STRESS RELAXATION RESISTANCE FOR IMPROVED FATIGUE PERFORMANCE OF SHOT PEENED TOOL COMPONENTS

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ABSTRACT

Shot peening is an extensively used process in the production of mechanical components to improve their fatigue strength at ambient temperature. At higher working temperatures of some mechanical components, e.g. from 300 to 600°C, the influence and behaviour of the compressive residual stresses are more uncertain, since they tend to relieve at higher temperatures. The response to shot peening induced residual stresses of low alloyed and hot work tool steels was evaluated with respect to stress relief heat treatments and isothermal high temperature fatigue testing. Not only the residual stresses, but also the material substructure and its dislocation characteristics are of importance. Dislocation structures were determined using X-ray diffraction to explain the preference of the different steel grades. Also, results obtained from bending fatigue testing at ambient temperature of tool components after shot peening and stress relief heat treatments demonstrated the different ability of retaining the fatigue strength.

KEY WORDS

Shot peening, Fatigue strength, Isothermal fatigue, Residual stress, Stress relaxation

INTRODUCTION

Tools used in machining operations are exposed to high temperatures and cyclic mechanical loads, which imposes high requirements on fatigue resistance. Shot peening has proved to be a powerful instrument in enhancing the resistance of components to fatigue damage by developing a layer of compressive residual stress as a result of difference in plastic deformation between the surface and its interior (S.R.Lampman (Ed.), 1996; N. Iwata, Y. Tomota, K. Katahira, et al., 2002; A. Tange, K. Ano, 2002). The free energy of a material is raised during deformation by generation of dislocations and interfaces, and a material containing these defects is thermodynamically unstable (F.J. Humphreys, M. Hatherly, 2002). That is why in mechanical loading and in particular at higher working temperatures, e.g. from 300 to 600°C for some tool components, the influence and behaviour of the compressive residual stresses are more uncertain and they tend to relieve. Not only the residual stresses but also the material substructure and its dislocation characteristics are of importance.

As the fatigue performance of shot peened tools to a large extent depends on the stress relaxation resistance in elevated temperature use, knowledge of stress and microstructure stability is essential for evaluating the service life of a tool. Earlier investigations have shown that stress relaxation and dislocation recovery is not a single microstructural process but a series of micromechanisms depending on a number of parameters. These include the material type, its microstructure and purity as well as the strain level and working temperature (F.J. Humphreys, M. Hatherly, 2002). It has also been demonstrated that residual stress relief increases with increasing time and temperature (V.Schulze, 2005).

Different steels for tool component applications exhibit a variety of stress relaxation resistance and, consequently, different fatigue strengths during use. The overall aim of the present study is to optimise the stress relaxation resistance of shot peened tool components to achieve better fatigue strength at elevated working temperatures. It is shown how the shot peened layer is induced in different tool steels and its response to mechanical and thermal loading. Residual stress and dislocation structure states, measured by X-ray diffraction, and room and elevated temperature fatigue data are presented.

METHODS

Materials

The steel grades THG2000 (Uddeholm designation) and SS2541 (Swedish standard) were used as test materials, Table 1. Also an experimental Cr-Mo-V-Ni alloyed grade with improved hot work properties was used, here called HWX.

Table 1. Chemical composition of steels, wt%

Steel	C	Si	Mn	Cr	Ni	Mo	V
THG2000	0,39	0,9	0,4	5,3	0,15	1,2	0,9
SS2541	0,37	0,3	0,7	1,4	1,40	0,20	0,06

The hardening treatment was performed in a vacuum furnace (austenitizing 1020°C/30 min for THG2000 and HWX and 850°C/60 min for SS2541), and subsequent tempering (600°C/2x2 hrs for THG2000 and HWX, and 450°C/1 hr for SS2541) was made to reach a similar hardness of 45 HRC in all tested grades.

