Increasing of Contact Fatigue Strength by Nitriding and Shot-Peening Treatment

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Abstract

This report describes the method of raising contact fatigue strength, designated for application in the manufacture of gears. Investigations were carried out on 41CrAlMo7 grade steel (closest equivalent: Nitralloy 135M) following quenching and tempering, nitriding and double shot-peening. Special emphasis should be placed on the combination of the nitriding and shot-peening technologies. Both nitriding and shot-peening have been significantly modified and differ from the classical processes. Nitriding was carried out in such a way as to prevent the formation on the surface of a compound layer, composed of nitrides ε and γ.

Shot-peening was carried out as a double stage operation, employing a change of parameters. As the result of combining of modernized processes, a new technology was developed, allowing the attaining of a contact fatigue limit that is comparable to that obtained by carburizing or induction hardening. The report describes the methodology and the experimental work, as well as the achieved values of contact fatigue strength. Other surface parameters are also given, such as roughness, hardness, state and distribution of residual stresses.

Keywords: contact fatigue strength, hardness, roughness, residual stresses, double shot-peening, nitriding and shot peening, thickness of nitrided layer.

Introduction

The problems of mechanical properties of nitrided structural steels remain an open issue, despite many years of implementation of this process. This is connected both with modification of nitriding, as well as with new possibilities of application, including nitriding, of other surface treatments, such as, e.g. shot-peening of nitrided surfaces. In this project, fatigue strength tests in static, dynamic and fatigue conditions were conducted on specimens of 41CrAlMo7 grade steel, subjected to quenching and tempering, controlled gas nitriding and finally strengthened by precision double stage shot-peening. The steel nitriding process was carried out at an unconventionally low temperature (470°C), advantageous from the point of view of fatigue strength. The application of double stage shot-peening, following precision nitriding constituted a novel, original solution.

Experimental

Investigations of mechanical properties in static, dynamic and fatigue conditions were carried out on specimens made from 41CrAlMo7 grade steel, quenched and tempered to a hardness of 43-44 HRC.

The investigations of mechanical properties in the static tests for tensile and impact strength were carried out on specimens of 41CrAlMo7 grade steel in the following conditions:

- Quenched and tempered (QT)
- Quenched, tempered and nitrided (QT +N)
- Quenched and tempered (QT), nitrided (N) and double shot-peened(2SP) - (QT+N+2SP)

Contact fatigue strength (T_H) tests with measurements of and distribution of residual stresses were carried out on specimens in the following conditions:

- Quenched, tempered and nitrided (QT +N)
- Quenched and tempered (QT), nitrided (N) and double shot-peened(2SP) (QT+N+2SP)

Preparation of specimens for testing:

The gas nitriding process

Nitriding was carried out on specimens made from quenched and tempered 41CrAlMo7 grade structural steel. The specimens prepared for this investigation were austenitized at 920^{0}C, oil quenched and tempered for 2 h at 490^{0}C to a hardness of 43-44 HRC.

Nitriding was carried out in an industrial pit -type furnace, model Nx609, manufactured by Nitrex Metal Inc., with a retort of 600 mm dia x 900 mm height, equipped with computer control, an ammonia dissociating equipment, a rapid cooling system, as well as a neutralizer of effluent gases. The nitriding process was carried out at 470^{0}C for 16 h, in an atmosphere comprising NH3 + NH3 diss., with a nitriding potential ranging from 4.99 to 1.74.

Shot-peening of specimens

Shot-peening of the surface of specimens was carried out by a pneumatic method, employing a special shot-peening stand, the PEEN-IMP, for which patent No PL204718 was obtained in 2009. This equipment enables continuous control of the shot impingement energy within a wide range and reduced the amount of shot needed to assure a continuous and uninterrupted flux of the air-shot mixture down to 0.25 kg. Shot grain size and process parameters (air pressure and exposure time) were experimentally determined in such a way as to assure that the R_a roughness parameter is not significantly altered after shot-peening in comparison with the initial measurement or that after nitriding. During shot peening, the specimen was rotated while the shot impinged perpendicularly to the specimen axis. Surfaces which were not subjected to shot-peening, were masked.

