Journal of International Scientific Publication:
Materials, Methods & Technologies, Volume 3

INFLUENCE OF SURFACE TREATMENT ON FATIGUE STRENGTH OF STEEL

Vytautas J. Ciuplys, Antanas Ciuplys

Department of Manufacturing Technologies, Kaunas University of Technology,

Kestucio 27, LT–44312 Kaunas, Lithuania. E-mail: vytautas.ciuplys@ktu.lt

Abstract

Conditions of details exploitation, also durability and security of all construction very depends from the state of metals surface layer. Hardening of metals surface allows changing expensive metals with cheap ones. Improvement of surface quality allows not to reduce, but even to increase the durability of all construction.

In this work the influence of various composited surface treatments on fatigue strength and character of fatigue crack of steel specimens were investigated. Analysed technology of surface hardening greatly increases fatigue strength and durability of specimens. The appearance and spreading of fatigue crack determines the fatigue strength of steel. Characteristics of fatigue crack allow determining the process related to kinetic of appearance and spreading of fatigue crack.

Key words: *steel, fatigue, surface, microstructure, mechanical properties, durability*

1. INTRODUCTION

Analysing plastic deformation and failure processes of metal materials, usually the following factors are discussed: material structure, deformation velocity, temperature, etc. However, the impact of surface layers on deformation process is taken into account very seldom, though they very often influence the mechanical properties, mechanisms of plastic deformation and failure [1 – 3].

Operational properties of a part, reliability and durability of the whole construction much depend on the state of metal surface layers. When manufacturing parts of cars, elements of important constructions and technological software, usually there is an objective to obtain a very strong, solid and resistant to wear surface, leaving a softer and more plastic core. This is beneficial from technological as well as economical point of view since cheaper metal is used, whereas mechanical properties remain good [2].

Fatigue resistance is one of the most important mechanical properties. Durability and reliability of car parts is often defined by their fatigue resistance, since most of them are loaded with dynamic, repeating or variable loads and the main type of failure is metal fatigue [2 – 3].

Fatigue failure usually starts on the metal surface. This is related with the fact that the most intensive fatigue plastic deformation occurs in the surface one grain thickness metal layer. State and properties of the layer determine durability before the occurrence of fatigue crack. The interrelationship of the surface layer together with the characteristics of internal metal volume determine the value of fatigue limit and the coefficient level of stresses' intensity, which is required for the start of fatigue crack [4 – 7].

Various hardening methods of surface have a huge impact on fatigue resistance of constructional materials [2, 8]. The choice of surface processing method is determined by properties and microstructure of a material, as well as the purpose and working conditions of part's material. Very

often the optimum processing is a combination of several methods, which enables to obtain the required properties (high fatigue resistance, wear, etc.) [1].

Exhibition of specific fatigue fracture properties enables to determine kinetics of the processes, related with fatigue crack initiation and propagation [4 – 6, 9 – 12]. Analysing fractures of machine parts and comparing them with the most specific "mode" fractures, it is possible to determined the nature of affecting loads, if it is unknown, and in many cases, the reason of part failure.

2. METHODOLOGY

The impact of several combined surfaces processing on the fatigue resistance of carbon steel samples is investigated in the work. Chemical composition and mechanical characteristics of steel are given in Table 1 and Table 2.

Table 1 - Chemical composition of steel (in wt. %)

C	Si	Mn	Cr	P	S	Cr	Cu
0.45	0.24	0.60	0.20	0.032	0.030	0.20	0.10

Table 2 - Mechanical characteristics of the investigated steels

$R_{p0.2}$, MPa	R_m, MPa	A, %	Z, %
335	650	14	40

The surface was hardened using different processing combinations: by hardening with high frequency electricity currents, rolling by rollers, heating and cooling under different temperatures. Fatigue resistance was investigated in the experimental facility *УКИ-10М* by rotating in cyclic bending. The experiments were carried out at room temperature and at a rate 3000 r/min. Round samples were used, the diameter of operational part of which was equal to 7.5 mm.

After the mechanical processing, all samples were annealed at 850°C in the protective environment. Steel's fatigue resistance was investigated using 6 series samples. The processing regimes are given in Table 3.

