

Residual Stress Evolution During Fatigue Test of a Shoot Peened Steel Sample

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Keywords: residual stress, X-ray diffraction, fatigue, modified $\sin^2\psi$

Abstract Directly-generated compressive residual stress has become a widely used surface modification technique. Intentional residual stress in solid materials can be produced by different surface compression methods. It is well known how residual stress field is influenced by the parameters of the shoot peening but only few articles address the phenomenon about the evolution of the stress during the operation of the machine component. The literature on residual stress decrease caused by fatigue load is scarce and the kinetics of this mechanism is not yet investigated. The present work reports on the examination of the effect of the fatigue load on compressive residual stress strengthened specimens. Investigations have been conducted at three stress levels. Residual stress data have been measured by X ray diffraction method before fatigue load and measurements have been repeated after defined fatigue cycles.

Introduction

The processing (e.g. welding, forming, plastic deformation, casting, and any kind of heat treatments) of machine elements induces a characteristic residual stress field [1, 2]. This kind of residual stress field may be a risk to the part functionality.

Several methods are used in the industry to induce direct compressive residual stress in the surface region of the machine parts to increase fatigue resistance [3]. These methods are called surface-compressing methods, such as shot peening, burnishing and rolling. The value and the distribution of the residual stress which can be induced by these methods depend on a number of parameters. One of the most important of these is the type of the material. It is more difficult to generate residual stress in the surface of low-strength alloys because the maximum available residual compressing stress is smaller and relaxes more easily in use [4]. Using different surface compression methods, the compressive stress profile in the surface can be widely modified e.g. velocity, size, hardness of balls used for shot peening, or applied force and tool geometry for burnishing [5,6].

Various procedures have been developed to measure residual stress such as Almen test, hole drilling, ultrasonic, Raman spectroscopy, Barkhausen noise method and diffraction techniques [7]. Unfortunately, few gives sufficient deviation and reproducibility while giving qualitative and quantitative results. The Almen strip has been used for more than 60 years in industrial quality control; however, quantitative results can be obtained only by diffraction methods.

The purpose of applying compressive residual stress is to raise fatigue tolerance of the material. However, while a surface compressed machine component is in operation, the residual compressive stress decreases. The kinetics of this phenomenon is not clarified. The kinetics of decreasing residual stress is likely to depend on the residual stress state, nature of base material, fatigue parameters but it is not described how and to what extent kinetics is influenced by particular parameters.

A series of measurements are reported in this paper. The objective was to observe residual stress change in specimens subjected to fatigue load for various cycles and at various stress levels. Residual stress data were obtained before cyclic loading and were repeated after defined number of cycles.

Theoretical background

Lattice spacing in crystalline materials can be determined by X-ray diffraction analysis. The fundamental equation of X-ray diffraction analysis is Bragg's law, which describes the interrelation between the interplanar distance d , the incident angle θ (angle between the incident beam and the diffracting lattice plane), the wave length λ of the X-ray used and the order number n of the diffraction.

$$n\lambda = 2d\sin\theta \quad (1)$$

If stress is present, this interplanar distance becomes larger (tensile stress) or smaller (compressive stress). Assuming linear elastic distortions, the related normal stresses can be calculated [8].

$$\sigma = \frac{d_{\psi} - d_0}{d_0} * \frac{E}{(1 + \nu)\sin^2 \psi} \quad (2)$$

where d_0 and d_{ψ} are the interplanar distances of the strained material in the normal and in the tilted position defined by the angle ψ respectively. E (Young modulus) and ν (Poisson number) are the elastic parameters of the material.

Experimental

Test specimens were taken for fatigue tests from a CM45 grade hardenable steel (according to the DIN17200-84 standard) with a chemical composition presented in Table 1. The specimens were machined from hot rolled blank with a size of 96*96 mm.

Table 1. The chemical composition of the examined alloy (w%)

C	Si	Mn	P	S
0.42-0.5	<0.4	0.5-0.8	<0.035	0.02-0.035

After cutting, specimens were hardened. The heat treatment was carried out in shielding gas (commercial grade Ar) at 980°C for 20 minutes and a subsequent quench into a polymer emulsion was performed. Finally, specimens were tempered at 600°C for 20 minutes and cooled in air. Next, the specimens were subjected to shot peening. During the shot peening the specimens were fixed by two holders, which covered the head of the samples. The holders were rotated during the shot peening. Almen test holders were welded on the top of specimen holders in two directions for checking the intensity of shot peening. The number of the two Almen tests is 2.8 and 3. The test specimen geometry, the specimens in the holders and the specimens after the shot peening treatment are shown on the Fig. 1.

