SCIENTIFIC PROBLEMS
OF MACHINES OPERATION
AND MAINTENANCE
4 (160) 2009

ADRIAN C. DRUMEANU[*], STELIAN T. PARSCHIVOIU[**],
IOAN TUDOR[*], RAZVAN G. RIPEANU[**]

Specific phenomena that characterize thermal fatigue wear of the forging die steels

Key words

Non-isothermal fatigue wear, forging die steel, cyclic strengthening/softening.

Summary

Thermal fatigue wear is a kind of degradation, which characterises the metallic element friction surface of some couples, like forging dies, fire guns, heavy-duty mechanical brakes, etc. 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 characterise the low cycle, fatigue. The paper presents the experimental results concerning specific aspects, which characterise thermal fatigue wear of the steels used in forging dies construction, e.g. equations which emphasise the cyclic durability and cyclic strengthening or softening phenomena of the die steels. These data can be used both in designing and exploitation of the forging dies.

1. Introduction

Non-isothermal fatigue wear characterises the degradation of the metallic element friction surface, like forging dies, fire guns, heavy-duty mechanical

[*] Petroleum-Gas University of Ploiesti, 39 Bucharest Blvd., 100680 Ploiesti, Romania, drumeanu@upg-ploiesti.ro, itudor@upg-ploiesti.ro
[**] S.C. UPETROM- 1 MAI S.A. Ploiesti, St.1 Decembrie, No.1, Ploiesti, Romania paraschivoiu.tibi@yahoo.com, rrapeanu@upg-ploiesti.ro

brakes, etc. In the case of forging dies, the thermal stresses and strains, which appear in the friction surface in the 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 characterises the low cycle, fatigue. These effects consist in the appearance of cracks 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 primarily determined by the non-isothermal fatigue wear, which causes the appearance of cracks 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 from the point of view of the non-isothermal fatigue wear.

For a correctly choosing and using metallic material, it is necessary to determine its intrinsic characteristics regarding its cyclic non-isothermal stress 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].

2. Experimental

The experiments were developed on a testing stand, specially built for non-isothermal fatigue of the metallic materials [4]. The sample piece heating on this stand is carried out through the thermal effect of electric current.

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 an 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).
- The maximum cycle temperature values were 700ºC and 800ºC, respectively, in accordance with the maximum temperature values which are reached during the forging process.
- The minimum cycle temperature value was 100ºC.
- The average heating rates of the test piece were in the range of 35…80°C/s.
- The average cooling rates of the test piece were in the range of 5.5…7.0°C/s.
- The absence of the sustained time at the maximum temperature of the cycle was included.

– The full test pieces were 4 mm in diameter and 30 mm in length of the calibrated part.
– The criterion of the testing breaks was the decrease of the initial strain amplitude value by 10 %.

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

Table 1. Chemical composition of tested steel

Chemical alloying elements [wt. %]						
C	Mn	Cr	Ni	Mo	S	P
0.34	0.55	1.55	1.60	0.23	max. 0.025	max. 0.025

Table 2. Mechanical characteristics of tested steel

Type of steel	Tensile strength, [MPa]	Yield limit, [MPa]	Elongation, [%]	Reduction of area, [%]	Hardness, HB
Normalised	900…1100	700	12	48	225
Temper hardened	1200…1400	1000	9	40	248

3. Results and discuSsions

In Figure 1 and Figure 2, the influence of the total relative strain variation respectively stress variations 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 [6]:

$$\Delta\varepsilon = C \cdot N^{k_1} \tag{1}$$

$$\Delta\sigma = B \cdot N^{k_2} \tag{2}$$

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.

The influence of total relative strain and stress variation on non-isothermal fatigue durability is emphasised by regression analysis based on equation (1) and (2), (Table 3).

The following observations can be made concerning the above results:

– 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.