Table 3 - Hardening methods, processing regimes and fatigue limit of steel surface

Series No	Hardening regimes of the surface	Fatigue limit, MPa
1	The unhardened sample is 6 h annealed at 750 ºC	350
2	The unhardened sample + rolling by rollers	510
3	The unhardened sample + rolling by rollers + hardening with high-frequency electric current	340
4	The unhardened sample + rolling by rollers + hardening with high-frequency electric current + 2 h tempering at 200 ºC	540

5	The unhardened sample + rolling by rollers + 6 h tempering at 500 ºC + hardening with high-frequency electric current + 2 h tempering at 200 ºC	560
6	The unhardened sample + rolling by rollers + 2 h tempering at 300 ºC + hardening with high-frequency electric current + 2 h tempering at 200 ºC	540

The fractography of fatigue failure was observed by optical microscopy, transmission electron microscope and scanning electron microscopy.

3. EXPERIMENTAL PART

The surface layer of metal has a huge impact on mechanical properties, plastic deformation and failure mechanisms, thus when manufacturing parts it is very important to form the surface layer of required properties on their surface. Steel's fatigue resistance may be increased using different surface hardening methods [1 – 2]. Various methods may be used: plastic deformation (rolling by rollers and balls, shot peening), surface hardening, laser and plasma processing, thermal and thermo-chemical processing and their different combinations. Selection of one method or the other depends on the specific operational conditions of the part.

According to the surface hardening regimes, presented in Table 3, fatigue curves of treated samples are presented in Figure 1. The numbers of curves correspond to the numbers of sample series.

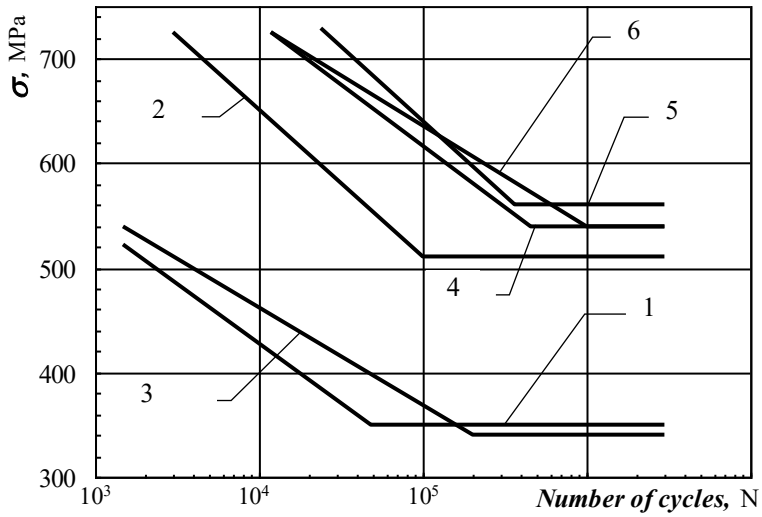


Figure 1. Fatigue resistance of 7.5 mm samples subject to surface hardening.
The numbers of curves corresponds to numbers of series in Table 3

From the Figure 1 it can be seen that the surface hardening enhances fatigue resistance and durability of carbon steel samples. Rolling samples of series 2 by rollers, their fatigue resistance, comparing with the unhardened samples of series 1, enhanced by 160 MPa, whereas the durability at 500 MPa stress increased almost 100 times (Figure 1, curves 1 and 2). Plastic deformation changes the structure and density of crystal grating defects of the surface layer, besides, the remaining compression stresses are formed on the surface, therefore fatigue resistance enhances.

After rolling by rollers and hardening samples with high-frequency electric currents, their cyclic resistance declines. Fatigue limit drops to 340 MPa, however durability enhances, comparing with the unhardened samples of series 1 (Figure 1, curves 1 and 3). After treating samples with the regime of series 3 and tempering for two hours at 200 ºC, fatigue resistance and durability significantly enhance (Figure 1, curve 4). The fatigue limit of samples of series 4 – 510 MPa 1.5 times exceed the fatigue limit of unhardened samples, whereas durability at 550 MPa increased by 1000 times.