Small flat samples, fatigue test specimens and tool components were produced from the three steel grades and shot peened according to the following conditions: pressure 4 bar, shot direction angle 90°, nozzle distance from surface 75±5 mm, peening intensity 15±2A(Almen A) with a 100% coverage. Shot peening media used was super conditioned cut wire with diameter of 0.35 mm and hardness of 700 HV. Tool components and fatigue test specimens were rotated with 37 rpm during shot peening, fatigue test specimens were additionally moved 2mm up and down.

Experimental procedure

Stress relief heat treatments were performed at different temperatures (200-700°C for 2 hours) on shot peened flat samples. Residual stress analysis including determination of surface stress and depth distribution was accomplished following treatments at the different temperatures.

Isothermal high temperature fatigue tests were carried out in air using a 100 kN servohydraulic INSTRON testing machine in push-pull type load mode. Symmetrical tests were performed in strain control (-0.5%/0.5%) at both 450 and 550°C. The tests had a sinusoidal strain wave shape, 0.5 Hz cycle frequency and tensile start direction. Cylindrical test specimens with 6.5 and 20 mm waist diameter and length, respectively, were used. Stress and microstructural state analyses were done before and after the tests.

Bending fatigue tests of specially designed tool components, Figure 1, were performed at room temperature using an Amsler 2 HFP 421 pulsator, running with 80 Hz load frequency. A load was applied at the tool tip, Figure 1b, with the shaft of the tool component rigidly fastened. The applied local stress in the tool critical radius was calculated using the finite element method and a three dimensional solid model of the tool component. Thus, the applied local stress was varied between 1780 MPa maximum and 60 MPa minimum stress. Fatigue tests were performed on shot peened tool components without and with subsequent stress relieving heat treatment at 550°C for 2 hours. The minimum number of test pieces of each condition was not less than six. The scatter in life range was determined assuming the normal Gaussian distribution in the Gaussian probability net (ISO 3800:1993).

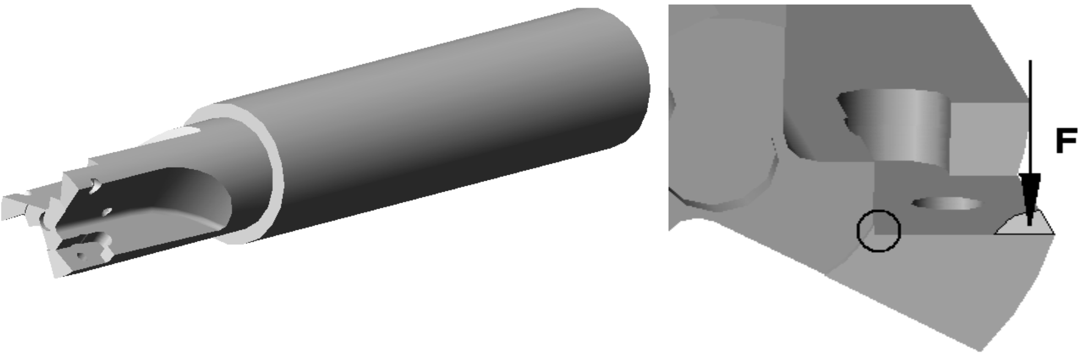

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Figure 1. a) The tested tool components. Length - 110 mm, diameter of the top - 19 mm, b) Loading of tool components, circular mark shows the crack initiation site, the critical radius in the pocket is 1 mm.

Residual stresses and dislocation structure were evaluated by X-ray diffraction (XRD) using Cr-Kα radiation on the (211) martensite/ferrite planes in a Seifert XRD 3000 PTS X-ray diffractometer, operating at 40 kV and 35 mA.

XRD line broadening analysis for microstructural state was accomplished by an integral breadth method. Separation of the size and strain contributions to the line broadening was made by deconvolution of their intensity distributions (simple and squared Lorentzian, respectively). Thus, the coherently diffracting domain size, D, and the average root mean square strain variation within the grain, the microstrain $<\varepsilon^2>^{1/2}$, were determined. Dislocation density was estimated as follows (J. Bergström, 1986):

$$\rho = \frac{2\cdot\sqrt{3}}{b}\cdot\frac{\langle\varepsilon^2\rangle^{1/2}}{D} \tag{1}$$

where b is the Burger’s vector. For simplicity, the dislocation density is expressed as a proportional value, using only the ratio between microstrain and domain size.

