SHOT PEENING OF NITRIDED LAYER

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ABSTRACT
Shot-peening is a method widely used in industrial practice in order to enhance service properties of machine components. Commonly known are such advantages derived from this dynamic surface cold working, i.e. shot-peening, as: increase of fatigue strength, contact fatigue, resistance to corrosion fatigue and to stress corrosion. The utilization of shot-peening to the enhancement of nitrided layers is the object of increased interest of researchers. The aim of this project was to determine the effect of a 2-step nitriding and shot-peening treatment on the mechanical properties of 40HM (AISI4140) grade steel. A new approach to the nitriding process was taken, enabling the formation of nitrided cases free of the iron nitride layers at the surface. The article contains the results of structural investigations, hardness measurements, measurements of residual stresses, rotational bending fatigue, as well as contact fatigue.

KEY WORDS
Shot-peening, nitrided layer, residual stresses, pitting, fatigue strength

INTRODUCTION
Shot-peening and nitriding are two technological processes widely utilized in industrial practice. As a rule, they are applied separately. In recent years, a growing interest is observed in literature in the joint utilization of a two-step treatment comprising nitriding and shot-peening. The effectiveness of utilization of such a compound treatment to enhance fatigue strength and contact fatigue has not been unequivocally determined. (I. F. Pariente, M. Guagliano, 2007) investigated the effect of shot-peening on the rotational bending fatigue of gas nitrided 42CrMo4 grade steel. In investigations carried out on specimens with a micro-hole, they achieved, after 3 million cycles, a fatigue limit at the level of 850 MPa. In the work by (M. Guagliano, L. Vergani, 2005), notched specimens made from 39NiCrMo3 grade steel were subjected to gas nitriding and subsequently to shot-peening with varying intensities. The nitrided specimens exhibited a bending fatigue strength level of 379 MPa. Following shot-peening, a significant rise in bending fatigue strength, 674-724 MPa was noted, depending on the intensity of the shot-peening operation and the depth of the notch. A strict correlation was indicated between the fatigue behaviour and the state of stresses in the material under investigation. It was determined that the source of initiation of the fatigue crack may lie on the surface or at an internal inclusion, depending on the stress applied and on the location of the inclusion relative to the field of residual stresses. Enhancement of fatigue strength was also indicated in the work by (M. Ohsawa, T. Yonemura, 1990), where shot-peening was applied to specimens following tufftriding and an increase of the order of 20% was achieved. In the work by (Z. Jingpu, 1984) the advantageous effect of shot-peening was shown on the contact fatigue strength of 40Cr (AISI5140) grade steel, following a complex heat treatment comprising ion nitriding and induction hardening. A contact fatigue level of 2900 N/mm^2 was achieved.

In the present work, a new approach is proposed, consisting of a two-stage treatment, involving controlled gas nitriding without the surface compound layer, followed by shot-peening. In this way the adverse affect of the brittle compound layer at the surface on contact fatigue strength is eliminated, which may be of high significance to the application.

EXPERIMENTAL

Investigations were carried out on specimens made from 40HM (AISI 4140) grade steel, characterized by the composition: 0.38-0.45 % C, 0.9-1.2 %Cr, 0.4-0.7 % Mn, max 0.035 %P, 0.035% S, 0.17-0.37%Si, 0.15-0.25 % Mo max 0.3%Ni, max 0.25% Cu, max 0.2 %W, max 0.05 % V, max 0.05 % Ti. The specimens were quenched and tempered to a hardness of 41 HRC.

Process of controlled gas nitriding was carried out in a computer-controlled furnace, type Nx609, manufactured by Nitrex Metal Inc. The process of gas nitriding was carried out at a temperature of 470°C and in a time of 16 h, using an atmosphere of NH_3/NH_{3diss}. Diffusion cases were formed with only a trace presence at the surface of a non-continuous iron nitride compound layer, of approx. 0.4 μm thickness. The effective nitrided case depth measured from the surface to a hardness of 500 HV0.5 was 0.15 mm.

Shot-peening was carried out pneumatically, utilizing a stand developed at the Institute of Precision Mechanics, which enables precise control of the energy of impingement of the shot flux on the surface being enhanced. The type and grain size of the shot were selected experimentally in such a way as to achieve maximum strengthening without, however, causing damage to the surfaces of nitrided cases. The shot applied was made of sintered tungsten carbides of 0.9 mm diameter and the air pressure was 0.3 MPa. The shot-peening intensity, as measured by A-type Almen strips was f_A=0.26mm. During the shot-peening operation the specimens were rotated and the shot impinged perpendicular to the axis of the specimen.

Hardness measurements, using loads of HV0.5, HV1, HV5 and HV10, were carried out using the Zwick 3212 hardness tester.