Shot-peening process parameters for specimens made from 41CrAlMo7 grade steel, following nitriding:
First stage
- shot: tungsten carbide of 0.9 mm diameter
- air pressure during operation: p = 4 bar
- exposure time t = 15 min
- distance from nozzle to peened surface, l = 400 – 420 mm.
- specimens rotated during shot-peening
- nozzle diameter: 6.4 mm
- shot-peening intensity, determined by A-type Almen strips: fA = 0.22 mm
- coverage of shot-peened surface: 98%.

Second stage:
- shot: tungsten carbide of 0.65 mm diameter
- air pressure during operation: p = 4 bar
- exposure time t = 18 min
- distance from nozzle to peened surface, l = 400 – 420 mm.
- specimens rotated during shot-peening
- nozzle diameter: 6.4 mm
- shot-peening intensity, determined by A-type Almen strips: f_A = 0.23 mm
- shot-peening intensity, determined by Al-type Almen strips after 1st and 2nd stage: f_A = 0.26 mm
- coverage of shot-peened surface: 98%

Methodology

The static tensile strength test
Investigations of strength properties in the static tensile test at ambient temperature were carried out in accordance with experimental procedure PB/2-1/LB-4, employing a hydraulic tensile machine, manufactured by Instron, model 8801, with a dynamometer range of 0 to 100 kN.

Contact fatigue strength (T_H) test was carried out with the aid of the ULP equipment. In it, the cylindrical specimen of 8 mm dia and 40 mm length cooperates with two pressure rollers (driving and driven) with a diameter of 150 mm and contact radius r = 10 mm, both made from LH15 (equiv. 52100) steel and a hardness of 60 HRC. The specimen is loaded by means of a system of levers and an appropriate deflection of a calibrated spring. The design of the equipment, as well as specimen dimensions allow up to 5 measurements to be made on it. During the test, the specimens and rollers move by rotation without slippage. A diagrammatic presentation of the specimen – roller contact system is shown in Fig. 1.

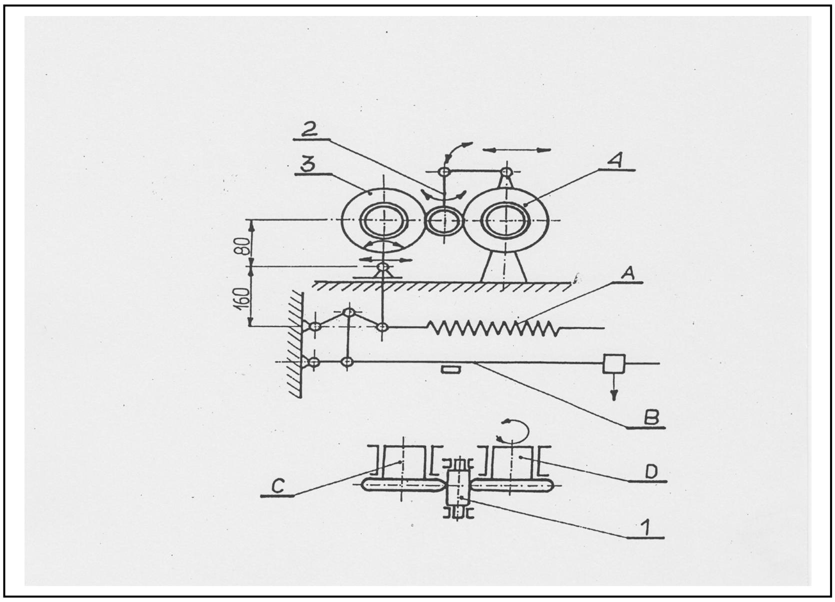


Fig 1. Schematic of contact between specimen and rollers in testing of contact fatigue strength.
1 – specimen being tested 2 – suspension of specimen, 3 – loading roller (driven),
4 – loading roller (driving), A,B – loading mechanism, C, D – housing of loading rollers.