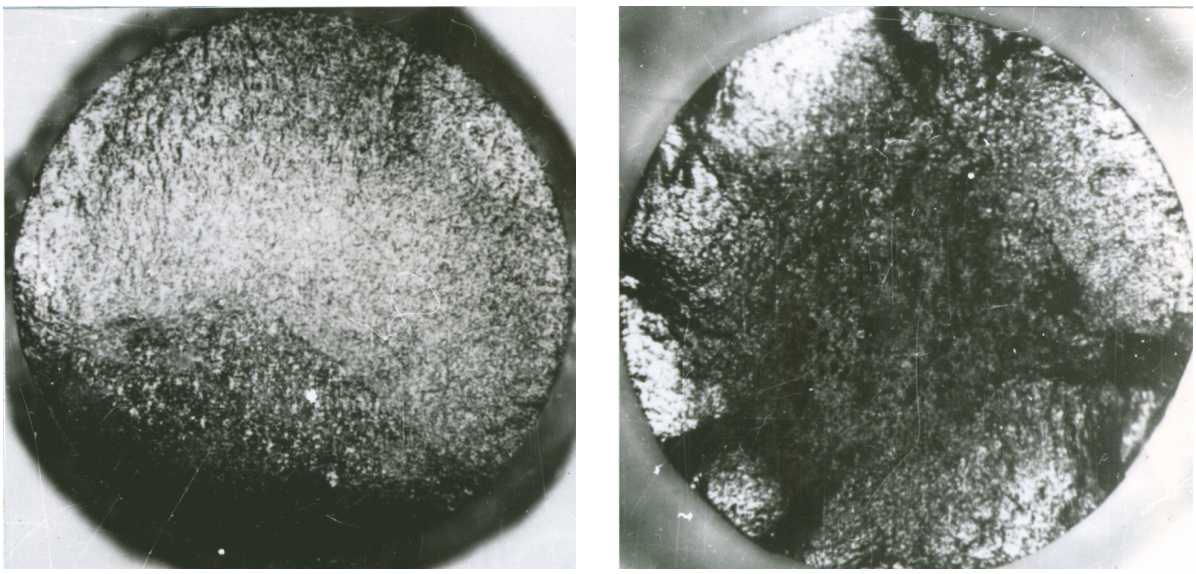
The supplement of surface hardening treatment with high (series 5) or low (series 6) tempering, which is performed after rolling by rollers, does not provide a more visible change of fatigue limit, comparing with the samples of series 4. Only after tempering samples for 6 hours at 500 ºC, fatigue limit and durability enhance insignificantly (Figure 1, curves 4 and 5). Taking into account fatigue resistance of samples of series 4, 5, and 6 it is difficult to give prominence to any of them. The most economical one is treatment of samples of series 4 since after rolling by rollers tempering is not applied to them, which is used for the samples of series 5 and 6.

From the fatigue curves (Figure 1) it can be seen that in order to enhance the fatigue resistance of the given steel, the most expedient way is to harden its surface according technological regimes of series 4. This is related with the optimal relation of properties and microstructure of the surface and internal samples. Microstructure research revealed that the sorbite structure developed in the hardened areas of series 4. Therefore the hardening processing, after which the sorbite is developed on the surface, is best for the parts, manufactured from the given steel and operating under cyclic load conditions.

Rolling samples of series 2 by rollers enhanced their fatigue resistance. After such processing, the remaining compression stresses [2] are developed on the surface of the samples, whereas pearlite reduces. However mechanical granulation of pearlite plates reduces fatigue resistance of samples of series 2, in comparison to series 4.

Hardening of samples with high-frequency electric currents after rolling by rollers (series 3) significantly reduce their fatigue resistance. This is related with the fact that surface resistance to the occurrence of fatigue cracks diminishes.

Intermediate tempering (series 5 and 6) does not evoke essential structural changes of the surface layer. Therefore fatigue resistance of the samples of these series does not differ much from the samples of series 4.



