Transactions on Engineering Sciences vol 2, © 1993 WIT Press, www.witpress.com, ISSN 1743-3533

Influence of changing of microstructure by the heat treatment on fatigue crack growth properties of the carbon cast steel

I. Černý, V. Linhart, F. Hnilica
Department of Strength, National Research Institute for Materials, Opletalova 25, 113 12 Prague 1, Czech Republic

ABSTRACT

An influence of the surface heat treatment on the CSN 422660 carbon cast steel, which is equivalent to the German GS-60 steel (DIN 1681), with a various content of Al on fatigue crack growth rates and threshold values of physically long cracks was studied. The microstructure is the most important factor, which determines the fatigue crack growth mechanism and resistance. Oxide debris on the crack faces reduce significantly the threshold values.

INTRODUCTION

The surface heat treatment is a widely used method in many engineering applications for an improving of mechanical properties of machine parts. An increase of the surface strength results in a better wear resistance, fatigue strength, etc. But in the case of a presence of surface or near surface crack like defects, which may occur especially in castings, another problem appears: i.e. if machine parts are variably loaded, the fatigue crack growth resistance of such defects. In such cases the surface heat treatment may have a detrimental effect on fatigue strength values, if the growth of defects becomes a dominant factor.

An influence of a microstructure on fatigue properties, especially on the crack growth, has been studied for various materials during last years. The significant role of the microstructure in the near threshold fatigue crack growth region is well known. On the other hand, a systematic knowledge of this problem still does not exist. The fatigue crack growth process is localized in the plastic zone, which is a very small region, especially in the threshold conditions; it is mostly of the same order as microstructural units. Moreover, the microstructure of real technical materials is a too complex system. Changes of the microstructure by the heat treatment are often associated with changes in monotonic strength and yield strength, which result in differences of the plastic zone size. This is another factor affecting the crack growth resistance.

A dependence of the crack growth properties of the low-alloy carbon steel on three types of microstructure, tempered martensite, two-phase structures of martensite-bainite and martensite- ferrite, was studied in [1]. The martensitic structure was of the worst crack growth resistance. The lowest crack growth rates were measured in the martensitic - ferritic structure. But in this work, the effect of microstructure was combined with that of strength, because the strength of the three materials was significantly different. A similar problem was studied in [2]: the crack growth resistance of three types of steel with different structures and different monotonic mechanical properties. The lowest crack thresholds were found out in a very high strength bainitic steel, medium values in a ferritic - pearlitic high strength steel and the highest values in a low strength, low carbon steel. Washida et al. [3] described an influence of various grain sizes on the fatigue crack threshold of the 0.45 % carbon steel. The authors explained an increase of the threshold value in the case of coarser structure by the roughness induced crack closure. Putatunda [4] conducted a research of an influence of material strength on crack growth properties and closure in the medium carbon alloy steel AISI 4130. Although yield strength values were more than twice different, the difference of the threshold values was vary small. A greater difference was found in the stable crack growth region. In fact, not only the effect of strength was studied in this work, but also the effect of microstructure, because the high strength material was heat treated, with a martensitic-bainitic structure, in a difference with the second one, which was annealed, having a pearlitic-ferritic structure.

The CSN 422660 carbon cast steel, which is chemically equivalent to the German GS-60 steel according to DIN 1681, is a typical material used for engine castings, such crankshafts, gears etc., which are high-cycle loaded and which should be surface treated to improve the wear resistance. An experimental research of the influence of the surface heat treatment to the crack growth properties was made to find out results, which are used for an evaluation of the size of acceptable defects or to take a decision on the treatment conditions.

EXPERIMENTS

Experimental measurements were carried out on two melts with a different content of Al and residual Al_{res}. The steel was of the following chemical composition (in weight %) - table 1.