RESULTS

Stress relief resistance

All tested materials exhibited stress relief of different magnitude with temperature, Figures 2 and 3, depending on temperature and steel grade. The initial compressive stresses on the surface due to shot peening were found to be approximately -700 MPa in all steels, but in HWX they were higher and deeper under the surface. The results showed that HWX has a greater stress relief resistance in the temperature range between 200 and 400°C, and at temperatures more than 600°C, Figures 2 and 3. However, THG2000 indicates some stabilization of stress relief between 450 and 550°C, similarly in both surface and interior compressive stress.

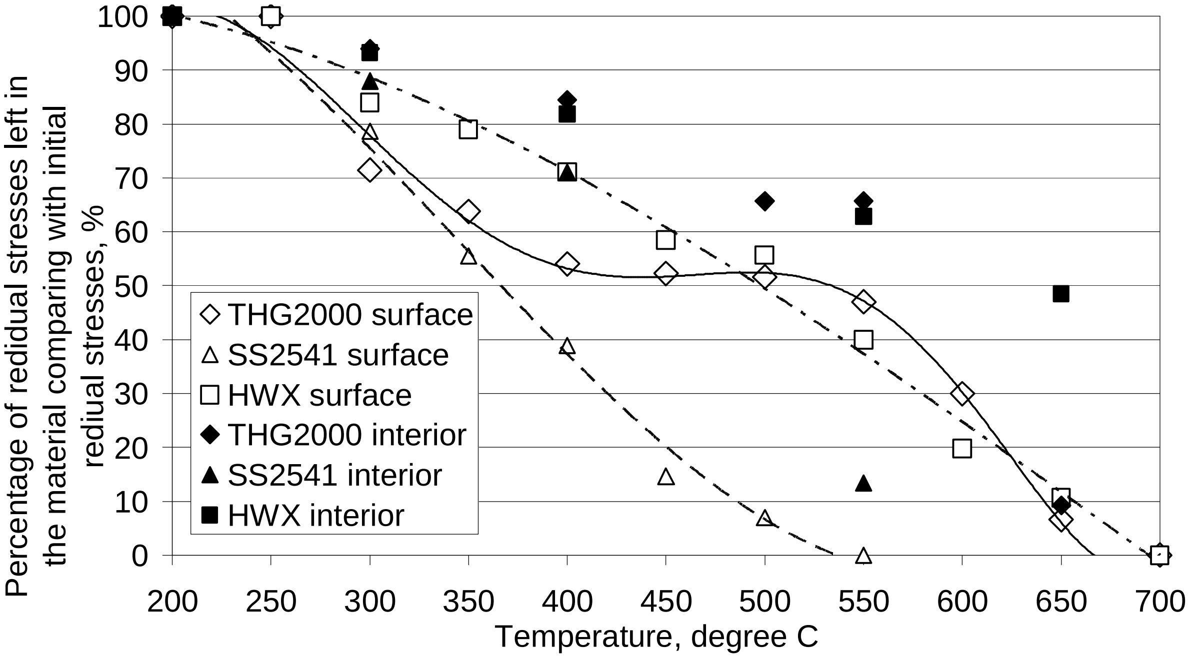

Figure 2. Percentage of compressive stresses left on the surface and in the interior of THG2000, SS2541 and HWX after stress relieving at different temperatures for 2 hours. Initial stresses after shot peening are set to 100%.