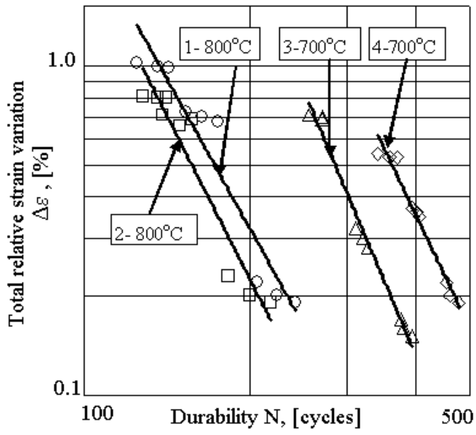

Fig. 1. Total relative strain variation vs. durability for different maximum temperatures of the cycle: 1, 3 – normalised steel; 2, 4 – temper hardened steel

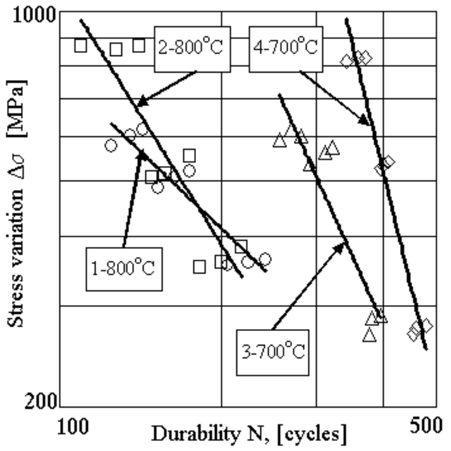

Fig. 2. Stress variation vs. durability for different maximum temperatures of the cycle: 1, 3 – normalised steel; 2, 4 – temper hardened steel

Table 3. The results of the regression analyses (2) and (3) [6]

Regression characteristics		Normalised steel		Temper hardened 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 … 577	289 … 590	363 … 853	277 … 814
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 (1)		0.9199	0.9827	0.9202	0.9681
Determination coefficient R^2 for equation (2)		0.8628	0.7403	0.7698	0.9400

– Small durability values ($N \leq 1000$ cycles) were registered; this fact justifies the utilisation of equation (1), because the strain deformations character is preponderantly plastic.
– For the high strain range and for the maximum temperature of 700ºC, the temper hardened steel has the best behaviour, while for the maximum temperature of 800ºC both types of steel have approximately the same behaviour.
– For T_{max} = 800ºC and small total relative strain values, the normalised steel has higher durability than temper hardened steel, while for T_{max}=700ºC, an inverse situation appears.
– For the determination coefficient of equation (1), 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, and this fact is shown by the determinations coefficient values of the equation (2) and it can be caused both by the Bauschinger effect and hardening phenomena which are different from normalised to temper hardened steel.
– The temper hardened steel, tested at 800ºC, confirms its better behaviour in the plastic range (the stress variation has values in a narrow range of 363 … 577 MPa, and also, for T_{max}=700ºC in the range of 289 … 590 Mpa.
– The temper hardened steel tested at T_{max}=700ºC has the worse plastic behaviour, because of the stress variation level that influences its durability in a large measure.

Specific for cyclic non-isothermal stresses is their progress, in most cases, between two fixed temperature limits. In this case, the interpretations concerning the strengthening or softening phenomena that characterise saturated hardening estate, gain specific aspects. From this point of view, for the steels tested in these conditions, the following observations can be made:
– For both tested steels, total elastoplastic strain stabilises because of the saturated hardening phenomenon that appears in the range of N = 40 … 140 cycles for a maximum temperature of 800ºC (Figure 3 and Figure 4), and, respectively, N = 50 … 200 cycles for maximum temperature of 700ºC;
– When the hysteresis cycle stabilisation occurs, because of initial stress variation increase and total strain decrease, the cyclic strengthening phenomenon appears.
– Cyclic softening presumes hysteresis cycle stabilisation because of initial stress variation decrease and the increase of total strain variation.

The above remarks are reflected in Figures 3, 4, 5, and 6, indicating the evolution of stress variation during test for different test piece fastened system rigidities which are subjected to compression at maximum temperature of the cycle.

