HIGH CYCLE FATIGUE OF ION NITRIDED 40Cr STEEL SPECIMENS

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ABSTRACT

In order to investigate the effect of ion nitration in glow discharge on the high cycle fatigue lives, ion nitrided specimens of Cr-alloyed steel were tested in uniaxial fatigue. The influence of depth of nitration on the fatigue strength is investigated.
The experimental investigations were carried out on a bending testing machine in constant amplitude cyclic loading and R=-1 stress condition. X-ray analysis and strain gage approach were used in order to evaluate the residual stresses in the depth and on the surface of the layer. Both approaches are in good agreement. Significant possibilities for increasing the fatigue strength, with about 80%, were observed.

INTRODUCTION

Induced residual stresses play important role in fatigue life. If they are tensile, they can reduce the fatigue life, if they are compressive they can increase it. The effect of residual stresses induced on surface and volume under it on fatigue strength is well known and many investigations are concerned with the tensile residual stresses in welded joints and compressive residual stresses in surface treated components. Surface nitriding methods such as plasma and conventional cathodic arc have been used to improve the surface and wear properties of steels and nonferrous metals. For ion nitrided steels it was found that the nitrided depth as well as residual compressive stresses control the fatigue crack initiation. When the residual stresses are induced into the surface, the net fatigue strength can be represented as a sum of the fatigue strength of the metal and the residual stress [1,3,4]. Therefore the tensile residual stresses reduce the fatigue strength but the compressive residual stresses increase the fatigue strength. Usually fatigue crack initiates from the surface or in the layer under it and the mechanical properties of this layer play an important role for the fatigue behaviour. The properties of this layer depend on the chemical composition, the surface treatment and especially they depend on the induced residual stresses [1-3]. After the ion nitration of the surface layer, compressive residual stresses are received and these residual stresses are considered to be the basic factor of increased fatigue strength [1-9]. The nitrided surfaces of the steel structures and components improve the wear resistance and increase the fatigue life. Ion nitriding is found to have significant influence on fatigue life in both the low cycle and the high cycle regions [5,6]. Recently it was reported [5-8] that the factors contributing to this influence are subsurface crack nucleation, multiaxial stress state and residual stresses. Residual stress measurements on nitrided cylindrical specimens showed biaxial compression. In contrast to residual stresses after welding, relaxation of residual stress during fatigue was found to be almost negligible [9].

In this paper the influence of induced residual stresses to fatigue strength and the material structure received by different ion nitration regimes (or depth of ion nitrided layer) are discussed.

EXPERIMENTAL DETAILS

The specimens used in this study ware produced from a chromium alloyed steel 40Cr, as found in the market. The material was quenched from 850^{o}C and tempered at 580^{o}C. The chemical composition (wt%) is shown in Table 1. Ion nitration regimes and mechanical properties (surface hardness, HV, and ultimate tensile stress) are presented in Table 2. The specimens were ion nitrided at T=540^{o} C, because this is the maximum temperature before a change of hardness and other mechanical properties to occur. The working pressure of the gas (NH_3) in the chamber was P=2.5 mbar. The geometry of the specimen is shown in Fig. 1a.

The prepared specimens with different ion nitration times as well as non-nitrided specimens were tested under fatigue constant amplitude loading and stress ratio R=-1. The experiments were performed on an electro-resonance testing machine. All the tests were carried out under load control, with frequency between 25 to 30 Hz. The stress amplitude was kept constant until the crack initiated.

The phase composition was identified at the same depths by X-ray diffraction analysis (DPA) using Co-Kα radiation. In depth residual stresses were determined by a biased picture technique for the (222) $d_{0.825A}$ on α-Fe at Cu-K_{α} radiation and a new strain gauge approach were used for surface measurement.

RESULTS AND DISCUSSION

Fatigue life of in nitrided specimens

Solid specimens of chromium alloyed steel 40Cr with different ion nitration times were fatigued as well as non-nitrided specimens. To describe the difference between these specimen groups, the time of ion nitration was used as parameter because a decisive influence of the depth of nitration had the time of the surface treatment. It is worth noting that under this loading condition the cracks propagate very fast through the specimen cross section, therefore the number of cycles for the crack propagation can be considered negligible.