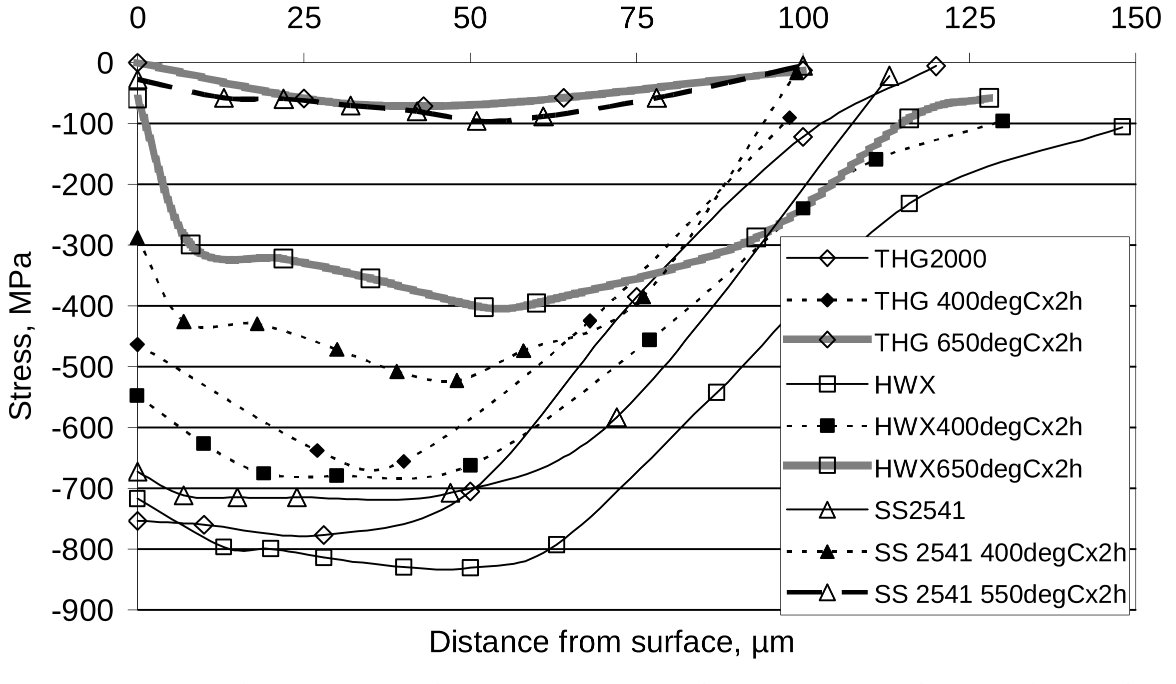

Figure 3. Compressive stress profile versus stress relief temperature in tested materials.

XRD line broadening analysis shows how the structure induced by shot peening disintegrates by temperature. Microstrain decreases and domain size increases with increasing stress relief temperature and distance from the surface of the sample, Figure 4a. Recalculated into dislocation density it decreases at higher stress relieving temperature and from the surface of the shot peened sample into the material, Figure 4b.