Table 1 Chemical composition of the CSN 422660 steel

C	Mn	Si	P	S	Cr
0.44	0.70	0.45	0.020	0.018	0.06

The Al content was as follows:

Melt A: Al_{tot} = 0.071 %, Al_{res} = 0.043 %

Melt B: Al_{tot} = 0.216 %, Al_{res} = 0.160 %

Both the melts were in two states after the different heat treatments 1 and 2 - table 2. Big casts were used for the treatment 1 in a difference with the second case, when directly fatigue specimens were treated.

Table 2 Two different heat treatments

Treatment	Annealing	Cooling	Tempering
1	900°C/5 h	Oil	600°C/4.5 h
2	880°C/0.5h	Water	620°C/0.75h

The microstructure of the melt A1, as well as of the most specimens of the melt B1, was of the typical normalized type with pearlite and ferrite. The volume content of ferrite was 13.4 % (A1) and 13.5 % (B1). Casts from the melt B1 partially contained mostly bainite besides pearlite and ferrite, but this bainitic islands were not present in some specimens of B1. The microstructure of both the re-treated melts (A2, B2) was of the type of tempered martensite and bainite, in the melt B2 a little finer then in the A2 melt. Mechanical properties (ultimate tensile strength UTS, yield strength σ_y and hardness HV 10) of all the four groups were similar:

A1 - UTS = 787 MPa, σ_y = 504 MPa, HV 10 = 243 + 12,
B1 - UTS = 766 MPa, σ_y = 497 MPa, HV 10 = 250 + 16,
A2 - HV 10 = 255 + 9 and B2 - HV 10 = 256 + 11.

The UTS and σ_y values were not determined for re-treated specimens A2, B2.

Fatigue crack growth measurements were conducted on the SCHENCK PHG machine with the constant frequency 50 Hz, using three point bend specimens loaded with the asymmetry R = 0.05 in the laboratory air conditions (temperature 20 - 30°C, relative humidity 40 - 80 %). Specimen dimensions were W = 25 mm (width) and B = 10 mm (thickness). Crack lengths were measured optically by a microscope on both sides of specimens and using a DC potential method [5]. The threshold values were measured by the load shedding method with the loading amplitude reductions of 5 - 7 % in last steps. The threshold measurements were carried on till cracks grew more than 0.02 mm in the period 10^6 cycles. The crack growth rates were measured under the constant-amplitude conditions, according to the ASTM standard [6]. The crack growth rate values were numerically calculated using the three point polynominal method. The stress intensity factor values were calculated according to the formula in [7]. The crack growth and threshold measurements were carried out on four specimens of the melts A1, B1 and on three specimens of the melts A2 and B2 (the threshold values of the melt A2 only on two specimens).

EXPERIMENTAL RESULTS AND DISCUSSION

The values of the threshold stress intensity factor range ΔK_{th} of all specimens are on the fig. 1. The mean values (in MPa $m^{1/2}$) are: A1 - ΔK_{th} = 10.9 + 0.5, A2 - ΔK_{th} = 7.80 + 0.04, B2 - ΔK_{th} = 9.0 + 0.6. The mean threshold value for the specimens B1 containing partially bainite is ΔK_{th} = 9.1 + 0.3, the specimen with the pure pearlitic-ferritic structure has the threshold value ΔK_{th} = 10.8 MPa $m^{1/2}$. The results of the crack growth rate measurements are shown in fig. 2.

A difference between materials with the pearlitic-ferritic and the martensitic-bainitic structures is the most distinct feature of the crack growth properties, especially in the near threshold region, but also in the stable crack growth region up to ΔK = 30 MPa $m^{1/2}$. The crack growthrates corresponding to the high ΔK values above 40 MPa $m^{1/2}$ are practically identical for all groups of the material. No significant differences are between the melts with the different content of Al. The threshold values are connected with the near threshold properties: the highest values in the case of the pearlitic-ferritic structure. But the threshold values are even more sensitive to microstructure differences. The value ΔK_{th} = 10.8 MPa $m^{1/2}$ of the specimen B1 without bainitic islands corresponds with the values of the specimens A1 very good, in a difference with other specimens B1 containing bainite, threshold values of them being similar to the values of the re-treated melt B2.