Preliminary fatigue tests were carried out (the details see in Table 2.). The fatigue load was uniaxial tension/compression with $R_{\sigma} = -1$ stress ratio in each case. Firstly $R < 1$ mm internal radius was applied but the local stress concentration resulted cracks at the head of specimens at a relatively low cycle number (specimens 63 and 33 signed with triangle in Fig.2.). For this reason the heads of the specimens were modified so that R was increased to 2mm. Thereafter, preliminary fatigue tests were continued at three different stress levels with modified geometry (specimens 12, 22 and 32 signed with square in Fig.2.). The Table 3 shows the applied fatigue scheme. After the defined number of fatigue cycles residual stress measurements were performed on the several parts of the samples. For the stress measurements Stresstech G3R X-ray diffractometer especially designed for residual stress measurements were used.

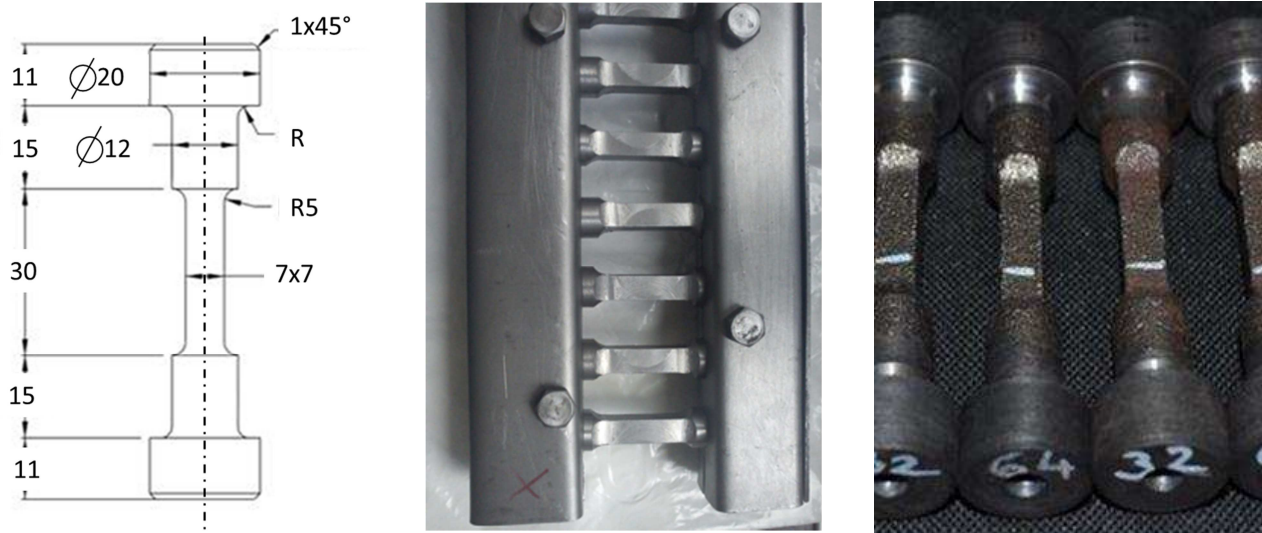


Fig.1. Specimen geometry and sizes, specimens in the holders and specimens after the shot peening

Table 2. Preliminary fatigue tests

Specimen ID	Load amplitude [kN]	Frequency [Hz]	Nominal stress amplitude [MPa]	R[mm]
63	± 20	15	408	<1
33	± 20	15	408	<1
12	± 20	15	408	2
22	± 16	20	327	2
32	± 12	25	245	2

Table 3. The applied fatigue scheme

Specimen ID	Load amplitude [kN]	Frequency [Hz]	Nominal stress amplitude [MPa]	Defined number of cycles [cycle]		
44	± 12	25	± 245	$1.5 \cdot 10^5$	$1.5 \cdot 10^5$	$1.5 \cdot 10^5$
62	± 16	20	± 327	$5 \cdot 10^4$	$5 \cdot 10^4$	$5 \cdot 10^4$
64	± 20	15	± 408	$2 \cdot 10^4$	$2 \cdot 10^4$	$8 \cdot 10^3$ cracked
12	± 20	15	± 408	$1.8 \cdot 10^5$ cracked		