Observations of the topography of specimen surface after nitriding and after the two-step treatment, i.e nitriding and shot-peening, as well as observations of fatigue fracture surfaces were carried out using the HITACHI S-3500N scanning electron microscope.

Investigations of microstructure of the surface layers formed were carried out on mounted, polished and etched cross-sections of specimens with the aid of a Zeiss Neofot 2 metallurgical microscope.

Measurements of residual stresses at the specimen surface were made with the aid of a RIGAKU-manufactured PSF-3M x-ray apparatus, employing a chromium gun and applying the $\sin^2\psi$ method. Next, the specimens were etched electrochemically to remove successive layers of the tested material in order to obtain a distribution of residual stresses as a function of distance from the surface.

Investigations of rotational bending fatigue strength were carried out on the PUN035Z machine, with a fixed bending moment along the measurement length of the specimen. The tests were carried out employing a frequency of load alternation f= 100Hz and a basis of N_G = 1x10^7 cycles. The fatigue limit was determined by the Dixon-Mood step method. Specimens diameter – 5,86 mm.

Investigations of contact fatigue strength T_H were carried out on a ULP-2 type equipment. In this type of equipment, a cylindrical specimen of 8 mm diameter and 40 mm length mates with two press rollers, driving and driven, of 150 mm diameter and contact radius r = 10 mm, made of LH15 (52100) grade steel, quenched and tempered to 60 HRC. The specimen is loaded by a system o levers and by appropriate deflection of a calibrated spring. The design of the equipment, as well as specimen dimensions allow taking 5 readings on the same specimen. During the test the specimen and rollers move by a rolling motion without slippage. A diagram of the specimen with rollers is shown in Fig. 1.

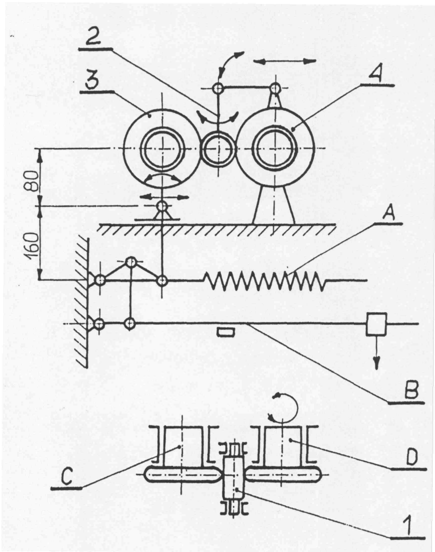

Fig. 1. Diagram showing contact of specimen with rollers in tests of contact fatigue: 1 – tested specimen, 2 specimen suspension, 3 – press roller – driven, 4 – press roller – driving, A, B – loading mechanism, C, D – press roller housing

The ULP-2 apparatus is equipped with an electronic safety system which trips the drive motor and thus takes the load off the specimen-rollers system when vibrations rise due to spalling of the specimen or roller surface. Tests were conducted using a frequency of 300 Hz and the assumed basis of N_G= 2 x 10^7 cycles.

RESULTS AND DISCUSSION

The microstructures of surface layers formed by nitriding, as well as those after the two-step treatment involving nitriding and shot-peening, are shown in Figs. 2-3, while photographs of surface topography are shown in Figs. 4-5.

