\Delta\sigma$ - the stress variation, MPa; $k_1$, $k_2$ – the durability exponents; $C$, $B$ – the durability factors.

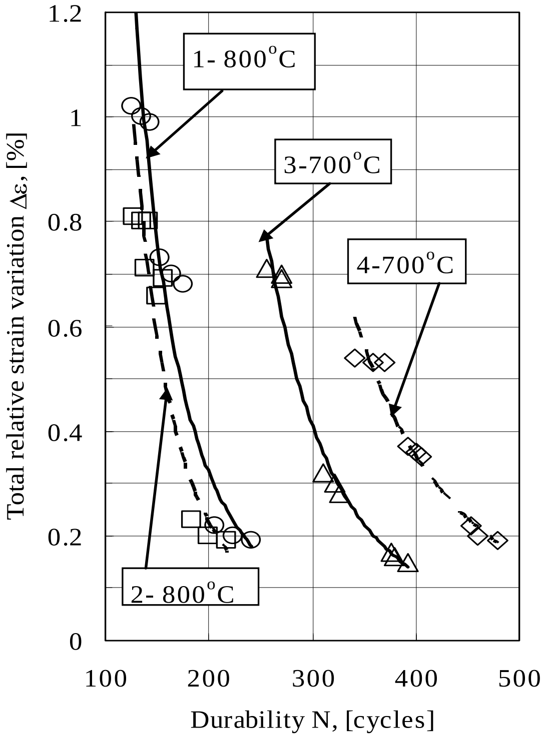

**Figure 4.** The dependence between total relative strain variation and durability for different maximum temperatures of the cycle: 1, 3 – normalized steel; 2, 4 – temper hardening steel

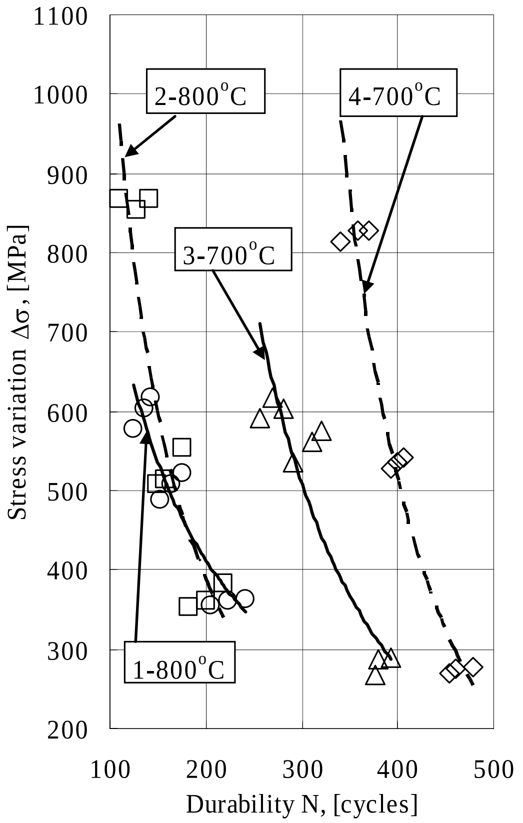

**Figure 5.** The dependence between stress variation and durability for different maximum temperatures of the cycle: 1, 3 – normalized steel; 2, 4 – temper hardening steel

The influence of total relative strain and stress variation on non-isothermal fatigue durability is emphasized by regression analysis based on equation (2) and (3), (Table 4).

**Table 4.** The results of the regression analyses (2) and (3)

| Regression characteristics | | Normalized steel | | Temper hardening steel | |
|---|---|---|---|---|---|
| Cycle maximum temperature [°C] | | 800 | 700 | 800 | 700 |
| Cycle minimum temperature [°C] | | 100 | | | |
| $\Delta\varepsilon$ variable range [%] | | 0,19... ...1,02 | 0,15… …0,71 | 0,19… …0,81 | 0,19… …0,54 |
| $\Delta\sigma$ variable range [MPa] | | 363,82 … 577,75 | 289,34 … 590,88 | 363,82 … 853,49 | 277,88 … 814,10 |
| $N$ variable range [cycles] | | 125 … …242 | 256 … …393 | 128 … …218 | 341 … …479 |
| Regression coefficients | $C$ | $3\cdot10^6$ | $1\cdot10^7$ | $3\cdot10^9$ | $5\cdot10^8$ |
| | $k_1$ | -3,028 | -3,314 | -3,983 | -3,523 |
| | $B$ | 51497 | $4\cdot10^7$ | $4\cdot10^6$ | $9\cdot10^{12}$ |
| | $k_2$ | -0,911 | -1,980 | -1,757 | -3,942 |
| Determination coefficient $R^2$ for equation (2) | | 0,9199 | 0,9827 | 0,9202 | 0,9681 |
| Determination coefficient $R^2$ for equation (3) | | 0,8628 | 0,7403 | 0,7698 | 0,9400 |