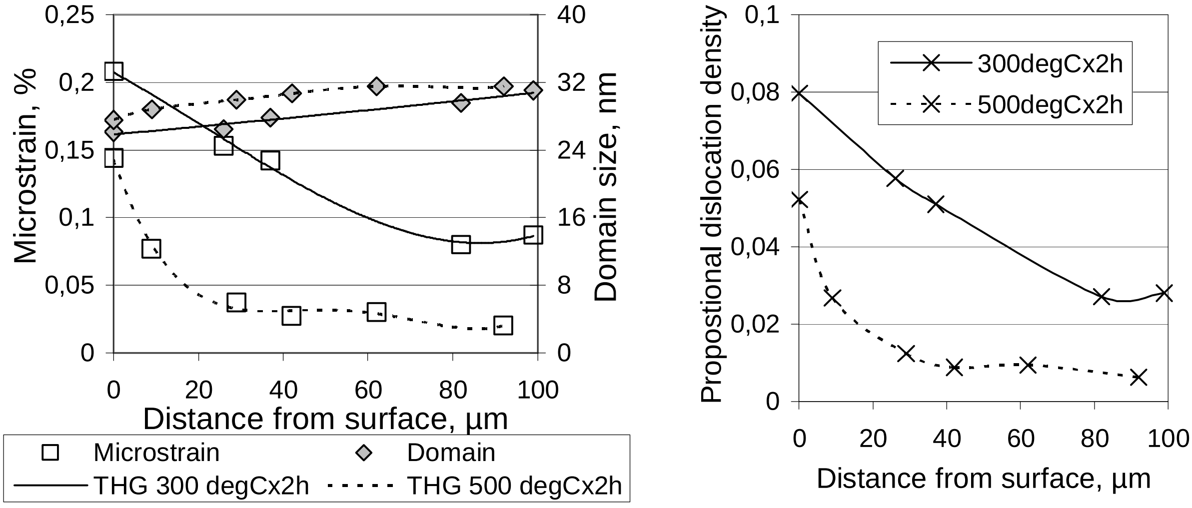

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Figure 4. a) Depth distribution of microstrain and domain size for shot peened THG2000 after stress relief heat treatment at 300 and 500°C, b) Calculated proportional dislocation density for THG2000.

Isothermal fatigue

All tested materials exhibited a cyclic stress softening of the bulk, Figure 5, where the softening behaviour depends on temperature and steel grade. Only THG2000 showed hardening behaviour the first 100 cycles at 450°C before softening followed by failure after 1000 cycles. HWX displayed a better softening resistance and longer fatigue lives than THG2000 at both 450 and 550°C. The shortest fatigue life and considerable softening was observed for SS2541. This steel did not stand any loading cycle at 550°C.

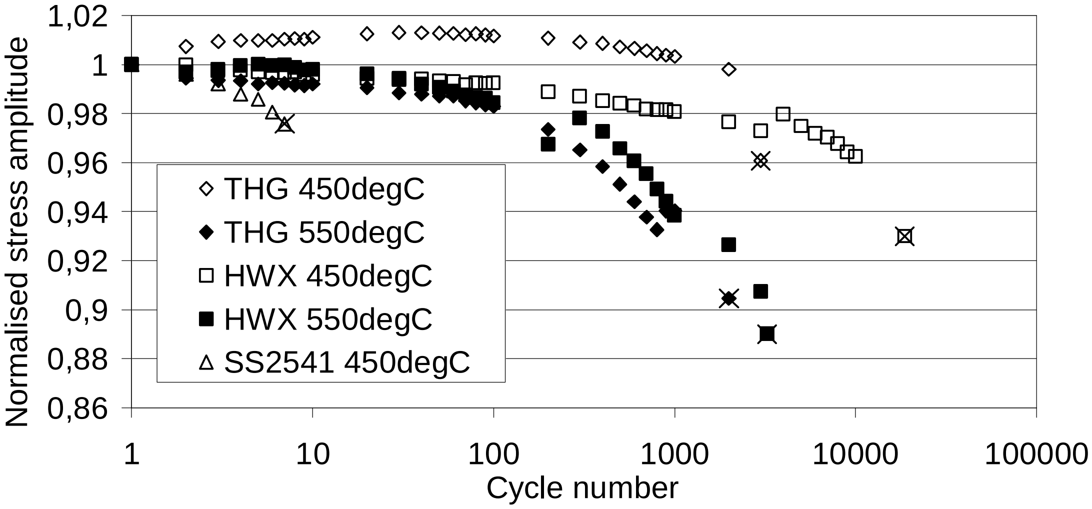

Figure 5. Normalized stress amplitude versus cycle number for THG2000, HWX and SS2541 in isothermal fatigue performed in strain control ±0.5% at 450 and 550°C. Each test series is averaged from three specimens. Crossed points mean specimen failure.

Figure 6 shows how the structure induced by shot peening disintegrates by temperature and mechanical loading. The steels exhibited different resistance to dislocation rearrangement at higher temperatures and external cyclic stress; the lowest resistance was found in SS2541 followed by THG2000 and HWX. HWX demonstrated the best resistance to dislocation rearrangement exposed to higher temperatures only, however the combined effect of temperature and external cyclic stress during isothermal fatigue testing greatly reduced the dislocation density in the steel at 450 and 550°C. THG2000 showed greater stability at test temperature 450°C, but again were greatly reduced after fatigue testing at 550°C. Also, the induced dislocation density by shot peening (corresponding to the degree of cold work induced) is varying amongst the steels; it was higher in the HWX followed by THG2000 and then SS2541, Figure 6.