The ULP-2 apparatus is equipped with an electronic safety system which causes shutting off of the driving power source and unloading of the specimen - roller system when vibrations caused by the spalling of the roller or specimen surface begin to rise. The tests were carried out with a frequency f = 300 Hz and the assumed base N_G = 2 x 10^7 cycles, in accordance with the specification [3] and procedure described in the machine service manual.
Measurements of residual stresses were carried out by the x-ray with the aid of a Rigaku diffractometer, model PSF-3M, employing the $\sin^2\psi$ method and radiation from a chromium source.
Measurements of surface roughness
Measurements of surface roughness of specimens on measurement parts were carried out with the aid of the Hommel Tester Type T 20, employing an LV 50 measuring head, along elementary distances of 5 mm.
Metallurgical evaluations comprised:
- surface hardness of specimens, employing loads of 0.5, 1, 5 and 10 kg
- HV0.5 microhardness profiles across the nitrided case
- thickness of the nitride compound layer
- effective case depth at 400 HV

Hardness measurements were carried out on a Zwick type 32.12.002 semi automatic hardness tester, as well on a Vickers hardness tester manufactured by Frank company and with a serial number of 620. The range of test loads used in surface hardness measurements and microhardness profiles allowed a characterization of specimen hardening, significant from the point of view of contact fatigue strength and wear resistance.

Metallography

The microstructure of nitrided cases was evaluated with the aid of a Zeiss Neophot 2 optical microscope, employing magnifications of 200x and 500x on mounts with sections perpendicular to the specimen surface, after etching them with Nital. The optical microscope was also used to measure the thickness of the superficial compound layer. The effective case depth at 400 HV, significant from the point of view of fatigue strength, was determined from microhardness profiles across the section.

Impact strength testing by the Charpy method:

Impact strength testing by the Charpy method was carried out in accordance with the PB/2-10/LB-4 procedure (edition 1 of 15.05.2002), employing an impact hammer manufactured by Alpha, with an initial energy of the pendulum of 150 J.

Results of investigations and discussion

The results pertaining to strength properties, obtained in the static tensile test on specimens after quenching and tempering (QT), quenching, tempering and nitriding (QT+N), as well as after quenching, tempering, nitriding and two-stage shot- peening (QT+A+2SP) have been put together in Table 1.

In the case of specimens which were quenched and tempered (QT) and nitrided (N) (QT+N), as well as quenched, tempered, nitrided and two-stage shot-peened (QT+A+2SP), tensile strength R_m value was

similar, with a rising tendency on the part of the shot-peened specimens. It was significant that the process of fracture of the nitrided case on specimens after two-stage shot-peening became noticeable only after exceeding the $R_{0.2}$ yield strength, while in the case of those only nitrided, it was noticeable before reaching the yield strength point.

Table 1 also shows results of impact strength measurements by the Charpy method on notched specimens, shaped like the letter U, after quenching and tempering (QT), quenching, tempering and nitriding (QT+N), as well as after quenching, tempering, nitriding and two-stage shot-peening (QT+A+2SP).The impact strength results obtained after quenching, tempering, nitriding and two-stage shot- peening (QT+A+2SP) exhibit a drop in impact strength by 26%, relative to impact strength of only quenched and tempered (QT) specimens. The impact strength of specimens which were quenched, tempered, nitrided and two-stage shot-peened (QT+A+2SP) is slightly higher (35.4 J/cm^2) than that of specimens which were only quenched, tempered and nitrided (QT+N). The latter was found to be 35.1 J/cm^2.