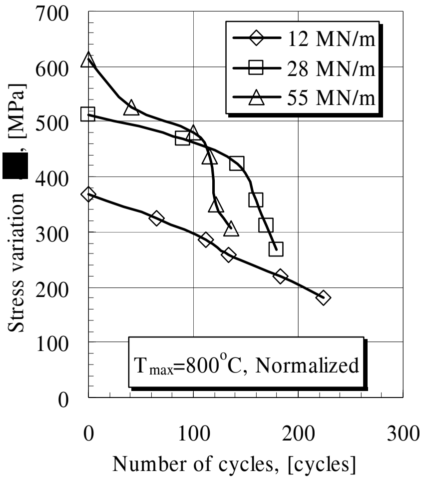

Fig. 3. Stress variation evolution during test for normalised steel non-isothermal stressed at T_{max}=800ºC and T_{min}=100ºC, and for different test piece fastened system rigidities

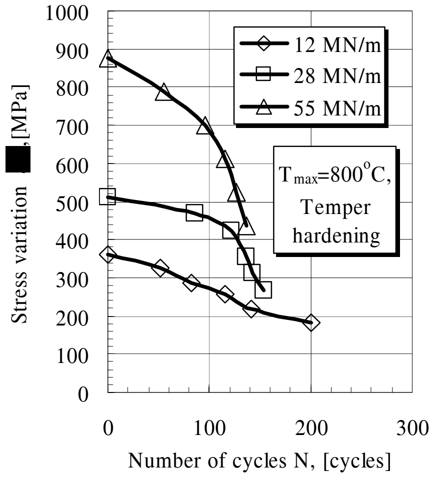

Fig. 4. Stress variation evolution during test for temper hardened steel non-isothermal stressed at T_{max}=800ºC and T_{min}=100ºC, and for different test piece fastened system rigidities

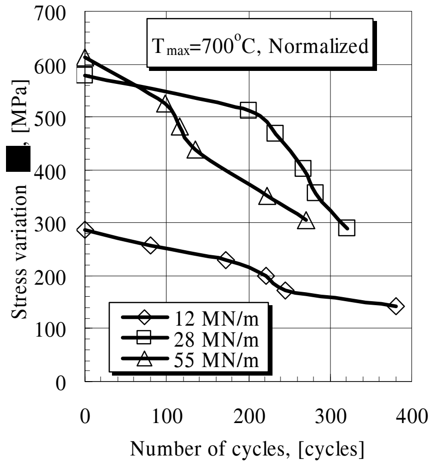

Fig. 5. Stress variation evolution during test for normalised steel non-isothermal stressed at T_{max}=700ºC and T_{min}=100ºC, and for different test piece fastened system rigidities

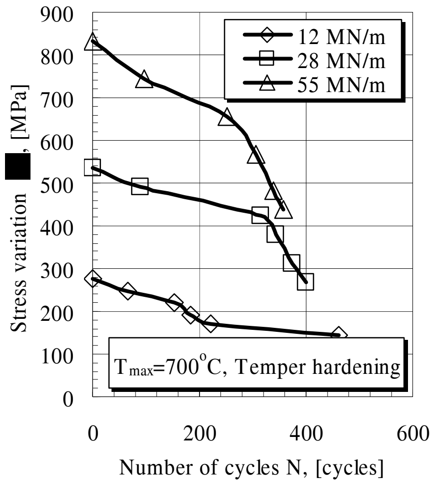

Fig. 6. Stress variation evolution during test for temper hardened steel non-isothermal stressed at T_{max}=700ºC and T_{min}=100ºC, and for different test piece fastened system rigidities

Therefore, from the point of view of cyclic strengthening/softening phenomena and saturated hardening state appearance, the tested steels present the following characteristics:

- For all tested steels appears cyclic softening phenomenon (Figure 3, 4, 5 and 6).
- For high rigidity values of the test piece fastened system, which correspond to high total strains, the cyclic tendency was the fastest, because it appeared, for tests carried out at T_{max}= 800ºC after 100 cycles, and for those developed at T_{max}= 700ºC after 200 – 250 cycles (see Figures 3, 4, 5 and 6).
- Normalised steel has better stress capacity than temper hardened steels.
- Cyclic elastoplastic strain capacity and stress potential can be shown on a limit stress diagram, representing the dependence between total strain variation and stress variation for N = 100 cycles (Figure 7), and N = 200 cycles (Figure 8);

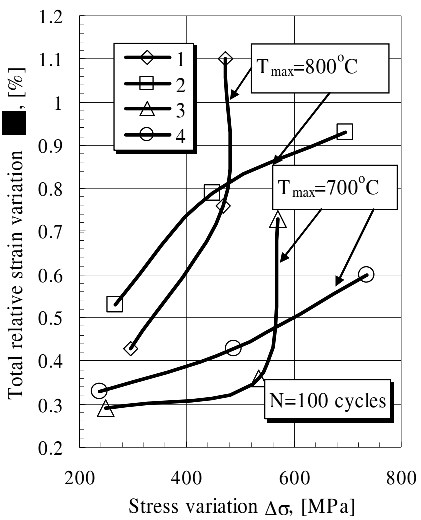

Fig. 7. Limit stress diagram at N=100 cycles and for different cycle maximum temperature: 1, 3 – normalised steel; 2, 4 – temper hardened steel