The fatigue testing results representing the change of the fatigue strength due to the depth of the nitrided layer are shown in Fig.2. A very strong influence of the nitration on the fatigue strength is observed. The S-N curves of the nitrided and non-nitrided specimens are clearly different. The behaviour of ion nitrided specimens became nearly elastic and fatigue strength for a number of cycles less than 100,000 is close to the ultimate tensile strength of the material. The fatigue strength and the fatigue limit of the nitrided specimens are 70-80 % higher than these of the non-nitrided specimens. In other hand a small change of the fatigue strength for the different depths of the nitrided layer is observed. The variation of the fatigue limit with depth of nitrided layer is shown in Fig.3. The fatigue limit increases with increasing the depth of nitrided layer and a power function, as shown in Fig.3, can be used to describe this behaviour. The reason of increased fatigue strength is that when nitrided layer increases above a specific level, the residual stresses change the fatigue strength and the fracture starts from a point under the nitrided layer. It have to be noted that for almost all fractured specimens nitrided at 8 h. and 16 h. and for all of them nitrided at 40h. and 60h. the crack began under the nitride layer.

It is well known that the surface hardness after the ion nitration increases [1-10]. The hardness on the surface of the specimens was measured and results are shown in Table 2. The thickness of the hardened layer is about 0.2, 0.3, 0.5 and 0.6 mm for the different ion nitration regimes and the maximum hardness is measured at the surface. The hardness decreases with the depth and reaches a level typical for the initial state of the steel. The analysis shows that there is no clear relationship between the fatigue strength and the surface hardness. The depth of nitrided layer, respectively the depth of compressive residual stresses distribution should be more important parameter to describe fatigue strength.

__Analysis of residual stresses__

In depth residual stresses were determined by a biased picture technique and a new strain gauge approach was used for surface measurement. For the last one, the residual stresses were obtained by cutting the specimen and continuously measuring the strains. Two strain gauges were bonded on the surface of fatigue fractured specimens with 60 h. nitration, as shown in Fig.1b,. To remove the soft core of the specimens, they were bored with bores starting from 4mm and finishing with 8.8mm i.e. the remaining wall thickness was 0.6 mm. The internal diameter was chosen thereby only nitrided surface to remain. Finally the specimens were cuted in axial and perpendicular to the axis direction, to allow the residual stresses in the nitrided layer to deform it and to measure the strains, Fig.1b. Strains at the end were used to determine the residual stresses. As on the surface exists biaxial state of stresses, it was simple to use the Hooke's law and to estimate the stresses according the equations bellow,

$$\sigma_1 = -\frac{E}{1-v^2}\left(\varepsilon_1 + v\varepsilon_2\right)$$

$$\sigma_2 = -\frac{E}{1-v^2}\left(\varepsilon_2 + v\varepsilon_1\right) \qquad (1)$$

where E and ν are modulus of elasticity and Poisson's ratio for the nitrided layer.

To determine the tensile properties of the ion nitrided layer thin walled specimens were used, Fig.1c. The thickness of the specimen wall was determined to be 0.6 mm, the same as the thickness of the nitrided layer of 60 h. ion nitrided solid specimens used in fatigue tests. It was assumed that if the same nitration procedure is applied to these thin walled specimens the same nitrided depth as in the solid specimens would be received. In fact total wall thickness will be nitrided. These thin walled specimens were tensile tested to obtain the mechanical properties of the nitrided material. Modulus of elasticity and Poisson ratio for nitrided material and non-nitrided material are 197GPa and 0.262 ; 221GPa and 0.285 respectively. These values were used in the stress calculations.