Another dependence, not very expressive, follows from the fig. 2: a decrease of the threshold values

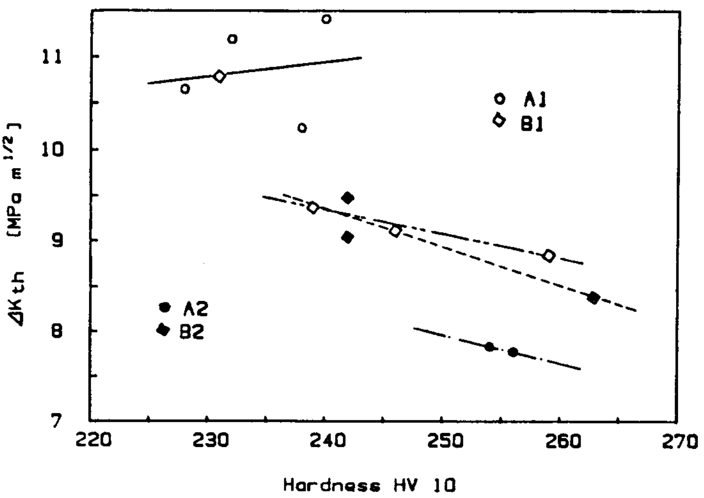

Fig. 1 A dependence of the ΔK_{th} values on hardness of specimens

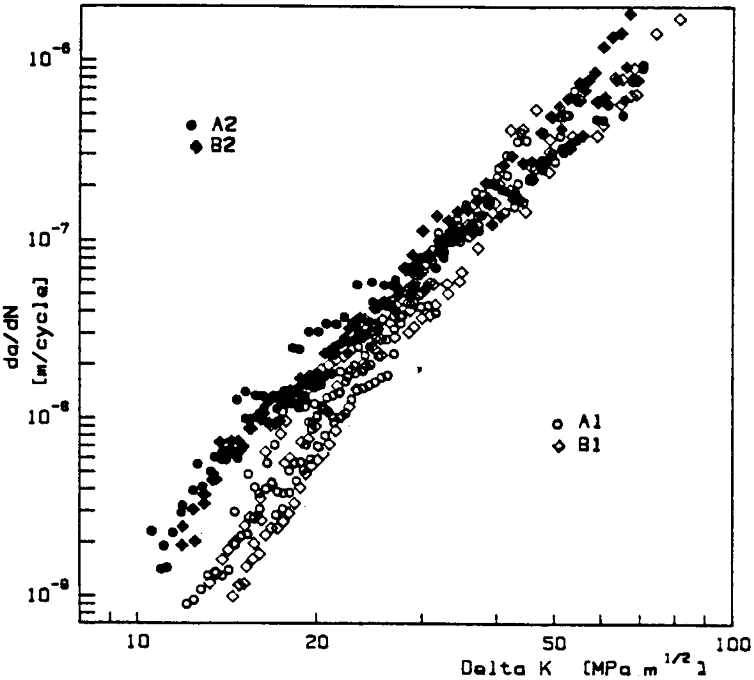

Fig. 2 A total diagram of fatigue crack growth rates

with the hardness, i.e. with the yield strength, in specimens with the same microstructure. This dependence is not clear only in the material A1, due to the high spread of values and the small interval of hardness. Such a dependence was not described in the previous literature mentioned in the Introduction section. The changes of strength were always connected with the microstructure changes. This dependence means, that both the plastic zone size, determined by the yield strength, and the microstructure in this zone affect the crack growth mechanism.

