CONTACT FATIGUE STRENGTH OF 41CrAlMo7 GRADE STEEL BY NITRIDING AND SHOT-PEENING TREATMENT

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This paper 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 the 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 paper 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.*

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, 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 41CrAlMo7 grade steel specimens, 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 of 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 41CrAlMo7 grade steel specimens 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: QT+N; QT+N+2SP.

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Preparation of specimens for testing. *The gas nitriding process.* Nitriding was carried out on specimens made of quenched and tempered 41CrAlMo7 grade structural steel. The specimens prepared for this investigation were austenitized at 920°C, oil quenched and tempered for 2 h at 490°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 × 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°C for 16 h, in an atmosphere comprising NH_3 + NH_3 diss., with a nitriding potential ranging from 4.99 to 1.74.

Shot-peening of specimens. Shot-peening of the specimens surface 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 reduces 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 was impinged perpendicularly to the specimen axis. Surfaces which were not subjected to shot-peening, were masked.

Shot-peening process parameters for 41CrAlMo7 grade steel specimens, were the following in two stages. First stage: shot: tungsten carbide of 0.9 mm diameter; air pressure during operation p = 4 bar; exposure time t = 15 min; distance from a nozzle to a 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 = 0.22 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 a nozzle to a 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 AI-type Almen strips after the 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 of 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.

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 = = $2 \cdot 10^7$ 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.

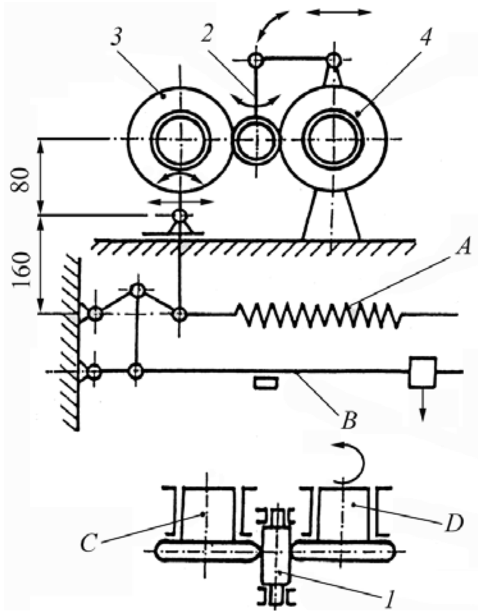

Fig. 1. Schematic of contact between a specimen and rollers in contact fatigue strength testing: *1* – specimen being tested; *2* – suspension of specimen; *3* – loading roller (driven); *4* – loading roller (driving); *A*, *B* – loading mechanism; *C*, *D* – housing of loading rollers.

Measurements of surface roughness. Measurements of the surface roughness of specimens on measurement parts were carried out with the aid of the Hommel Tester Type T20, employing a LV50 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; HV 0.5 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.

The microstructure of nitrided cases was evaluated with the aid of a Zeiss Neophot 2 optical microscope, employing magnifications of ×200 and ×500 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 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 the pendulum initial energy of 150 J.

Results of investigations and discussion. The results pertaining to strength properties, obtained in the static tensile tests QT, QT+N, as well as after QT+A+2SP have been put together in Table 1.

In the case of specimens which were QT and QT+N, as well as QT+A+2SP, tensile strength σ_{uTS} 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 σ_y yield strength, while in the case of only nitrided ones, it was noticeable before reaching the yield strength point.

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

The results of investigations of contact fatigue strength of the three groups of specimens are given in the table. 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.

Results of investigations of mechanical properties of specimens made of 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)
σ_y, MPa	1274.0	1251.0	1227.0
σ_{uTS}, 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. 2 shows distribution of residual stresses after the above described processes. After quenching and tempering only, the mean value of residual compressive stresses was –526.2 MPa, 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 a 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.

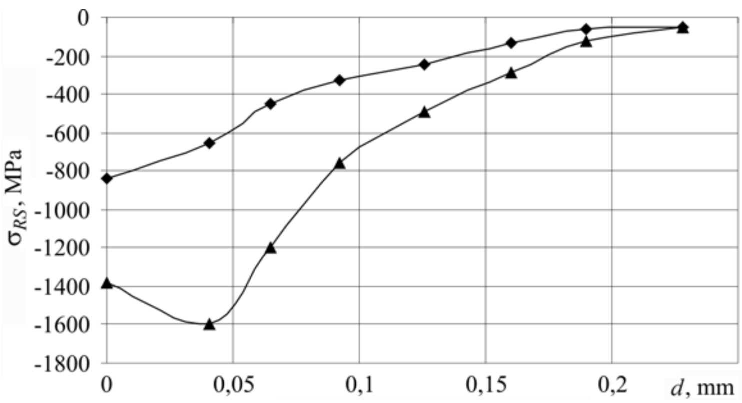

Fig. 2. Diagrams of average value of distribution of residual stresses, σ_{RS}, of two 41CrAlMo7 steel samples after QT+N (◆) and QT+N+2SP (▲) in dependence of distance from surface, *d*.