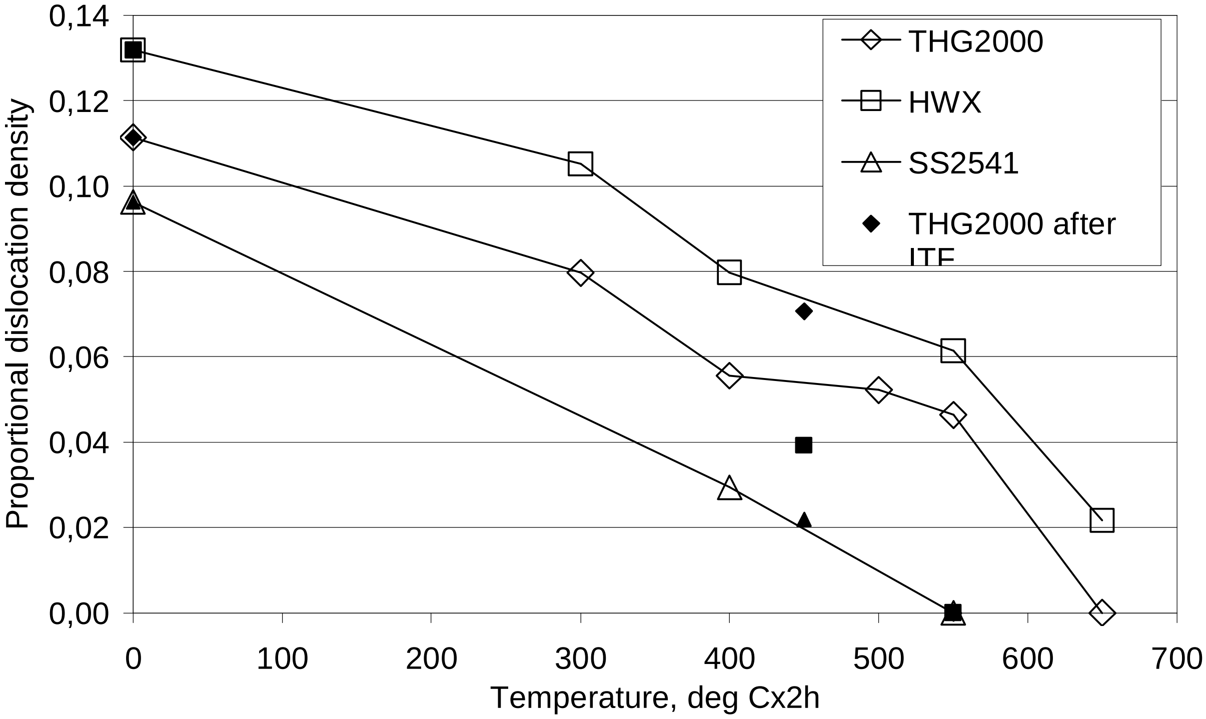

Figure 6. Proportional dislocation density for flat samples after stress relieving heat treatment at different temperatures and for fatigue specimens after isothermal fatigue (ITF) testing at 450 and 550°C.

Bending fatigue of tool components

The room temperature bending fatigue test results demonstrates the ability to resist thermal stress relaxation of the different steel grades, as well as the increasing fatigue life effect of shot peening, Figure 7. Fatigue life at the test stress level 1780 MPa (maximum local stress) for tool components sets the base line equally for THG2000 and SS2541 as hardened and tempered after machining. A large improvement is made by shot peening (only runouts at 2 million cycles for HWX) from where a reduction in fatigue life is caused by the stress relief treatment. Ranking the different steel grades the HWX performs the best in the shot peened conditions, both without and with stress relief treatment, and second is THG2000 with a better response to shot peening than SS2541. Stress relief of SS2541 brings it back to the same life as in the original hardened and tempered condition.