A SEM fractographic analysis was carried out on the crack faces of all materials. It provided information of different crack growth mechanisms. An important effect is a higher roughness of the material with the ferritic-pearlitic structure in comparison with the martensitic one in the threshold and the near-threshold regions (fig. 3). The roughness is supposed to be responsible for the crack closure, which may significantly influence the effective stress intensity factor range and so the growth rates and the threshold values. A confirmation of this hypothesis would be meaningful, because the closure effect does not explain the differences in the threshold values of materials with different structures in various steels, such as in a dual phase martensitic steel [8] or in a ferritic-austenitic steel [9]. Further effect, which may influence the threshold values, is the fretting oxidation. Oxide debris in the threshold regions were visible on all crack surfaces as black "beach markings" and they are apparent also on the SEM photographs. A thicker layer of oxide debris in the case of the material B2 in comparison with the A2 one (fig. 3) may cause a little higher thres-

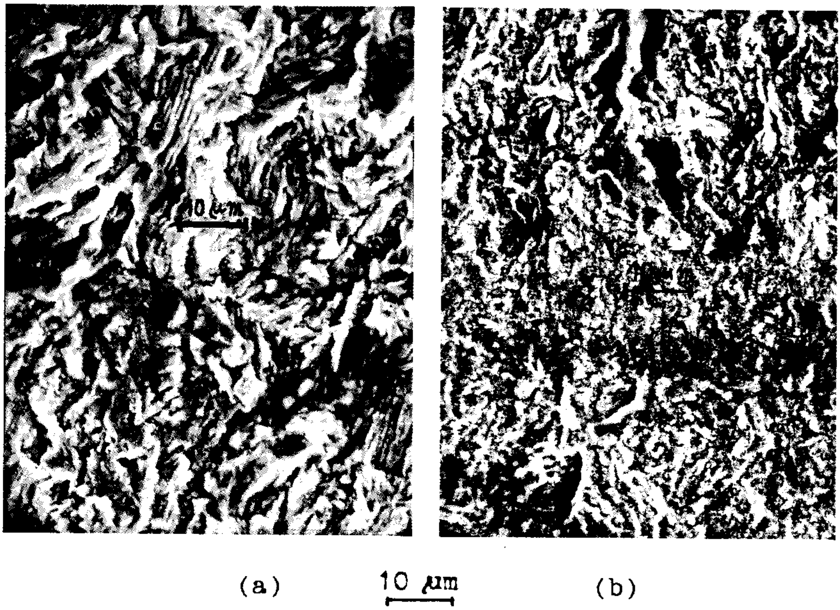

Fig. 3 Crack surface in the threshold region; (a) material A1, (b) material A2

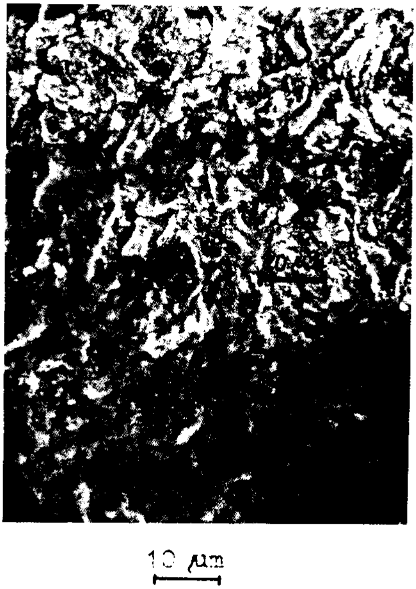

Fig. 3 (c) Material B2

Fig. 4 Crack surface in the near-threshold region in the P-F material (A1)

hold values of this material. The fretting oxidation in the material B2 was so forceful, that oxide debris were pushed out of the crack to the specimen sides during the slow crack growth, and they caused a gradual crack growth retardation in the last load shedding step, up to the crack arrest. A crack closure measurement might confirm hypotheses of the oxide closure effect on the crack growth properties.