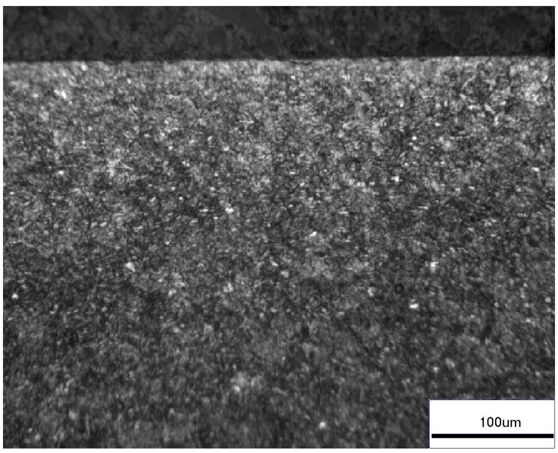

Fig. 2. Microstructure of nitrided layer produced at 470°C, for 16h

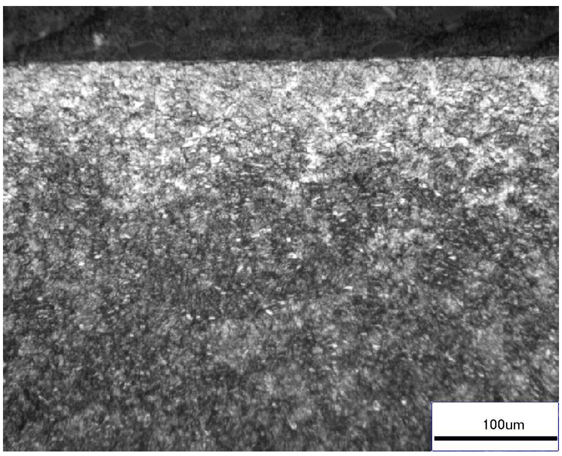

Fig. 3. Microstructure of nitrided layer after shot-peening treatment

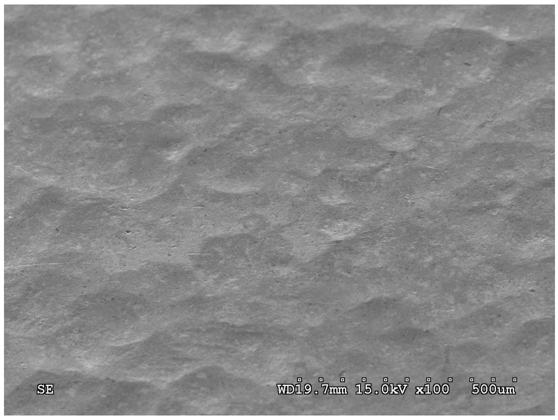

Fig. 4. Surface morphology of nitrided layer produced at 470°C, for 16h

Fig. 5. Surface morphology of nitrided layer (470°C, 4h) after shot-peening treatment.

On the surface layers formed as the result controlled gas nitriding, the following values of surface hardness were obtained: 761HV0.5, 780HV1, 748HV5 and 715HV10. It was determined that shot-peening results in an increase of hardness with all the loads employed and the values are accordingly: 841HV0.5, 840HV1, 846HV5 and 814HV10.

As the result of the nitriding processes carried out, followed by shot-peening, a significant rise of compressive stresses took place in the surface zone. In the quenched and tempered condition, the value of residual compressive stresses at the surface was -487 MPa, following nitriding, this value rose slightly to -641 MPa, while after shot-peening, a significant increase in residual compressive stresses occurred to -1556 MPa.

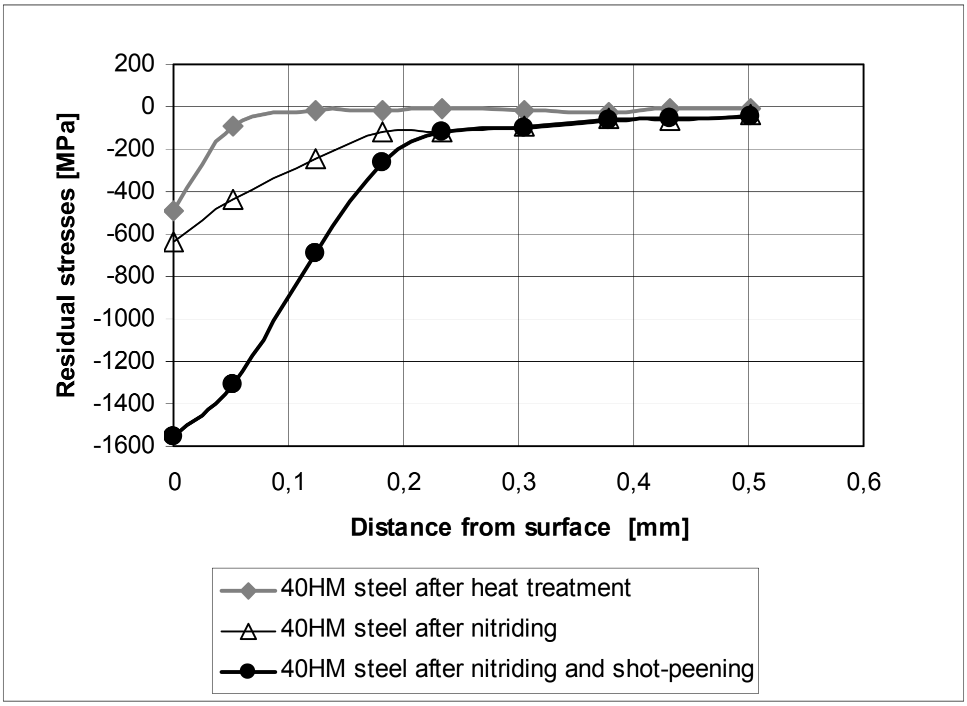

Fig. 6. Distribution of residual stresses vs. distance from surface

Fig. 6 shows the distribution of residual stresses in specimens after quenching and tempering, same, followed by nitriding, as well as same followed by nitriding and shot-peening. Shot-peening caused a decisively advantageous state of residual compressive stresses in specimens, reaching the depth of approx. 0.24 mm.