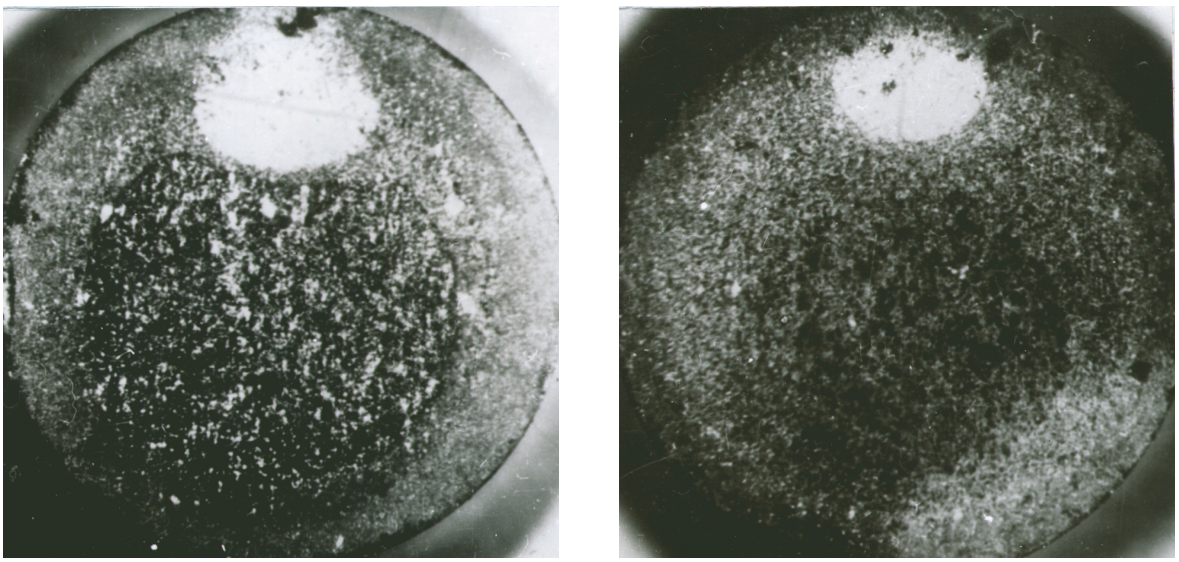
a) b)

Figure 2. Fatigue fractures, when the fatigue crack is initiated on the sample surface:
a – series 3, σ = 400 MPa, N = $9.5 \cdot 10^3$ cycles; b – series 1, σ = 400 MPa, N = $1.0 \cdot 10^5$ cycles

Microfractographic testing of the carbon steel fatigue fracture in all amplitudes of loads has revealed that the samples of series 1 and 3 decompose due to the fatigue crack, which originates on their surface and further progresses. In this case, a smooth and glossy segment region was seen in the fracture, where the fatigue crack initiated and slowly grew (Figure 2). The investigation has revealed that specific gloss of the fatigue crack propagation region has initiated not due to the crack propagation mechanism, but due to the crack surface mandreling in the compression cycle. The fracture surface gloss in the fatigue crack propagation region is more expressed at the loads similar to the fatigue limit, and it is more emphasized at bigger number of cycles till failure.

Thus according to the nature of the fatigue crack propagation region (its size, gloss, contour, etc.) it may be decided only upon the duration and size of the cyclic load affect. Small loads and a big number of cycles till failure evoke the formation of big, smooth and glossy region. The load increase evokes the glossy region reduction and the contour increase.

According the fracture nature, failure of the samples with the hardened surface (series 2, 4, 5 and 6) in the small load region begins inside the sample, in the boundary, which separates the hardened and unhardened metal (Figure 3). In the samples of the series, the fatigue crack propagation region is a glossy ellipse spot. Such kind of fatigue failure is usually formed in hardened and high strength metals, whereas the ellipse fatigue crack propagation region is called a “fish eye” [6, 13, 14]. The “fish eye” region area reduces with increase of stress and after reaching a certain load range σ_{max}, the fatigue crack initiation on the surface becomes energetically more beneficial.



a) b)

Figure 3. Fatigue fractures, when the fatigue crack is initiated inside the sample:
a – series 6, σ = 680 MPa, N = $6.2 \cdot 10^5$ cycles; b – series 2, σ = 630 MPa, N = $2.3 \cdot 10^5$ cycles

Fracture analysis of the samples, the fatigue fracture of which have initiated under the surface, has enabled to highlight some common fractographic patterns.

At stress, similar to the fatigue boundary, the maximum "fish eye" region area in the samples of the given series was observed. Final failure of the sample at this stress is brittle, situated on the opposite fracture side of the "fish eye" and occupies major region of the unhardened sample part. Final failure of the samples of series 6, tested at 680 MPa, is brittle and it borders on the "fish eye" region.

Let's analyse basic fracture regularities of the samples, the failure of which has initiated on the surface (series 1 and 3). Fractures of the samples have such specific properties.

During testing in the area of low loads one, sometimes two-three glossy fatigue regions were developed in fatigue fractures. With increase of load, the number of fatigue crack hotbeds increased. For example, the sample (Fig.2 a) tested at σ = 400 MPa had one fatigue crack hotbed, whereas the sample (Fig.2 b) – 7 hotbeds.