A detailed fractographic analysis with a high magnification showed a different crack growth micromechanism in the near-threshold region in various structural elements in the pearlitic- ferritic material. Striation mechanism was typical for the ferritic phase in a difference with the pearlitic phase, where no striation appeared (fig. 4). The growth mechanism is less determined by the microstructure in the medium rate region of the stable crack growth (ΔK = 25 MPa $m^{1/2}$). Striation appear in both the phases, but it is deformed in the pearlitic phase, according to the direction of the carbidic particles. In the high growth rate region, the striation mechanism is dominant, with secondary cracks. A different mechanism worked in the martensitic material: no striation, but very fine secondary cracks in the threshold region and nets of deep secondary cracks in the higher growth rate regions.

The distinct striation on the ferritic islands involves to evaluate the microscopic crack growth rate, i.e. the crack increments per one cycle. A comparison of the microscopic and the macroscopic rates in one of the specimens with the pearlitic-ferritic structure is shown on the fig. 5. Especially in the near-threshold region, the microscopic rate is signi-

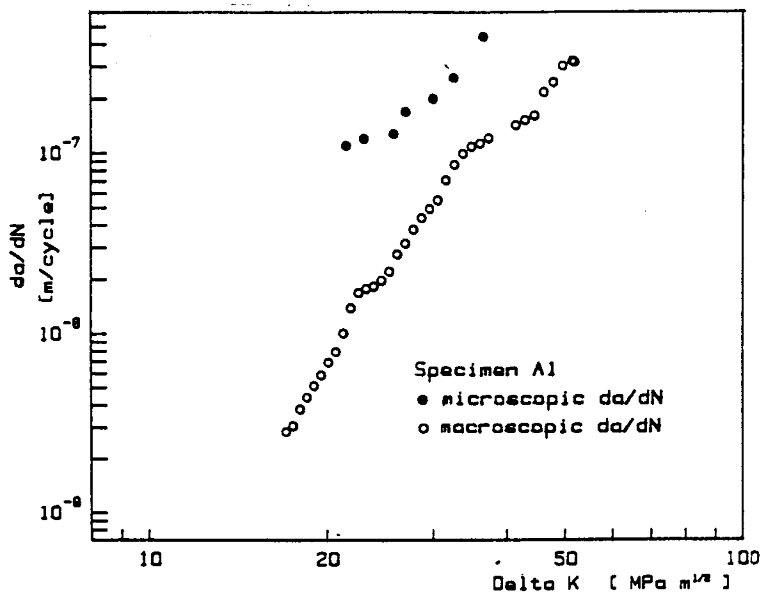

Fig. 5 A comparison of the micro- and macroscopic rates in the P-F specimen (melt A1)

ficantly higher, more than one order, than the macroscopic one. It means, that one stria in the ferritic island corresponds to more than ten loading cycles. We can deduce a hypothesis of the growth mechanism under these conditions. The pearlite phase, which is a composite material from the microscopical point of view, is of a higher strength than the ferritic phase and it limits the plastic deformation of the ferrite in the plastic zone. After the cyclic hardening during several cycles of a plastic deformation, the pearlite particles break and the strength as well as the plastic deformation are transferred to the neighbour ferritic islands. This deformation increase causes an appearance of crack microincrements per ever cycle in the ferrite islands up to their gradual rupture.

The significance of the oxide-induced closure effect can be documented by a measurement of the threshold value of a crack filled by a silicone oil. The threshold value in the melt A2 (martensitic structure) $\Delta K = 3.4$ MPa $m^{1/2}$ is more than twice lower than that in the air. The difference is markedly greater than in the case of a lower strength bainitic steel, where the threshold range in the silicon oil was $\Delta K = 5.7$ MPa $m^{1/2}$ in comparison with the 7.7 MPa $m^{1/2}$ in the air [10]. No oxide debris were apparent on crack faces in our case. This result is very important for practical applications, because many parts made from this steel work in oil environments.