An XTronic software package was used to determine the stress value from the θ shift of the reflection of $\{220\}$ miller indexed plane series at $\psi = 0^\circ, \pm 20.7^\circ, \pm 30^\circ, \pm 37.8^\circ, \pm 45^\circ$ tilting positions. Residual stress data were measured on the surface and in different depths as well.

For the latter case controlled removal of the surface layer an electrolytic etching tool was used. This method does not generate further residual stress and is easy to control. The electrolyte was stirred using vacuum. As the etching tool was wider than the examined surface, the surface of the specimen was enlarged with two component high strength epoxy resin (Fig. 3.). The residual stress data were taken in twelve surface points of a quadratic side of the specimen (3 from each side). The existing residual stress state was recorded before the first and after each fatigue step from each side of the samples. Direction of each measured residual stress data was parallel to the longitudinal axis of the specimen. A 3mm spot size of X ray beam was used in each case. Measurements were carried out after shot peening and the same parts of the samples were remeasured after each fatigue steps. A step means a defined number of cycles (see in Table 3).

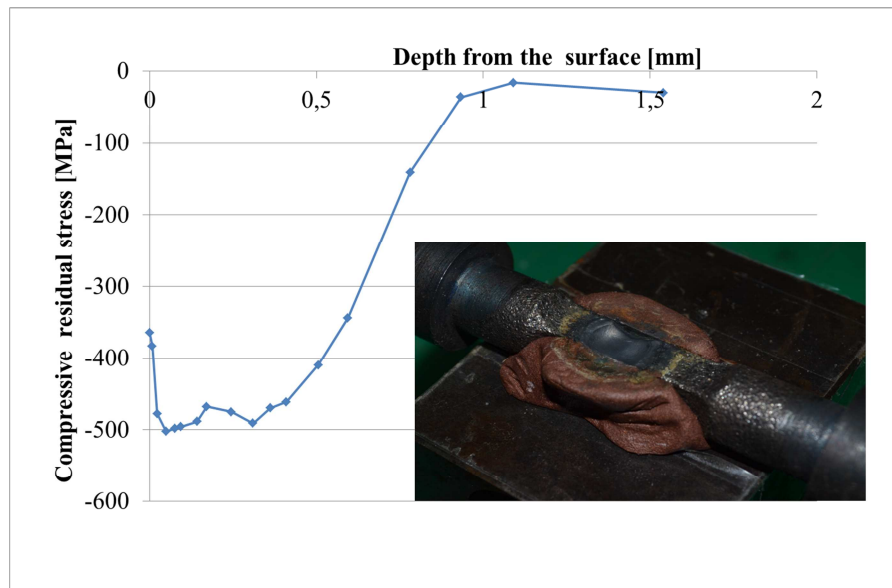


Fig. 3. Residual stress in depth, with the photo of the enlarged and etched area of the specimen