The high increase of residual stresses as the result of the shot-peening operation carried out is, however, not tantamount to a rise in fatigue strength. The fatigue strength of specimens after the nitriding process, as well as after the two-step treatment involving nitriding and shot-peening was at the same level and amounted to, accordingly 872±12.6 MPa for nitrided specimens and 866.4±15.6 MPa for specimens nitrided and shot-peened. It should be mentioned that the value of fatigue strength for specimens made of 40HM (AISI 4140) grade steel was 790 MPa in the quenched and tempered condition. In both of the investigated cases, propagation of fatigue fractures began at internal inclusions, the fatigue source in nitrided specimens being well deeper than the diffusion zone (Fig. 7), and after shot-peening (Fig. 8) it shifted closer to the surface. Absence of increase of fatigue strength after shot-peening of nitrided specimens, despite residual stresses increase, can be explained by relaxation of residual stresses during the test and by the fact that the origin of fatigue cracking is located below the zone of presence of residual stresses (approx. 0.4 mm for nitrided and shot-peened specimens and approx. 0.7 mm for specimens only nitrided).

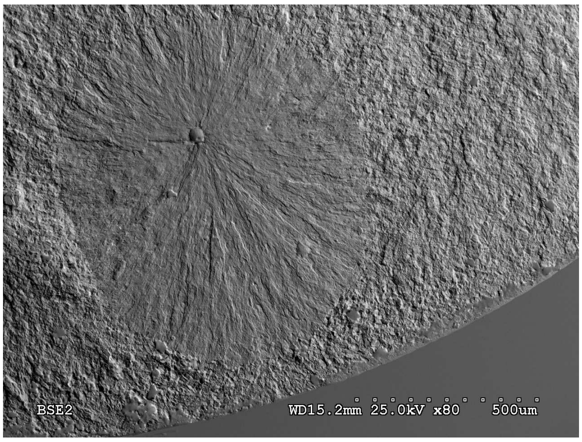

Fig. 7. Fatigue source in nitrided specimen

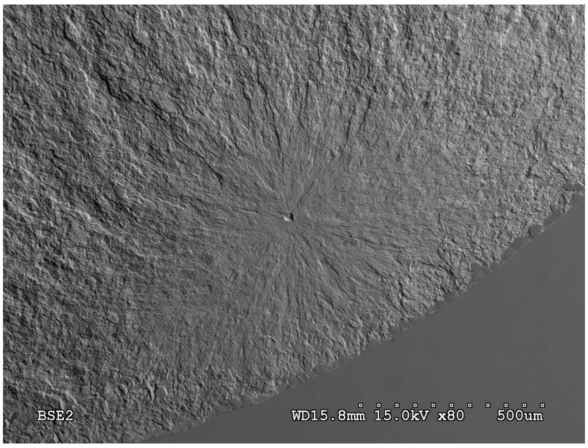

Fig. 8. Fatigue source in nitrided and shot-peened specimen

Deserving mention are the results of contact fatigue strength tests. The value of contact fatigue strength T_H for nitrided specimens was determined at 4130 MPa. In comparison with results of tests carried out in earlier years on nitrided layers with the presence of the surface compound layer, where the contact fatigue limit was of the order of 3000 – 3100 MPa, the present result is a very good one. In the case of specimens which were nitrided and shot-peened, problems arose with the application of higher loads, due to the well-developed surface being tested. The manufacturer of the machine recommends that the surface roughness of the test portion of the specimen be not greater than Ra = 0.32 μm. Despite these problems, tests were carried out up to the stress level of T_H = 3937 MPa. At higher load levels major problems were encountered with getting the machine to run, and further testing was discontinued.

The results obtained for nitrided, as well as nitrided and shot-peened specimens are put together in Table 1.

Table 1. Comprehensive results of testing of surface hardness, residual stresses, rotational bending fatigue strength and contact fatigue strength

	HV0.5	HV1	HV5	HV10	Residual stresses [MPa]	Bending fatigue strength [MPa]	Contact fatigue strength [MPa]
40HM steel after nitriding	761	780	748	715	-641 ± 45	872 ± 12.6	4130
40HM steel after nitriding and shot-peening	841	840	846	814	-1556 ± 48	866,4 ± 15.6	>3937

CONCLUSIONS

As the result of application of low temperature controlled gas nitriding, diffusion cases, without the iron nitride compound layer, were obtained on 40HM (AISI4140) grade steel. These exhibited high contact fatigue strength, as well as good values of hardness, residual compressive stresses and rotational bending fatigue strength. The shot-peening process carried out on these layers contributed to an enhancement of their surface hardness, as well as significant increase of residual compressive stresses, while retaining fatigue strength at the same level. In view of a fairly high contact fatigue strength level of the nitrided and shot-peened specimens, it is envisaged in future investigations to incorporate surface smoothing procedures, which may contribute to an even greater enhancement of that value. The two-step processing involving diffusion nitriding (without the compound layer) and shot-peening, may find broad practical application in e.g. the manufacture of gears.

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