CONCLUSIONS

An influence of a different microstructure of the CSN 42 2660 carbon cast steel (GS-60 according to the DIN 1681) with a different content of Al after different heat treatments on the fatigue crack growth properties and the threshold values in the case of the constant amplitude loading with the asymmetry $R = 0.05$ and the frequency $f = 50$ Hz was studied using three point bend specimens. Three types of a microstructure occured in two melts: a pearlitic- ferritic structure, a bainitic structure combined with pearlitic-ferritic regions and a structure of tempered martensite. The mechanical properties of all groups of the material were similar. The main results can be summarized as follows:

The most important factor affecting the near-threshold properties, especially the threshold values, was the microstructure. The threshold values of the pearlitic-ferritic material were significantly

Transactions on Engineering Sciences vol 2, © 1993 WIT Press, www.witpress.com, ISSN 1743-3533

higher than those of the martensitic material. The material with the combined bainitic and pearlitic-ferritic structure was of similar properties as the martensitic one. The microstructure did not affect the crack growth properties in the high growth rate region.

The oxide debris were apparent in the threshold regions of crack surfaces of all specimens, but the fretting oxidation was the most forceful in the martensitic material, especially in the melt with a higher content of Al, with the finest microstructure. No fretting oxidation arose in the silicone oil environment, where the threshold values of the martensitic material were more than twice lower than those in the air. The higher roughness of the crack surface of the pearlitic - ferritic material in comparison with the martensitic one is supposed to be another factor affecting the crack growth properties.

The striation mechanism is dominant in the stable crack growth region of the pearlitic-ferritic material. No striation, but nets of secondary microcracks appear in the martensitic material.

REFERENCES

1. Huang, L. and Xiong, X. 'The Influence of the Microstructure on Fatigue Crack Propagation in Medium Carbon Low-Alloy Steel' Transactions of Material Heat Treatment, Vol.6, No.2, pp. 30-43, 1985
2. Mazhar, A.A., Khokhar, E.A. and Khan, A.Q. 'Tension-Tension Fatigue Crack Propagation in High Strength, Low Alloy Steel Sheets' Materials Science and Technology, Vol.4, pp. 16-21, 1988

3. Washida, A., Tsuchida, E. and Kobayashi, H. 'Crack Growth and Threshold Characteristics of Surface Fatigue Crack in Plate Specimen of 0.45 % Carbon Steel' Bulletin of JSME, Vol.29, pp. 2403-2409, 1986

4. Putatunda, S.K. 'Influence of Material Strength Level on Fatigue Crack Closure' Engineering Fracture Mechanics, Vol.30, No.5, pp. 627-639, 1988

5. Černý, I., Linhart, V., Minárik, J. and Hulík, P. 'Modification of D.C. Potential Method for Short Specimens,' in Proceedings of the 2nd Int. Conf. Computer Aided Assessment and Control - Localized Damage, Southampton, U.K., 1992

6. 'Standard Test Method for Constant-Load-Amplitude Fatigue Crack Growth Rates Above 10^{-8} m/cycle.' ASTM E 647-88, 1988

7. Srawley, J.E. 'Wide Range Stress Intensity Factor Expression for ASTM E 399 Standard Fracture Toughness Specimens' International Journal of Fracture, No.12, pp. 475-476, 1976

8. Beatty, J.H., Shiflet, G.J. and Jata, K.V. 'The Influence of Mo_2C Morphology and Distribution on the Fatigue Crack Initiation and Propagation Behaviour of Fe-C-Mo Dual-Phase Steels' Metallurgical Transactions, Vol.19A, pp. 973-986, 1988

9. Murakami, R.I., Kim, Y.H. and Ferguson, W.G. 'The Effects of Microstructure and Fracture Surface Roughness on Near Threshold Fatigue Crack Propagation Characteristics of a Two-Phase Cast Stainless Steel' Fatigue and Fracture of Engineering Materials and Structures, Vol.14, No.7, pp. 741-748, 1991

10. Tzou, J.L., Suresh, S. and Ritchie, R.O. 'Fatigue Crack Propagation in Oil Environments - I. Crack Growth Behaviour in Silicone and Paraffin Oils' Acta Metallurgica, Vol.33, No.1, pp. 105-116, 1985