The results form the residual stresses estimation are shown in Fig.4, where solid symbols represent residual stresses obtained by the strain gage approach. It is clear that this measurement technique can identify the residual stress on the surface. Also it is in a good agreement with the results of other investigators [1,4,9] using different measurement techniques. The significant residual stresses that were identified can explain in the best way the improvement of the fatigue strength of the specimens, Fig 5. According to it crack initiates at a point where the applied stress exceeds the fatigue strength. Gaussian model for fatigue strength gives good approximation of the experimental results. The data points representing the fatigue strength distribution were estimated as algebraic sum of fatigue limit of non-nitrided material and the compresive residual stresses on the surface and idepth of the specimen.

CONCLUSIONS

The fatigue strength and residual stresses of ion nitrided specimens with different nitration times and non-nitrided specimens of steel 40Cr were investigated. The following conclusions were reached:

1. After the ion nitration of the specimens their fatigue strength improves significantly. The fatigue strength increases compared with the non-nitrided specimens and the specimens with deepest nitride layer have the highest fatigue strength.
2. Strain gage measurement approach was used for surface residual stresses estimation. The presence of high compressive stresses on surface can explain the increased fatigue strength and crack initiation under the nitrided layer.

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TABLE 1

CHEMICAL COMPOSITION OF MATERIAL USED , (WT.%)

C	Cr	Mn	Si	P	S
0.42	0.96	0.67	0.37	0.017	0.016

TABLE 2

MECHANICAL PROPERTIES AND PHASE ANALYSIS RESULTS

Nitration time	Phases	Phase amount		Thickness of nitrided layer, mm	Surface hardness HV5	Ultimate Tensile Strength, MPa
		γ' wt.%	ε wt.%			
-				-	HRC 30-32	1065
8 h	γ' +ε	85	15	0.2	638±15	1020
16 h	γ' +ε	70	30	0.3	575±18	1019
40 h	γ' +ε	75	25	0.5	608±29	1049
60 h	γ' +ε	75	25	0.6	608±17	1031

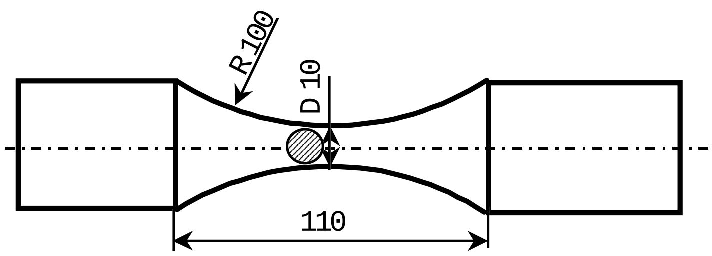

Fig. 1a. Specimen geometry for fatigue testing.

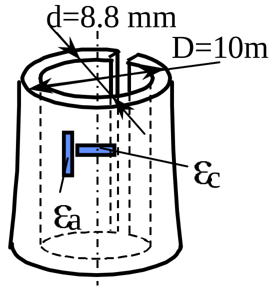

Fig1b. Specimen dimensions after residual stress measurement.

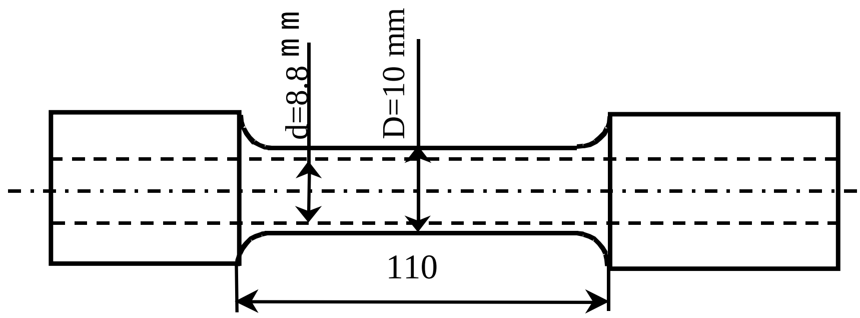

Fig.1c. Specimen geometry for tensile testing of ion nitrided layer.