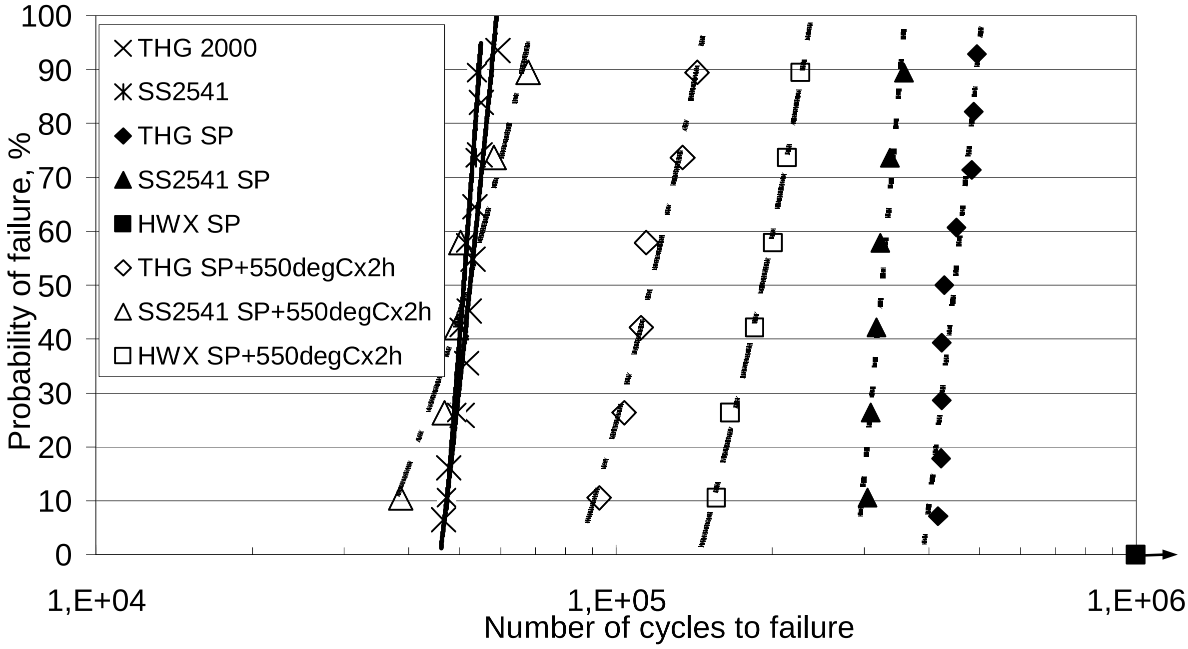

Figure 7. Probability of failure of tool components versus cycle number tested at maximum local stress 1780 MPa. Obtained for THG2000 and SS2541 hardened and tempered after machining, THG2000, SS2541 and HWX shot peened (SP) and shot peened with subsequent stress relieving heat treatment at 550°C for 2 hours.

DISCUSSION

The shot peening process induces a work hardened surface layer with large compressive residual stresses well below 50μm depth, Figure 3 and 4. Initial compressive stress level is equal (-700 MPa) to all three steels, while they during subsequent thermal treatment and mechanical loading show different ability to retain the residual stress and work hardening. Obviously, HWX is the best and SS2541 is the worst in this respect. Particular about THG2000 is its plateau range at 450 to 550°C where stress relaxation seems to stabilize. In general, dislocation density decreases with temperature and surface depth due to the rapid microstrain decrease and domain size increase, Figure 4. It was also noted during XRD measurements that initial dislocation density after shot peening is highest in HWX and lowest in SS2541, and the 450 to 550°C plateau range was revealed in terms of dislocation density as well (more pronounced in THG2000, some also in HWX but none in SS2541), Figure 6. This may be related to remnants of secondary hardening effects occurring during tempering in the two hot-work steels but not in SS2541.