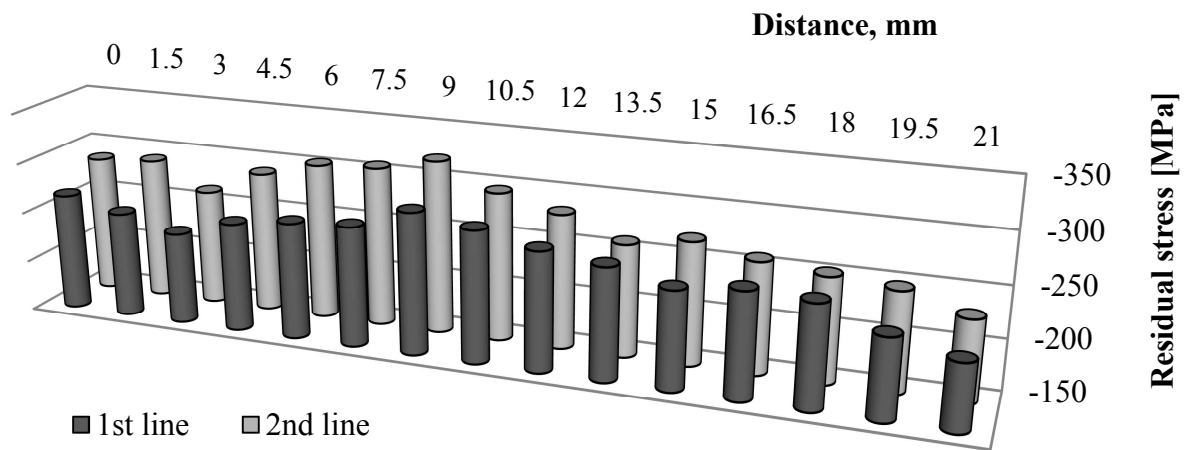


Fig. 4. Characterization of distribution of shot peening induced residual stress field on the surface