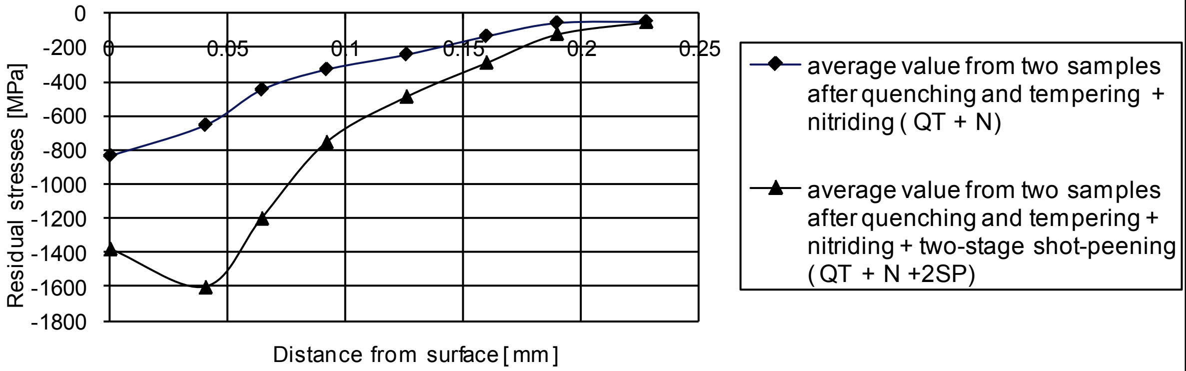
Table 1 also includes results of investigations of contact fatigue strength of the three groups of specimens. The contact fatigue limit T_H for nitrided specimens was determined at a level of 4130 MPa, while that for specimens which were nitrided and shot-peened at 4453 MPa.

Table 1. Results of investigations of mechanical properties of specimens made from 41CrAlMo7 grade steel, following three modes of treatment.

Treatment / Property	Quench and temper (QT) (43-44 HRC)	Quench and temper + nitriding (QT+N)	Quench and temper + nitriding + two-stage shot peening (QT+N+2SP)
$R_{0.2}$ [MPa]	1274.0	1251.0	1227.0
Rm [MPa]	1394.0	1329.0	1336.0
Impact strength KCU [J/cm^2]	47.8	35.1	35.4
Contact fatigue strength T_H [MPa]	-	4130.0	4453.0
Roughness R_a parameter [μm]	0.235	0.392	0.523
Residual compressive stresses at surface σ [MPa]	- 526.2	- 834.4	- 1598.8
Surface hardness HV1	440.0	1281.0	1372,0

Fig. 3 shows distribution of residual stresses after the above described processes. After only quenching and tempering, the mean value of residual compressive stresses was -526.2 Pa, and after gas nitriding, the value of stresses increased, attaining -834.4 MPa. Following the two-stage shot-peening process, there was a marked increase in residual compressive stresses, reaching -1598.8 MPa. As the result of this shot-peening operation, a decisively advantageous state of residual stresses was achieved in the specimens down to a depth of 0.18 mm.

Fig.3. Diagrams of average value of distribution of residual stresses from two samples from steel 41CrAlMo7 after quenching and tempering + nitriding (QT + N) and after quenching and tempering nitriding and two-stage shot- peening (QT + N + 2SP)



Metallurgical evaluation

In the course of hardness testing by the Vickers method, employing test loads of 0.5, 1, 5 and 10 kg, the following surface hardness values were obtained on the steel specimens:

- on quenched and tempered specimens: 448HV05, 440HV1, 442HV5 and 440HV10.
- on quenched, tempered and nitrided specimens: 1245.2HV05, 1291HV1, 1171HV5 and 1054.4 HV10.
- on quenched, tempered, nitrided and two-stage shot-peened specimens: 1351.2HV05, 1362.4HV1, 1248HV5 and 1142.8HV10.

The double shot-peening of quenched, tempered and nitrided specimens caused an increase of surface hardness by approx. 90 HV units.

The hardness of the nitrided case, measured at a m from the surface, was 1098 HV0.5 and the core hardness was □distance of 50 443 HV0.5. The effective hardened case depth at 600, 500 and 400 HV0.5 was accordingly: 0.125 mm, 0.165 mm and 0.31 mm. Microstructures obtained on polished and etched sections of metallographic specimens (cylindrical after testing for contact fatigue strength) are shown in Figs. 4 and 5.