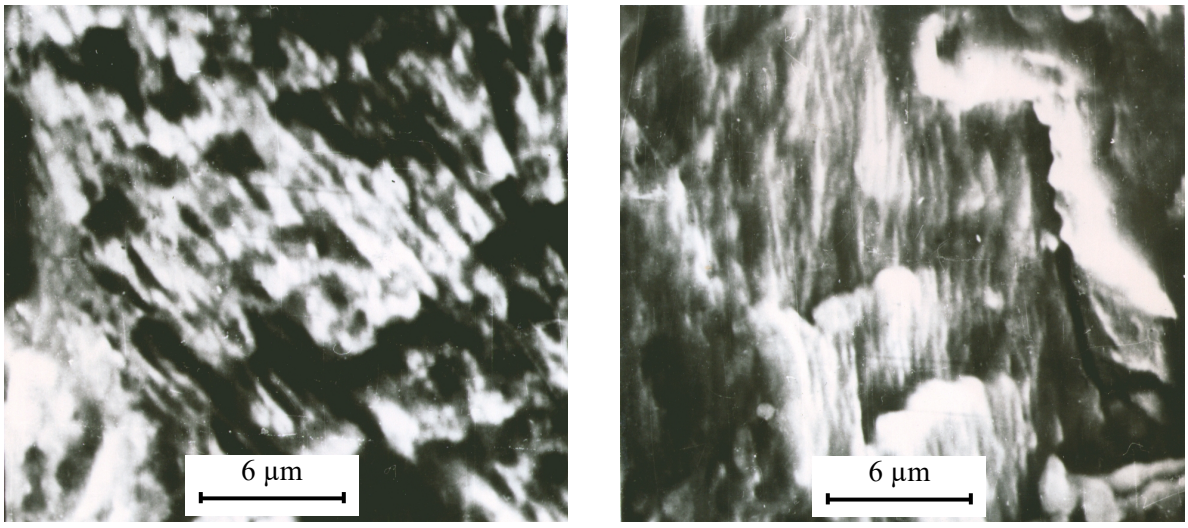
In the samples of series 1, in the area of fatigue crack propagation, the fracture is plane and smooth, whereas in the samples of series 3 – stepped. The final failure region in the samples of 1 and 3 was ductile, however, at small loads, brittle bands were found in the final failure region.

Load increase reduces the final failure region. Around the brittle region, developed at small loads, with increase of load, the circular ductile failure region has been developed. At big loads, the fragile region completely vanishes. Such pattern of final failure region variation, depending on the stress amplitude is common to all series of the investigated samples. The ductile region initiation around the final failure region is probably conditioned by big plastic deformations initiating in the fatigue crack node, due to which metal disintegrity occurs and its structure changes significantly. Thus anticipatedly propagating crack moves ductily across the friable strained structure metal. The fragile region which remains in the central part of the final failure region reveals that affecting load did not evoke any

changes, which would stimulate the initiation of pores, their augmentation and occurrence of hole contour with crack propagation in the fracture.

Samples, which dissociated with the development of the “fish eye”, always have higher fatigue resistance than the samples, the failure of which begins on the surface. This is due to different stress state crack in the node, which depends on the fact whether the fatigue crack occurs on the sample surface or inside it. When the fatigue crack is developed inside the sample due to small opening when it grows, the conditions of plane deformation are exhibited more clearly than in the situation when the crack initiates on the surface and when propagating it opens up more widely.

Replicas, taken from the fractures in the fish eye region and in the anticipated crack propagation region, were tested using a transmission electron microscope. The fatigue crack initiation region, the “fish eye” region as well as the regions of anticipated crack propagation and final failure were investigated using a bitmap electronic microscope.



a) b)

Figure 4. Testing of the unhardened core fatigue fracture with electronic microscope:
a – in the central part of the “fish eye”; b – in the periphery of the “fish eye”

In fracture regions, which correspond the crack propagation in the unhardened core, specific fatigue micro bands have been observed. Investigation of fatigue micro band nature has revealed that they are situated in close circles around fatigue crack initiation region. Fatigue fracture microfractography of the “fish eye” region is given in Figure 4.