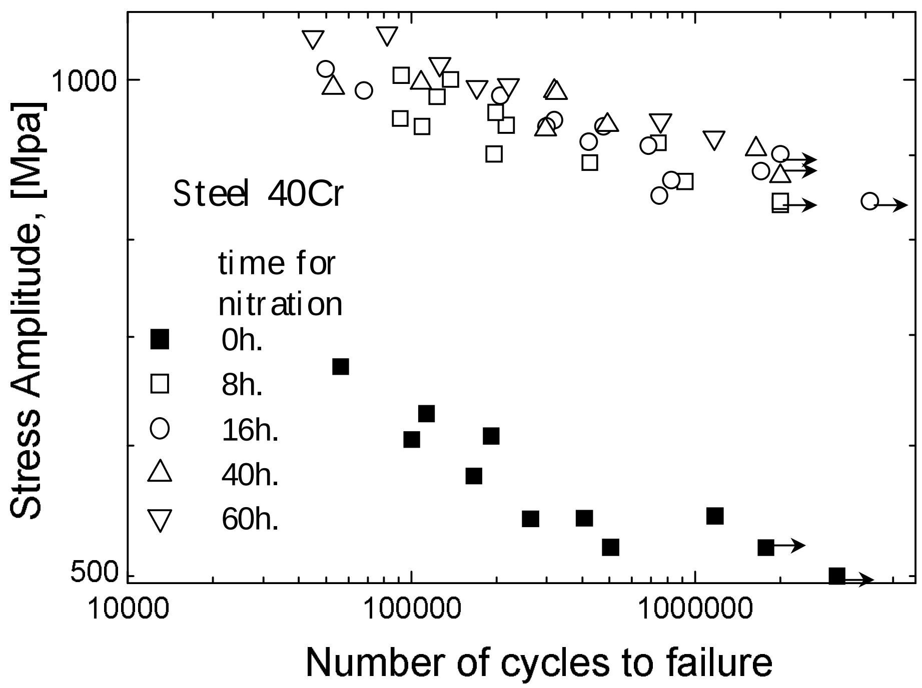

Fig. 2. S-N curves for steel 40Cr annealed specimens and after ion nitration.

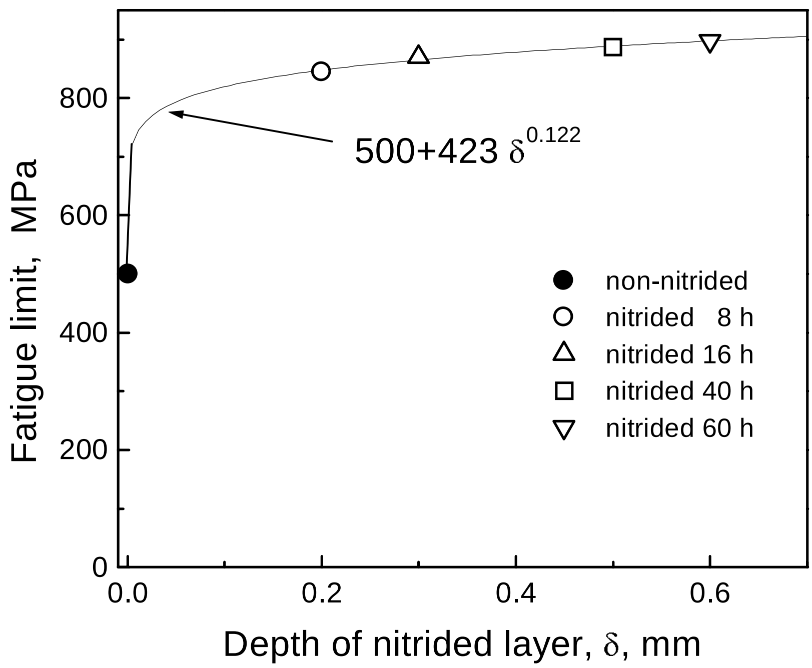

Fig. 3 Variation of fatigue limit with depth of nitrided layer.