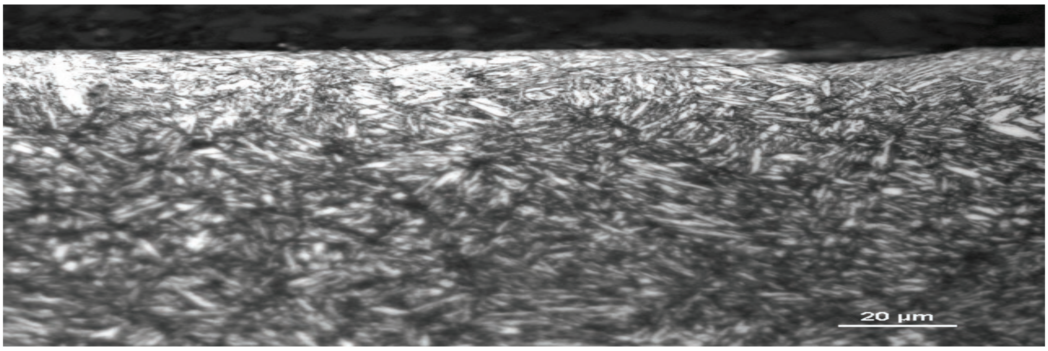


Fig 4. Microstructure of steel after quenching, tempering and nitriding

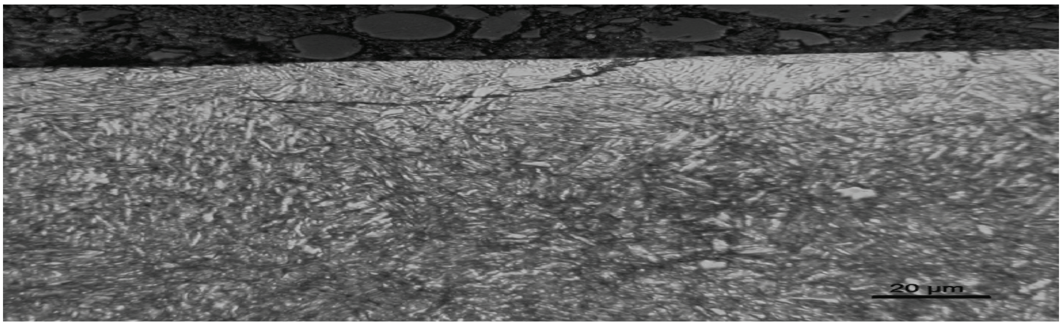


Fig 5. Microstructure of steel after quenching, tempering, nitriding and two- stage shot- peening

In the course of metallographic evaluations of all specimens, no evidence was observed of a compound nitride layer, which can be regarded as beneficial from the point of view of contact fatigue strength. The microstructure of the specimen which was subjected to shot-peening exhibits a zone of plastic deformation at the surface.

Summary and closing comments

The results of mechanical properties, measured in the static, dynamic and fatigue systems are good. Such good properties on this steel have hitherto not been attained in tests and, in consequence, allow the following conclusions to be drawn:

1. In the nitriding process carried out on 41CrAIMO7 grade steel, a nitrided layer of approx. 0.3 mm was generated, free of the surface compound layer.
2. As the result of two-stage shot-peening of specimens made from that steel, residual compressive stresses were achieved at the surface, with a mean value of -1599 MPa. This resulted in a beneficial distribution of residual compressive stresses in specimens down to a depth of 0.18 mm.
3. The two-stage shot-peening operation of specimens prior quenched and tempered and nitrided caused a rise in surface hardness by approx. 90 HV units.
4. Two-stage shot-peening of specimens caused a 34% increase in the R_a surface roughness parameter, relative to that of specimens after nitriding
5. Strength properties of 41CrAlMo7 grade steel, determined by a static tensile test ($R_{0.2}$ and R_m parameters) for specimens which were nitrided only and those two-stage shot-peened following nitriding ,were similar, with a rising tendency in the case of the shot-peened pieces. It was significant that the process of surface decohesion of shot-peened specimens became apparent only after exceeding the $R_{0.2}$ yield strength, while in the case of nitrided only specimens it occurred before reaching that point.
6. The impact strength of the steel after two-stage shot-peening was found to be slightly higher than that of specimens after nitriding only.
7. The value of contact fatigue limit (T_H) for shot-peened specimens rose by approx. 8 in comparison with that for nitrided only specimens.
8. The results achieved in this study are of major significance to the development of a new method of treatment of gears and other components made from 41CrAlMo7 grade steel, with a view to increasing their reliability and service life.

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