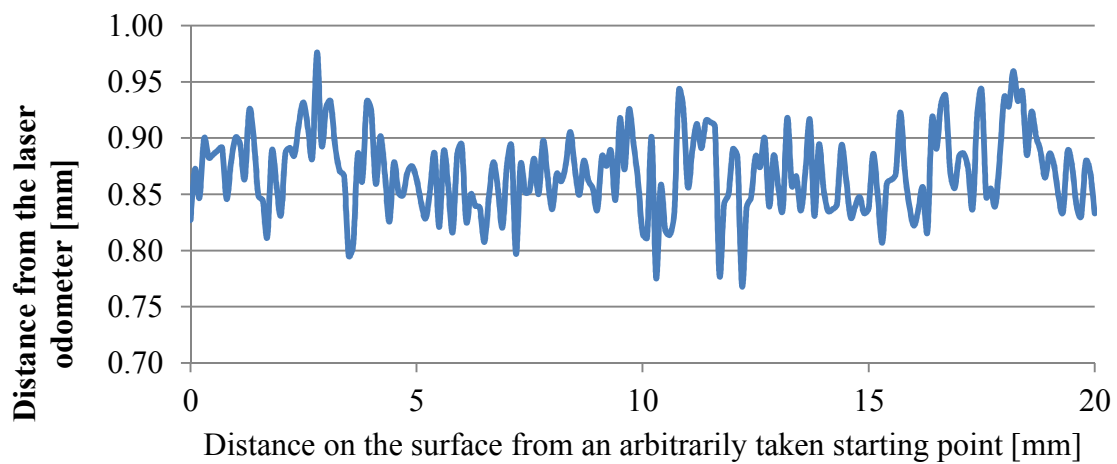


Fig. 5 Laser scanned surface roughness of a shot peened sample

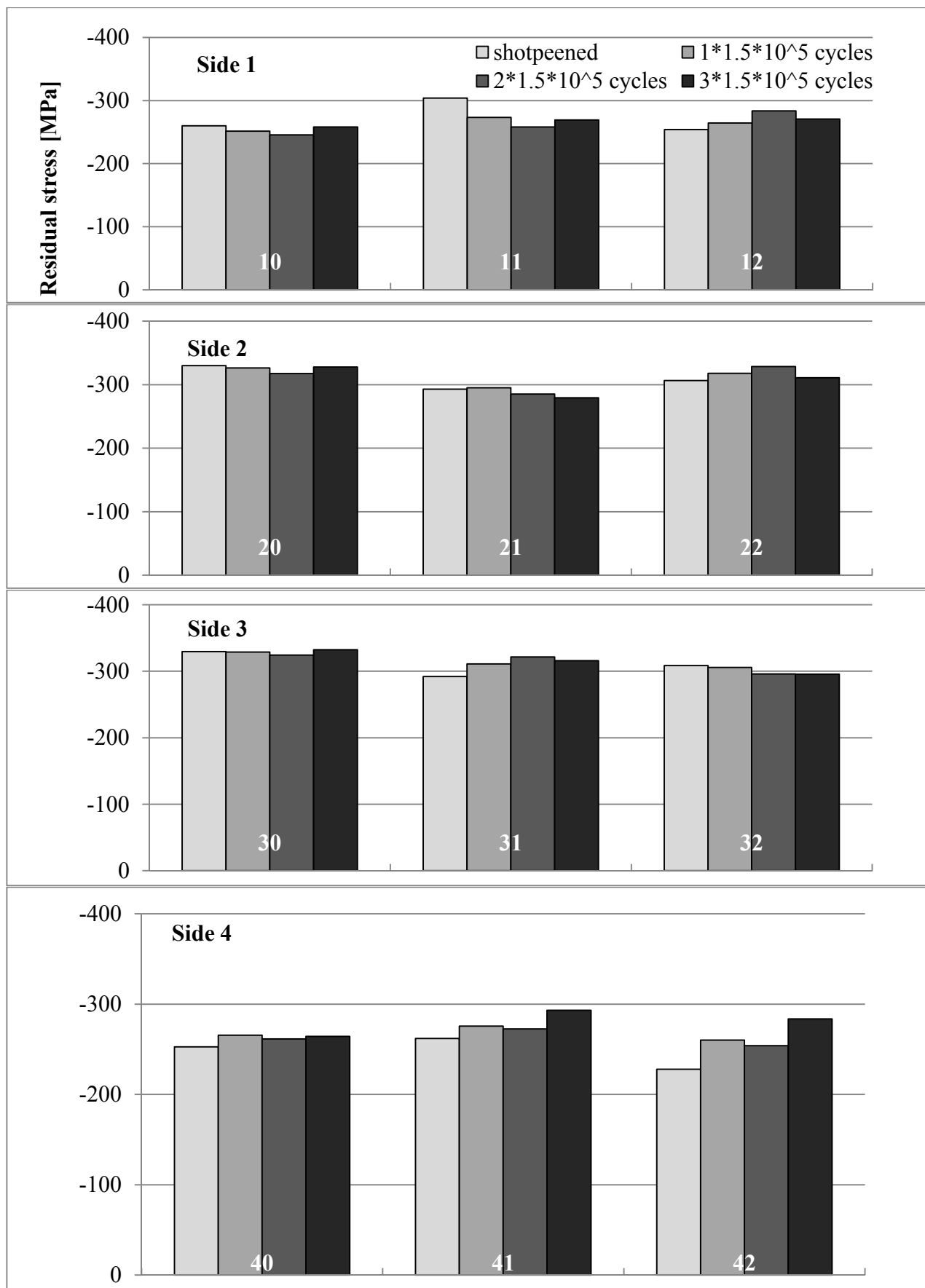


Fig. 6. Residual stress data on the four measured surface of specimen 44 before and during fatigue test at 245 MPa nominal stress level