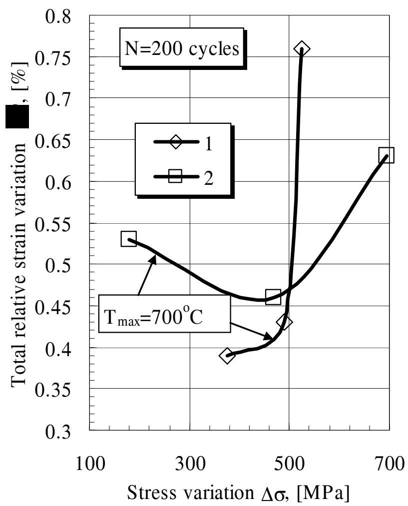

Fig. 8. Limit stress diagram at N=200 cycles and for cycle maximum temperature of 700ºC: 1 – normalised steel; 2 – temper hardened steel

- Therefore, from this point of view, for N = 100 cycles, the normalised steel has the best plastic behaviour at T_{max}= 100ºC and total relative strain values higher than 0.8%, and at T_{max}=700ºC and total relative strain values higher than 0.46%, respectively.
- For relative total strain values, smaller than those presented above, temper hardened steel has a better plastic behaviour (Figure 7).
- For N = 200 cycles and T_{max}= 700ºC, normalised steel can take better total strains bigger than 0.5%, and temper hardened steel has a better behaviour for smaller total relative strain values (Figure 8).

4. Conclusions

The starting point for the design and carrying out of the above-described experiments was represented by cyclic thermal stresses of the hot forging dies. 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.
– In the range of high total strain values, the temper hardened steel has the best behaviour for cycle maximum temperature values of 700ºC, while for the maximum temperature of 800ºC both steel types have approximately the same behaviour.
– For T_{max}= 800ºC and low values of the total relative strain, the normalised steel has higher durability than the temper hardened steel, while, for the cycle maximum temperature of 700ºC, the situation is the opposite
– For both steel types, during the experiments, the trend was cyclic softening.
– Normalised steel generally has a better plastic strain capacity than the temper hardened steel, especially for cycle maximum temperature value of T_{max}= 800ºC.
– The above determined experimental results represent non-isothermal fatigue durability intrinsic characteristics of tested steel that can be used both in designing and the exploitation of hot forging dies.

References

[1] R.A. Dulnev, P.I. Kotov: *Termiceskaia ustalost metallov*, Masinostroenie, Moskva, 1980.
[2] G.A. Tuleakov: *Termiceskaia ustalost v teploenerghetike*, Masinostroenie, Moskva, 1978.
[3] S.V. Serensen, P.I. Kotov: *Ob otenke soprotivlenyia termiceskoi ustalosti po metodu varirucmoi jestkosty nagrujenyia,* Zavodskaia laboratoryia, Vol.28, No. 10, pp. 1233-1238, 1962.
[4] A.C. Drumeanu, N.N. Antonescu, R.G. Ripeanu: *Some Aspects Concerning the Experimental Determinations Methodology for the Non-Isothermal Cyclic Durability of the Machine Steels*, Proceedings of 3rd International Conference on manufacturing Engineering, *ICMEN'08*, 01-03.10.2008, Kallithea of Chalkidiki, Greece, pp.423-434.
[5] M.M. Aleksiuk, V.A. Borisenko, V.P. Krascenko: *Mehaniceskie ispitanyia materialov pri visokih temperaturah*, Naukova Dumka, Kiev, 1980.
[6] Drumeanu, A.C., Paraschivoiu, S.T., Tudor, I., Ripeanu, R.G., *Some Considerations about Non-Isothermal Fatigue Wear of the Forging Die Steel*, 11th International Conference on Tribology, SERBIATRIB'09 Proceedings, May 13-15, 2009, Belgrade, Serbia, pp. 255-260.

Manuscript received by Editorial Board, May 15th, 2010