There are two primary processes, annihilation and rearrangement of dislocations into lower energy configurations, that explain the stress relaxation at higher temperatures (F.J. Humphreys, M. Hatherly, 2002). Different dislocation mobility at higher temperatures in the investigated steels may be explained by different microstructure stability of the steels. Precipitation of secondary carbides in THG2000 and the HWX may affect the dislocation reconfiguration (dislocations themselves promote the heterogeneous nucleation of precipitates), increasing stress relaxation resistance in these steels comparing to the low-alloyed SS2541. During the annihilation and rearrangement of dislocations, the particles may pin dislocations and thus inhibit their movement. Smaller, finely coherent particles are more preferable for stronger pinning.

The stronger stress relaxation at temperatures above 550°C in THG2000 than in HWX is proposed to be due to more rapid over-aging of carbides.

Combining thermal effects and mechanical loading in the IsoThermal Fatigue test (ITF), Figure 5, led again to the conclusion that HWX has better long term properties at the higher test temperatures than THG2000 and SS2541, and the latter has the least good properties. Cyclic straining processes lead to microstructural changes causing cyclic hardening and/or softening of the steel. Softening behaviour was observed in all steels at 550°C and in the HWX and SS2541 at 450°C. THG2000 showed hardening behaviour the first 100 cycles at 450°C and then softening followed by failure after 1000 cycles. Researchers have proposed various mechanisms and their combinations explain the softening behaviour of steels: resolution of precipitates after being cut by dislocations to a size smaller than the critical size for particle nucleation (S.Suresh, 1998); over-aging of precipitates (A.F. Armas, C. Petersen, R. Smitt, et al., 2002); and rearrangement of dislocation substructure into a dislocation subgrain structure of lower internal stress (A.F. Armas, C. Petersen, R. Smitt, et al., 2002; J. Sjöström, 2004; N. Mebarki, P. Lamelse, D. Delagnesand, et al., 2002).

The bulk cyclic softening observed here, Figure 5, characterizes the steels general behaviour in mechanical loading at elevated temperatures. On the same specimens the shot peened surface was subjected to the same nominal strain range ±0.5% where softening equally takes place. Here, it is considered to be caused by the rearrangement of the initial high dislocation density to a lower dislocation density, Figure 6. Coarsening of carbides may also contribute to this effect as it reduces the ability of precipitates to stabilise the structure, so that the HWX has higher softening resistance at 550°C than THG2000, Figure 5. However, the dislocation density is low in both steels after testing at 550°C leading to more pronounced softening behaviour at higher temperatures alleviated also by carbide over-aging. The cyclic hardening in THG2000 at 450°C may be the result of stabilising a dislocation substructure enhanced by remnant secondary carbide precipitation.

The bending fatigue strength of the tool components displays a significant difference depending only in the selection of steel grade. The test geometry typical of a tool gives a strong dependence on surface and notch properties in the critically loaded radius. Combining these results with the observations on residual stress relaxation, Figures 2 and 3, it is clearly related to the residual stress state. The more of compressive residual stresses induced by shot peening are retained, the better the fatigue strength. Here, the HWX performs the best with a higher stress relaxation resistance, followed by THG2000 and SS2541 as least good. The ranking of fatigue life in the only shot peened condition without stress relief treatment is clearly in descending order HWX, THG2000 and SS2541. It may be related to the same order in differences in work hardening induced by shot peening as measured by XRD dislocation density parameter, and/or by differences in inherent stress relaxation in room temperature fatigue.

CONCLUSION AND IMPLICATIONS

It is important to select the proper tool steel in applications where the shot peened component is subjected to fatigue at elevated temperature, as the fatigue properties severely depend on its stress relaxation resistance. Different tool steels exhibit a variety of stress relaxation resistance that depends on their microstructure, temper resistance, and the working temperature. The present study have shown that decrease of dislocation density is one of the mechanisms involved in the stress relieving and softening of different steels. Hot work tool steels showed to be more preferable before the low alloyed tool steels in fatigue application at working temperatures from 300 to 650°C, or prior exposure in that temperature range, because of their ability to inhibit the rearrangement and annihilation of dislocations induced by shot peening. Also, the effect of steel grade selection in room temperature bending fatigue of notched components and the significant different response to shot peening was demonstrated.

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