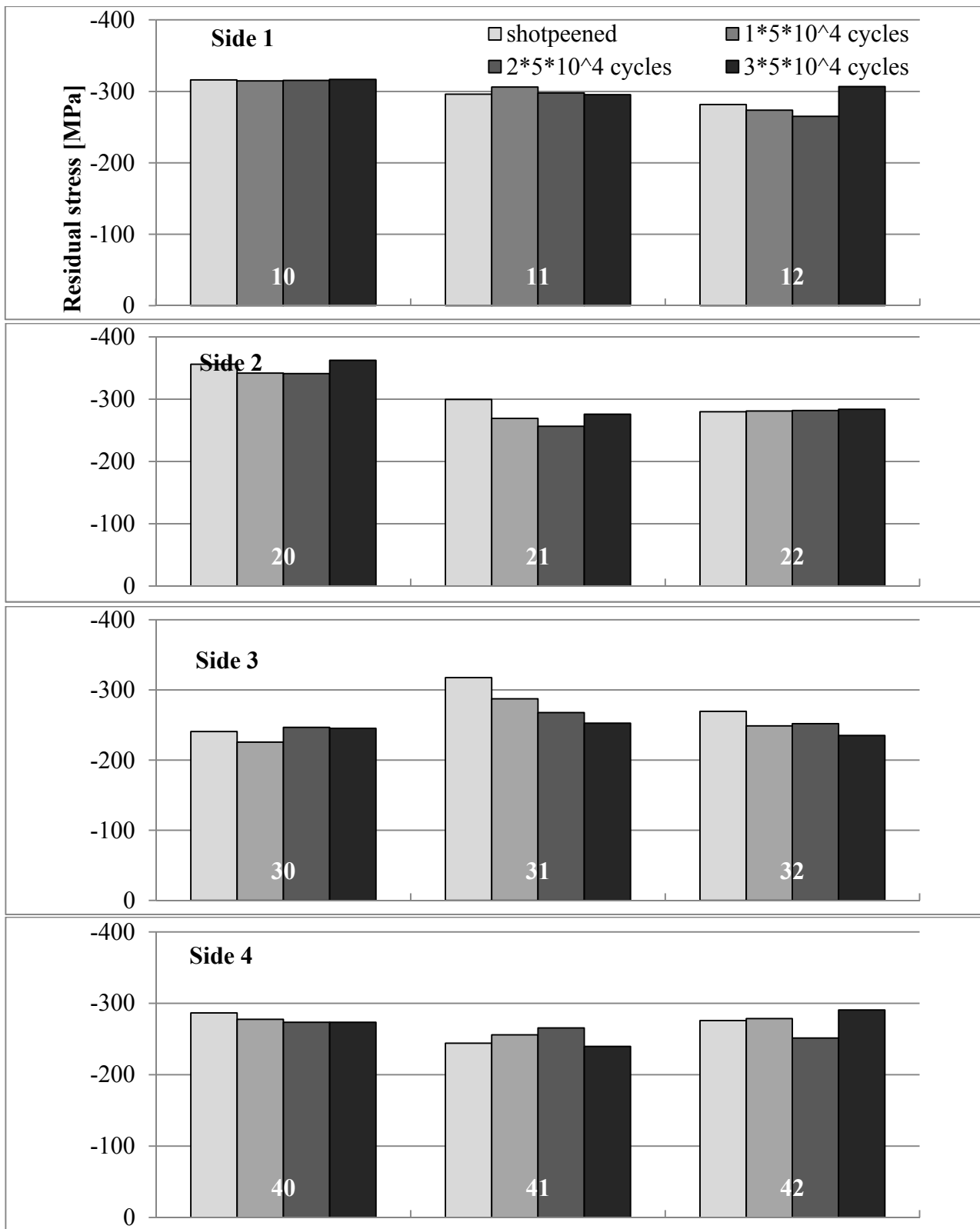


Fig. 7. Residual stress data on the four measured surface of specimen 62 before and during fatigue test at 327 MPa nominal stress level