Investigation of the hardened samples of the „fish eye“ region has revealed that the fatigue crack is initiated in the zone, which is at a certain distance from the hardened layer in the unhardened core (Figure 4). Fractographic testing has revealed that failure in this region occurs when heavily oxidized friable surface is developed. Such fracture contour does not have most common fracture types (brittle, ductile, inter-crystal and fatigue) though friable derivatives remind of pit failure. Such fracture nature in the fatigue hotbed, according literature data [15], is conditioned by non-metallic inclusions.

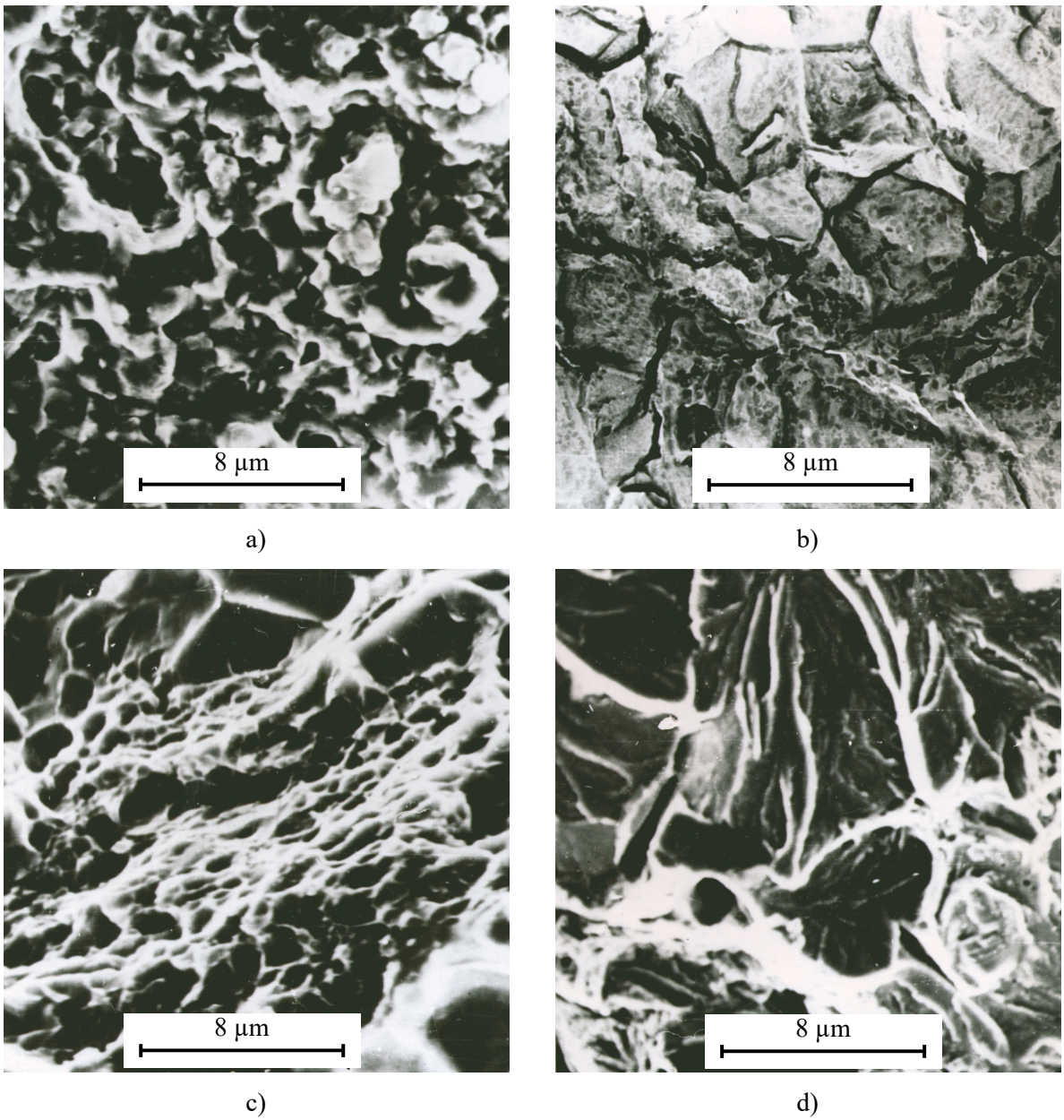


Figure 5. Testing of the fatigue fracture with electronic microscope in the final failure region

Investigation of secondary fatigue cracks at big increases has revealed that they do not differ in their composition from the „fish eye“ region and that they also have an initiation hotbed with fatigue micro bands surrounding it. A chain of glossy bands has been observed on the border of the hardened surface and unhardened core, which may be attributed to the unpropagating fatigue cracks. However, the investigation using an electronic microscope has revealed that these bands are unitary crack facets.