About the above presented experimental results the following observations can be done:

- the sample pieces were tested with a relative elastoplastic strain in the range of 0.19 … 1.02 %, which are in accordance with forging dies thermal strains;
- small durability values ($N \leq 1000$ cycles) were registered; this fact justifies the utilization of equation (2) because the strain deformations character is preponderant plastic;
- for high strain range and for maximum temperature of 700°C the temper hardening steel has the best behaviour, while for maximum temperature of 800°C both types of steel have approximately the same behaviour;
- for $t_{max}$ = 800°C and small total relative strain values, the normalized steel has higher durabilities than temper hardening steel, while for $t_{max}$=700°C an inverse situation is appearing;
- for determination coefficient of eq. (2), high values in the range of 0.9199 … 0.9827 were obtained, as a result of the major influence of total strain;
- the stress variation has a smaller influence on non-isothermal durability; this fact is shown by the determinations coefficient values of the eq. (3) and it can be caused both by the Bauschinger effect and hardening phenomena which are different from normalized to temper hardening steel;
- the temper hardening steel, tested at 800°C, confirms its better behaviour in plastic range (the stress variation has values in a narrow range of 363 … 577 MPa, and also, for $t_{max}$=700°C in the range of 289 … 590 MPa;
- the temper hardening steel tested at $t_{max}$=700°C has the worse plastic behaviour because of stress variation level that influences its durability in a large measure.

For a better characterization of the cyclic non-isothermal stress behaviour, there were drawn the curves (Figure 6), which show the dependence between the stress variation (Δσ), and total relative strain variation (Δε).

The dependence presented in Figure 6 can be described by the following relation:

$$\Delta\sigma = a_1 + b_1 \cdot (\Delta\varepsilon) \qquad (4)$$

where: Δσ is the stress variation corresponding to stabilized value of relative elastoplastic strain variation, MPa; Δε - relative elastoplastic strain variation, %; $a_1$, $b_1$ – material constants, which are calculated as a result of a regression analysis (Table 5).

From Figure 6 it can be observed that the temper hardening steel tested at $t_{max}$ = 800 °C and normalized steel tested at $t_{max}$ = 700 °C present the lowest strain capacity in elastoplastic range.

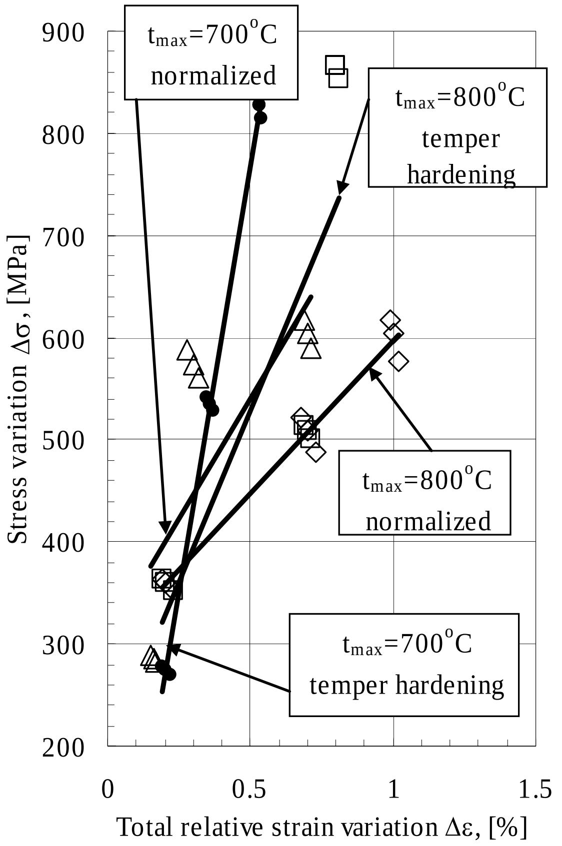

**Figure 6.** Stress variation vs. total relative strain variation

**Table 5.** The results of regression analysis (4)

| Regression characteristics | | Normalized steel | | Temper hardening steel | |
|---|---|---|---|---|---|
| Cycle maximum temperature [°C] | | 800 | 700 | 800 | 700 |
| Cycle minimum temperature [°C] | | 100 | | | |
| Δε variable range [%] | | 0,19… …1,02 | 0,15… …0,71 | 0,19… …0,81 | 0,19… …0,54 |
| Δσ variable range [MPa] | | 363,82 … 577,75 | 289,34 … 590,88 | 363,82 … 853,49 | 277,88 … 814,10 |
| Regression coefficients | $a_1$ | 298,99 | 305,66 | 193,41 | - 61,11 |
| | $b_1$ | 296,87 | 471,57 | 671,01 | 1654,1 |
| Determination coefficient $R^2$ | | 0,9704 | 0,8859 | 0,8659 | 0,9925 |

Stress time, which generally is expressed through the cycle period, has a different influence from each material.