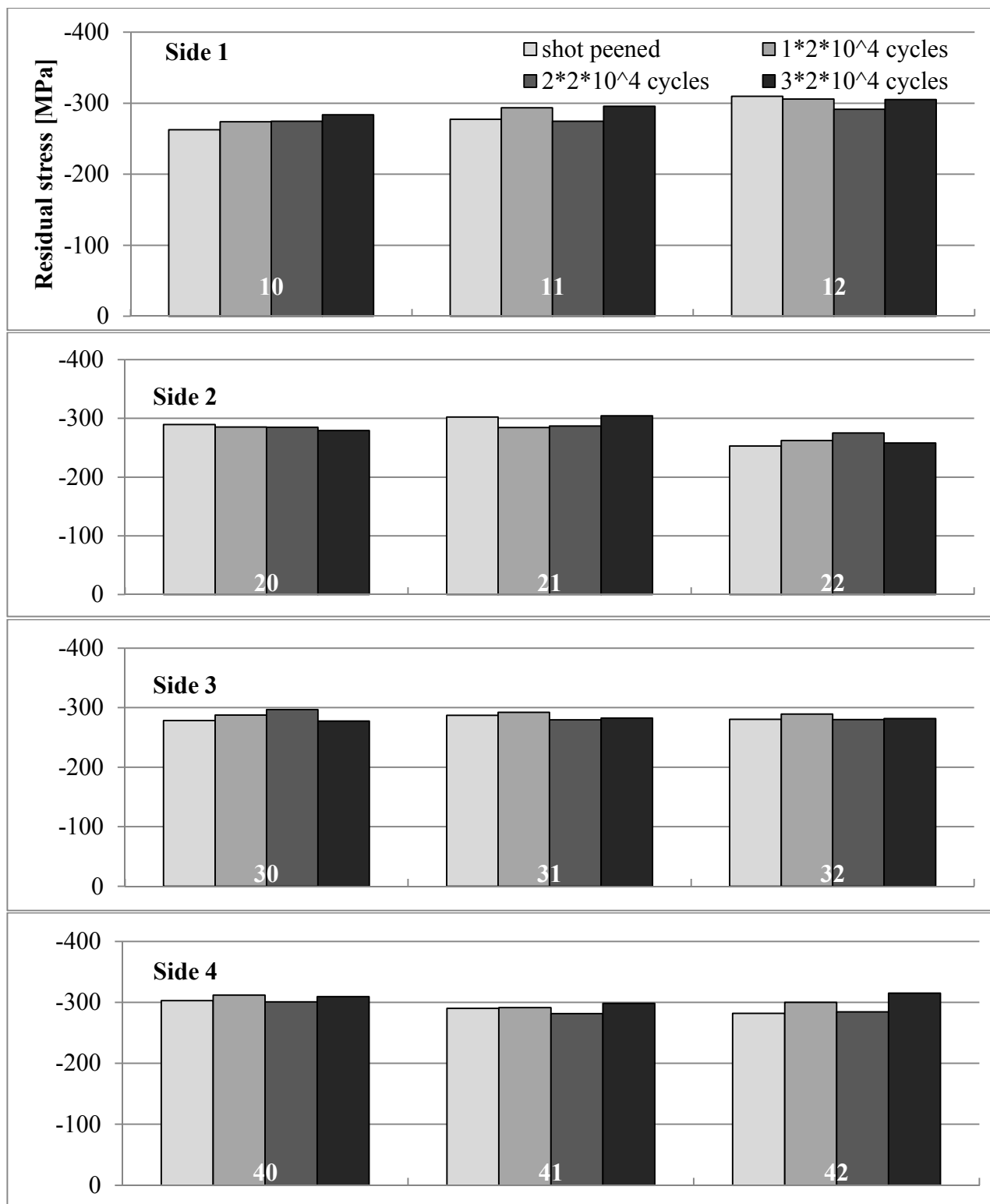


Fig. 8. Residual stress data on the four measured surface of specimen 64 before and during fatigue test at 408 MPa nominal stress level

Comparing initial residual stress data of specimen 44, 62 and 64 as well as the four side of a specimen variation can be noticed. This variation is caused by the statistical character of shoot peening (During the shoot peening shots bomb the surface. As the shots contact the surface the moving energy of the shots cause plastic deformation, and another part of this energy transform residual stress. And it is not possible to ensure that each point of the surface be affected equally by the shots.) Fig. 5 also proves this phenomenon. The variation of data gained from measured points, in the four states is probably caused also by this phenomenon. The other source of variation could

be the surface roughness caused by defocusing. Based on the measurement theory and the formation from the G3R supplier it is countable that 1mm difference from the focus causes an error of about 10 MPa in residual stress counting. The maximal oscillation the surface is about 0.2 mm, which does not influence the counted residual stress.