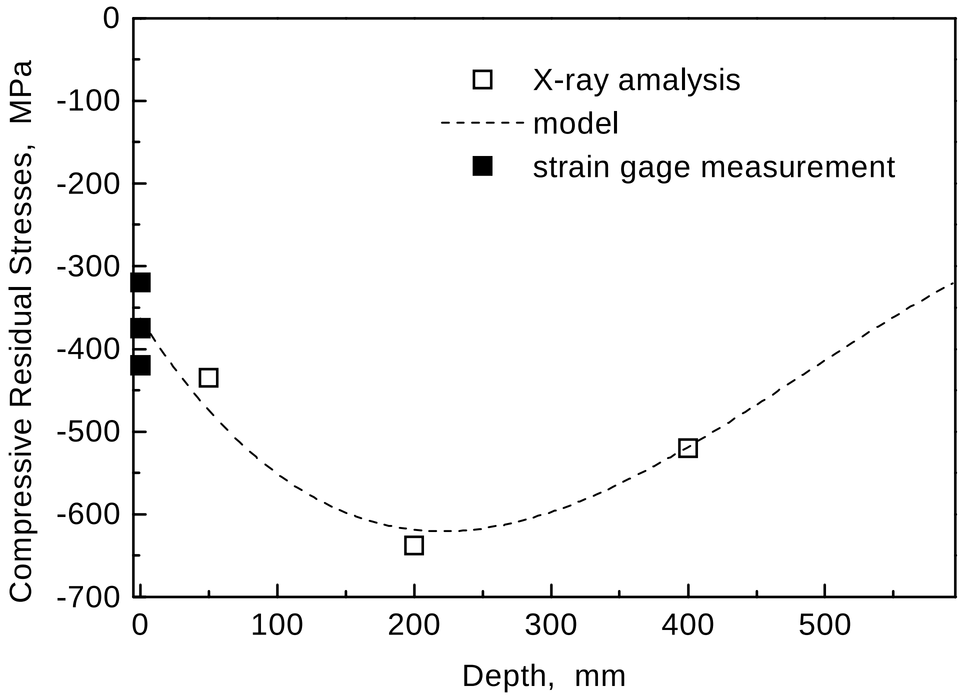

Fig.4. Variation of compressive residual stresses with depth of nitration.

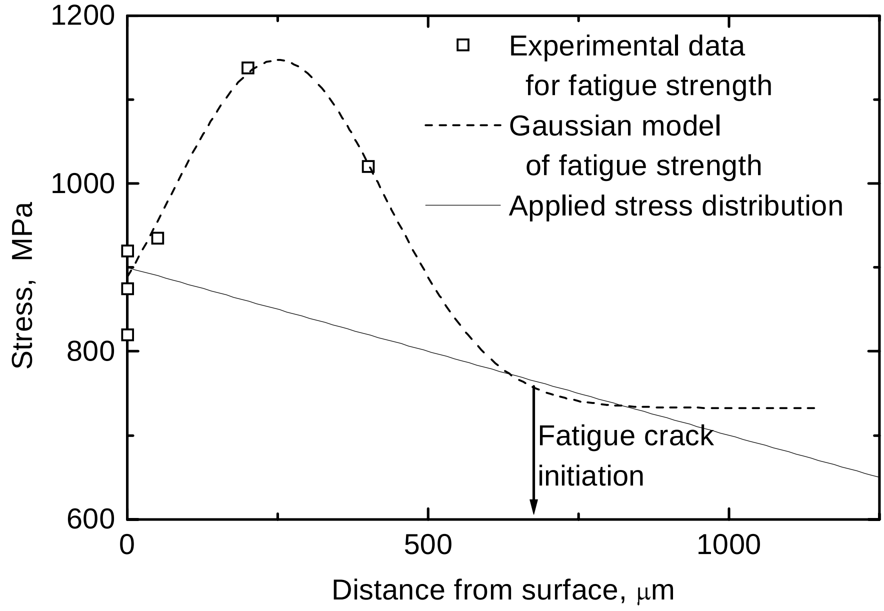

Fig. 5 Gaussian model of fatigue strength variation with distance from surface.