Thus, for the cyclic non-isothermal stresses with keeping at the maximum cycle temperature, the keeping time has a major influence on the durability, while for the thermal cycles without keeping at the maximum cycle temperature has to be taken into consideration the total cycle period.

For emphasizing the influences of the heating time and total relative elastoplastic deformation on durability, in Figure 7 it was represented the dependence between the heating strain speed and durability.

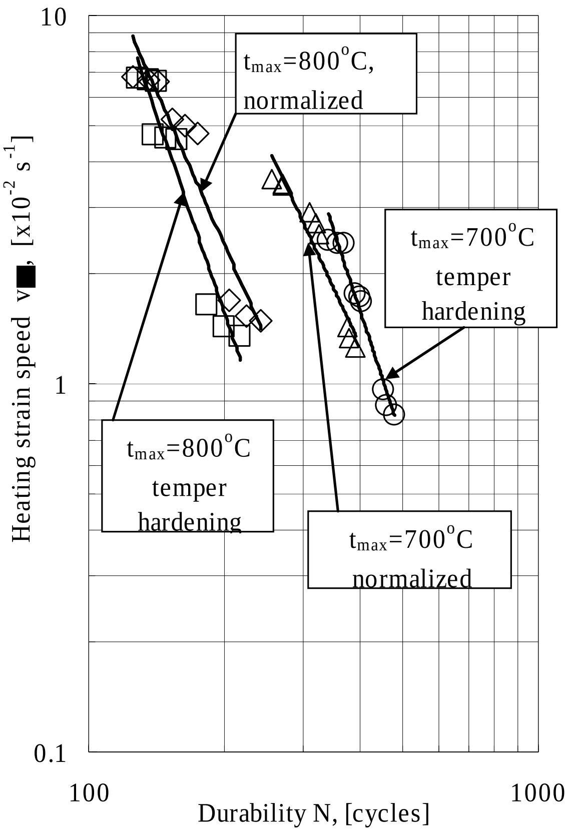

**Figure 7.** Heating strain speed vs. durability

For modeling this dependence it was used the relation (5) obtained as a result of a regression analysis:

$$v_{\Delta\varepsilon} = D \cdot N^{d} \tag{5}$$

where: $v_{\Delta\varepsilon}$ is the heating strain speed, s$^{-1}$; $N$ – durability, cycles; $D$, $d$ – coefficient respectively durability exponent (material constants presented in Table 6).

From Figure 7 it can be observed that for maximum cycle temperature of 800°C the heating strain speed does not influence to much the durability of both steel types.

**Table 6.** The results of regression analysis (5)

| Regression characteristics | Normalized steel | | Temper hardening steel | |
|---|---|---|---|---|
| Cycle maximum temperature [°C] | 800 | 700 | 800 | 700 |
| Coefficient $D$ | $6\cdot10^6$ | $9\cdot10^6$ | $2\cdot10^8$ | $7\cdot10^9$ |
| Coefficient $d$ | -2.76 | -2.63 | -3.55 | -3.70 |
| Determination coefficient $R^2$ | 0.9124 | 0.9257 | 0.9355 | 0.9599 |

For the tests where the cycle maximum temperature was 700°C, the small values of the heating strain speed imply high durabilities of the temper hardening steel. Also, it can be remarked, from Table 6, the high values of the determination coefficient. This fact shows, once again, the strong connection between the considered parameters.

## 4. CONCLUSIONS

The starting point for the design and carrying out of the experiments was represented by cyclic thermal stresses of the hot forging dies.

Based on the Manson – Coffin model of metallic materials behaviour at thermal fatigue it was used a testing stand specially built for non-isothermal fatigue experiments.

The main conclusions of the paper are the following:

- the determinations with the highest verisimilar degree of non-isothermal fatigue durability were carried out when the sample piece was fastened at both ends and subjected to compression at maximum cycle temperature;
- the characterization of a metallic material at cyclic non-isothermal stresses implies taking into account a lot of factors like: the temperature limits of the non-isothermal cycle; the size of elastoplastic strain variation; the stress variation size; the thermal stress duration; the strain speed value;
- in the range of high total strain values the temper hardening steel has the best behaviour for cycle maximum temperature values of 700°C, while for the maximum temperature of 800°C both steel types have approximately the same behaviour;
- for $t_{\max}$=800°C and low values of the total relative strain the normalized steel has higher durabilities than the temper hardening steel, while for the cycle maximum temperature of 700°C the situation is inversely;
- for both steel types, during the experiments, the trend was cyclic softening;
- the above determined experimental results represents intrinsic characteristics, by the point of view of the non-isothermal fatigue durability, for the tested steels, and they can be used both in designing and exploitation of hot forging dies.

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