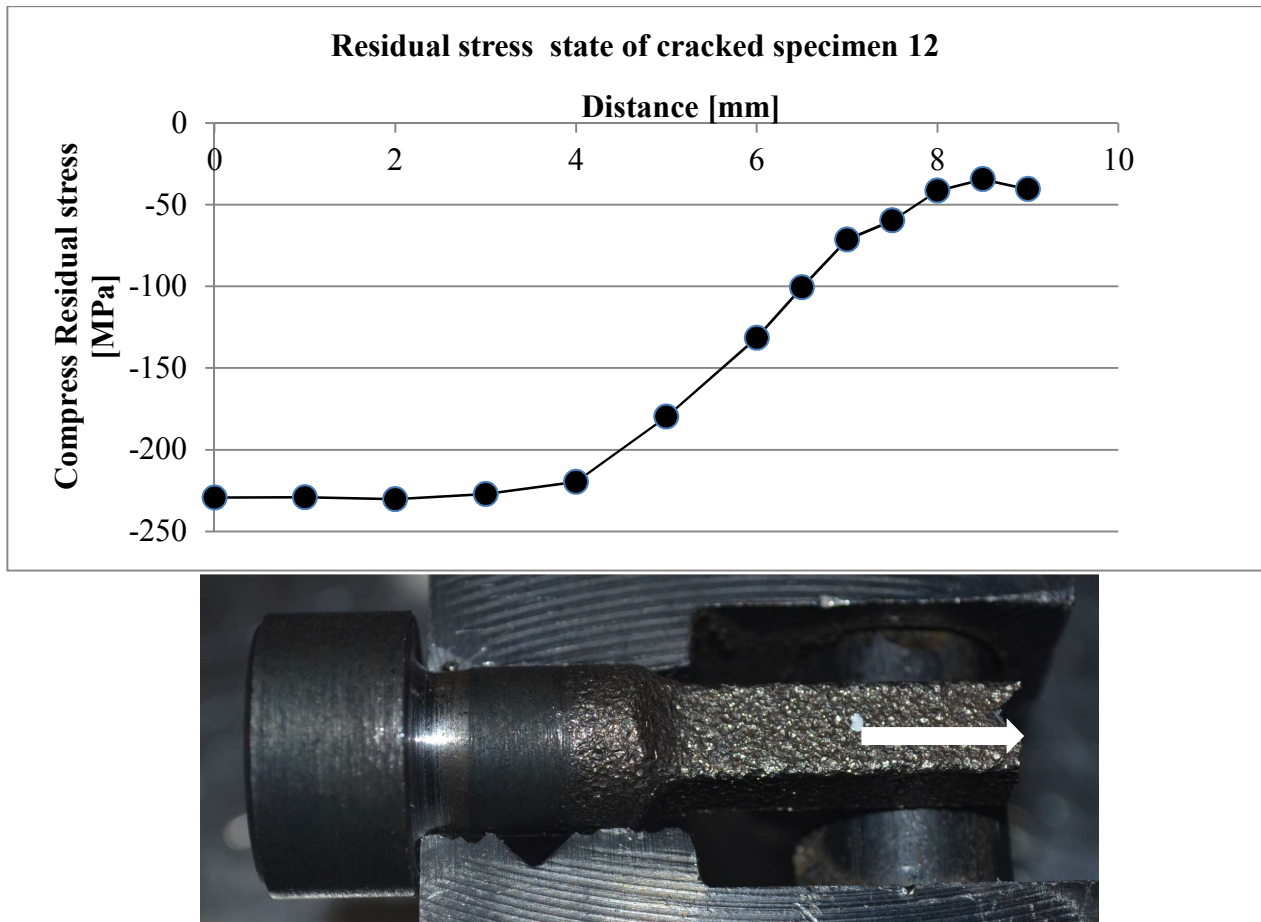


Fig. 9 Cracked sample (specimen 12) and its residual stress state at the surface. (The white arrow shows the line of measurement points.)

Fig. 9 shows the residual stress distribution along the white arrow on a failed sample surface. The decrease in compressive residual stress is clearly visible. The residual stress state was disturbed by the cracking. The residual stresses striving to achieve a state of equilibrium which result its relaxing near the rupture.

Summary

Shot peened specimens with compressive residual stress were subject to different fatigue cycles and examined stress levels using an X-ray diffractometer. The generated residual stress distribution was measured at the surface and in depth. The origin of scatter of the surface stress data is the characteristic of shot peening. The residual stress in depth curve corresponds with industrial experiences. Surface roughness measurements were done to check the effect of roughness on the problem of defocusing.

The initial residual stress states of the specimens were not identical so after the fatigue tests the same places were remeasured. Three specimens, which were fatigued at three different stress levels in steps, was X-ray analysed before the fatigue load and after each step. A step means a defined number of cycles. It was experimentally showed that the investigated alloy holds the residual stress state at this stress levels during the performed fatigue cycles. A detectable decrease of stress value was measured only in case of failed sample surface.

To check the effect of the roughness on the defocusing caused error, the roughness was scanned by a laser odometer. The maximal roughness was 0.2mm which do not cause error in residual stress calculations. Future work should be focusing on other alternative specimen geometry, which let to use so stress levels, which result observable residual stress decreasing.

Acknowledgements

The present work was carried out as part of the TÁMOP-4.2.1.B-10/2/KONV-2010-0001 project in the framework of the New Hungarian Development Plan. The realization of this project was supported by the European Union, co-financed by the European Social Fund. The authors would like to thank Jenő Sólyom for the valuable discussions, Arnold Rónaföldi for the laser odometer and Ferenc Tancsics for his help during the preparation of the specimen.

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10.4028/www.scientific.net/MSF.752

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10.4028/www.scientific.net/MSF.752.95