Microfractographic testings of other fields have revealed that failure in the sample core is intercrystal (Figure 5, a and b). In ductile failure region ductile failure was observed when holes typical of such

kind of failure, are developed (Figure 5, c), whereas failure of brittle failure region is brittle when crack facets are developed (Figure 5, d).

4. CONCLUSIONS

1. It has been determined that thermal processing of deformed carbon steel significantly enhances its resistance to fatigue.
2. It is proven that after hardening the steel surface with the given regime, the microstructure and remaining stresses are formed due to which the fatigue crack begins to develop under the hardened sample surface.
3. Samples, in which the fatigue crack initiates inside the sample, have higher resistance than the samples, the fatigue crack of which initiates on the surface.

REFERENCES

1. Vilys J., Ciuplys V., Terentjev V., Kolmakov A., Kvedaras V. (2003) Particularies of Plastic Deformation of Metals Near Surface Layer. Kaunas, Technologija, 207 p.

2. Terentjev V.F. (2002) Fatigue of Metallic Materials. Moskva, Nauka, 248 p. (in Russian).

3. Schijve. J. (2003) Fatigue of structures and materials in the 20th century and the state of the art *International Journal of Fatigue*, 25: pp. 679 – 702.

4. Nascimento, M.P., Souza R.C., Pigatin W.L., Voorwald H.J.C. (2001) Effects of Surface Treatments on the Fatigue Strength of AISI 4340 Aeronautical Steel *International Journal of Fatigue*, 23: pp. 607 – 618.

5. Ceshcini L., Minak G. (2008) Fatigue Behavior of Low Temperature Carburised AISI 316L Austenitic Stainless Steel *Surface Coatings Technology*, 202: pp. 1778 – 1784.

6. Limodin N., Verreman Y. (2006) Fatigue Strength Improvement of a 4140 Steel by Gas Nitriding: Influence of Notch Severity *Materials Science and Engineering A*, 435: pp. 460 – 467.

7. Shulov V.A., Nochovnaya N.A. (2002) Fatigue Strenght of Metals and Alloys Modified by Ion Beams *Surface Coatings Technology*, 158-159: 33 – 41.

8. De la Cruz P., Oden M., Ericson T. (1998) Effect of Laser Hardening on the Fatigue Strength and Fracture of a B-Mn Steel *International Journal of Fatigue* 20: pp. 389 – 398.

9. Sun W.X., Nishida S., Hattori N., Usui I. (2004) Fatigue properties of cold-rolled notched eutectoid steel *International Journal of Fatigue*, 26: pp. 1139 – 1145.

10. Slamečka K., Ponižil P., Pokluda J. (2007) Quantitative fractography in bending-torsion fatigue *Materials Science and Engineering A*, 462: pp. 359 – 467.

11. Puchi-Cabrera E.S., Staia M.H., Quinto D.T., Villalobos-Gutierrez C., Ochoa-Perez E. (2007) Fatigue properties ot a SAE 4340 steel coated with TiCN by PAPVD *International Journal of Fatigue*, 29: pp. 471 – 480.

12. Sun Y., Hanaki S., Yamashita M., Uchida H., Tsujii H. (2004) Fatigue behavior and fractography of laser-processed hot work tool steel *Vacuum*, 73: pp. 655 – 660.

13. Marines-Garcia I., Paris P.C., Tada H., Bathias C., Lados D. (2008) Fatigue Crack Growth from

Small to Large Cracks on Very High Cycle Fatigue with Fish-Eye Failures *Engineering Fracture Mechanins*, 75: pp. 1657 – 1665.

14. Murakami R., Yonekura D., Ni Z. (2002) Fatigue Fracture Behavior of High-Strength Steel in Super Long Life Range *JSME International Journal Series A – Solid Mechanics and Material Engineering* 45: pp. 517 – 522.

15. Zhou Ch., Qian G., Hong, Y. (2006) Fractography and crack initiation of very-high-cycle fatigue for a high carbon low alloy steel. In *Fracture and Damage Mechanics V, Pts 1 and 2*, Trans Tech Puplications Ltd, Zurich, Switzerland, pp. 1113-1116.