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: 448HV0.5, 440HV1, 442HV5 and 440HV10;

– on quenched, tempered and nitrided specimens: 1245.2HV0.5, 1291HV1, 1171HV5 and 1054.4 HV10;

– on quenched, tempered, nitrided and two-stage shot-peened specimens: 1351.2HV0.5, 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 layer, measured at depth 50 μm from the surface, was 1098 HV0.5 and the core hardness was of 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 contact fatigue strength testing) are shown in Fig. 3.

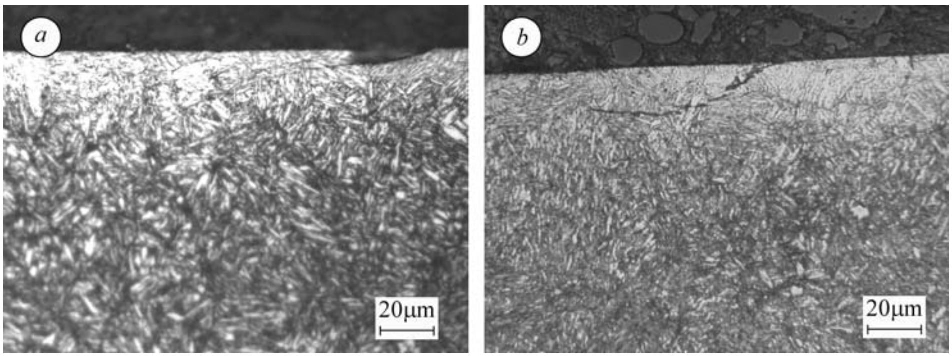

Fig. 3. Microstructure of steel after quenching, tempering and nitriding (*a*) and after quenching, tempering, nitriding and two-stage shot-peening (*b*).

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.

CONCLUSIONS

The results of measuring mechanical properties in the static, dynamic and fatigue systems are good. Such good properties on this steel have not been attained until now and, in consequence, allow the following conclusions to be drawn: In the nitriding process carried out on 41CrAlMo7 grade steel, a nitrided layer of approx. 0.3 mm was generated, free of the surface compound layer. As a result of two-stage shot-peening of specimens made of 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. The two-stage shot-peening of specimens prior quenched and tempered and nitrided caused a rise in surface hardness by approx. 90 HV units. Two-stage shot-peening of specimens caused a 34% increase in the Ra surface roughness parameter, relative to that of specimens after nitriding. Strength properties of 41CrAlMo7 grade steel, determined by a static tensile test (σ_y and σ_{uTS} parameters) for specimens which were nitrided only and for those two-stage shot-peened following nitriding ,were similar, with a rising tendency in the case of the shot-peened pieces. It was important that the process of surface decohesion of shot-peened specimens became apparent only after exceeding the σ_y yield strength, while in the case of nitrided only specimens it occurred before reaching that point. The impact strength of the steel after two-stage shot-peening was found to be slightly higher than that of specimens after nitriding only. The value of contact fatigue limit (T_H) for shot-peened specimens rose by approx. 8 in comparison with that for nitrided only specimens. 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 of 41CrAlMo7 grade steel, with a view to increasing their reliability and service life.

РЕЗЮМЕ. Описано метод підвищення контактної втомної міцності сталі для виробництва механічних приводів. Досліджено сталь 41CrAlMo7 (еквівалент: Nitralloy 135M) після гартування та відпуску, азотування та подвійної дробиноструминної обробки. Особливу увагу приділено поєднанню азотування та дробиноструминної обробки. Азотували так, щоб попередити утворення на поверхні складного шару з нітридів ε та γ. Дробиноструминну обробку виконували у два етапи, змінюючи параметри. В результаті створено нову технологію, що дає можливість досягати межі контактної втоми, яку можна порівняти з отриманою за навуглецювання чи індукційного зміцнення.

РЕЗЮМЕ. Описан метод повышения контактной усталостной прочности стали для производства механических приводов. Исследована сталь 41CrAlMo7 (эквивалент: Nitralloy 135M) после закалки и отпуска, азотирования и двойной дробеструйной обработки. Особенное внимание обращено на сочетание азотирования и дробеструйной обработки. Азотировали так, чтобы предупредить образование на поверхности сложного слоя из нитридов ε и γ. Дробеструйную обработку выполняли в два этапа, изменяя параметры. В результате создана новая технология, которая дает возможность достигать предела контактной усталости, которую можно сравнить с полученной при науглероживании или индукционном упрочнении.

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