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Increasing of Carbon Steel Durability by Surface Hardening

Vytautas ČIUPLYS[1*], Antanas ČIUPLYS[1], Jonas VILYS[1], Valdas KVEDARAS[2]

[1]*Department of Manufacturing Technologies, Kaunas University of Technology, Kęstučio 27, LT-44312 Kaunas, Lithuania*
[2]*Department of Technological Processing, Klaipėda University, Bijūnų 17, LT-91225 Klaipėda, Lithuania*

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Conditions of machine elements during exploitation, also durability and security of all construction depends a lot on the state of metals surface layer. Hardening of metals surface allows to change expensive metals to cheap ones. Improvement of surface quality allows to increase the durability of all construction. In this work the influence of various kinds of surface treatments (hardening with high frequency electric current, rolling by rollers, tempering) on fatigue strength of carbon steel specimens were investigated. Analysed technology of surface hardening greatly increases the fatigue strength and durability of specimens. It was estimated that hardening effect depends on the residual stresses introduced applying deformation and thermal treatment regimes. The optimal treatment of the analysed carbon steel is deformation up to 1 mm depth, hardening with high-frequency electric current and tempering for 2 hours at 200 ºC.
Keywords: carbon steel, fatigue, surface hardening, mechanical properties, durability.

1. INTRODUCTION

Analysing plastic deformation and failure processes of metal materials, usually the following factors are discussed: material structure, deformation rate, temperature, etc. However, the influence 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].

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

Failure of fatigue usually starts on the metal surface. This is related with the fact that the most intensive fatigue plastic deformation occurs in the surface of one grain thickness metal layer [2]. 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 necessary for the start of fatigue crack [4 – 8].

Various hardening methods of surface have a huge influence on fatigue strength of structural materials [9, 10]. The choice of surface treatment 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 treatment is a combination of several methods, which enables to obtain the required properties (high fatigue strength, wear, etc.) [11 – 15].

The surface layer of metal has a huge influence 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 strength may be increased using different surface hardening methods [16 – 20]. Various methods may be used: plastic deformation (rolling by rollers and balls, shot peening), surface hardening, laser and plasma treatment, thermal and thermo-chemical treatment and their different combinations. Selection of one method or the other depends on the specific operational conditions of the part.

Hardening with high-frequency electric current (HfEC) is widely used process for the surface hardening of steel. The components are heated by means of an alternating magnetic field to a temperature within or above the transformation range followed by immediate quenching. The core of the component remains unaffected by the treatment and its physical properties are those of the bar from which it was machined. Carbon and alloy steels with an equivalent carbon content in the range 0.40 / 0.45 % are most suitable for this process [21].

The purpose of the work was to investigate the influence of several combined surface treatments on the fatigue strength of carbon steel samples.

2. EXPERIMENTAL

Chemical composition and mechanical characteristics of the investigated 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

*Corresponding author. Tel.: +370-37-300420, fax.: +370-37-323769.
E-mail address: *vytautas.ciuplys@ktu.lt* (V. Čiuplys)

Table 3. Hardening methods, treatment regimes and fatigue limit of steel surface

Series No	Hardening regimes of the surface	Diameter of gauge length of the sample, mm	Fatigue limit, MPa
1	The unhardened sample is annealed for 6 hours at 850 ºC	7.5	350
2	The unhardened sample + rolling by rollers	7.5	510
3	The unhardened sample + rolling by rollers + hardening with HfEC	7.5	340
4	The unhardened sample + rolling by rollers + hardening with HfEC + 2 h tempering at 200 ºC	7.5	540
5	The unhardened sample + rolling by rollers + 6 h tempering at 500 ºC + hardening with HfEC + 2 h tempering at 200 ºC	7.5	560
6	The unhardened sample + rolling by rollers + 2 h tempering at 300 ºC + hardening with HfEC + 2 h tempering at 200 ºC	7.5	540
7	The unhardened sample is annealed for 6 hours at 850 ºC	10	330
8	The unhardened sample + rolling by rollers + hardening with HfEC + 2 h tempering at 200 ºC + smoothing	10	520
9	The unhardened sample + rolling by rollers + hardening with HfEC + 2 h tempering at 200 ºC + smoothing + 1 h tempering at 300 ºC	10	455
10	The unhardened sample + rolling by rollers + hardening with HfEC + 2 h tempering at 200 ºC	10	500

exceed the fatigue limit of unhardened samples, whereas durability at 550 MPa increased by 1000 times.

The additional surface hardening treatment with high (series 5) or low (series 6) tempering, which is performed after rolling by rollers, does not demonstrate 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 increase insignificantly (Fig. 2, curves 4 and 5). Taking into account fatigue strength of samples of series 4, 5, and 6 it is difficult to give importance 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.

Surface hardening of samples with 10 mm diameter of gauge length (series 7 – 10) was carried out according the most effective treatment technology of samples of series 4 (series 10) with further smoothing (series 8) and the smoothing with a 1 hour tempering at 300 ºC (series 9).

As can be seen from Fig. 3, the smoothing in the final surface hardening stage, comparing with the samples, which do not involve this kind of technological operation (series 10), increase the fatigue limit by 20 MPa (series 8). However after the smoothing carrying out a one hour tempering at 300 ºC (series 9) fatigue strength of samples decreases. The fatigue limit of samples of series 9, comparing with the samples of series 10, decreased by 45 MPa, whereas durability decreases more than 10 times.

Curves 4 (Fig. 2) and 10 (Fig. 3) show the influence of scale factor on fatigue strength for the samples, which have a different diameter of gauge length and an equally hardened surface. The fatigue limit of 7.5 mm diameter samples (series 4) is 40 MPa higher than the fatigue limit of 10 mm diameter samples (series 10).

From the fatigue curves of Fig. 2 and 3 it can be seen that in order to increase the fatigue strength of the given steel, the most useful way is to harden its surface according technological regimes of series 4 and 10. Samples of the series differ according the diameter of gauge length, however, their fatigue strength increased mostly when comparing with the samples, the gauge length surface of which had not been hardened. This is related with the optimal relation of properties and microstructure of the surface and internal samples [24]. Microstructure examination revealed that the sorbite structure forms in the hardened areas of series 4 and 10. Therefore the hardening treatment, after which the sorbite was formed in the surface, is the best for the parts, manufactured from the given steel and operating under cyclic load conditions.

Rolling samples of series 2 by rollers increase their fatigue strength. After rolling, the residual compression stresses are developed on the surface of the samples, whereas pearlite reduces [25]. However mechanical granulation of pearlite plates decreases fatigue strength of samples of series 2, in comparison to series 4 and 10.

Hardening of the samples with high-frequency electric current after rolling by rollers (series 3) significantly decrease their fatigue strength. This is related with the fact that surface resistance to the occurrence of fatigue cracks decreases [26].

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

Fatigue strength of the samples of series 9, for which a one hour tempering at 300 ºC was employed in the final treatment stage, decreases due to tempering brittleness. Due to such tempering, brittleness increases in grain limits, which is revealed in fractographies of fatigue fracture. During the process of fatigue a lot of micro cracks occur in the samples of the series, which when binding develop a rather massive steps. Fatigue cracks are developed on the surface of the samples of the series. This reveals a low resistance of the hardened surface layer to the formation of micro cracks.

Comparing the series 8 and 10, it may be stated that

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