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# Analysis of residual stress in 1.4539 austenitic steel joints welded with TIG method

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**Abstract.** The article compares the results of tests of residual stress determined based on Knoop microhardness measurements and obtained experimentally with the use of an x-ray diffractometer. Distribution of residual stress in the weld after strengthening of the surface layer, resulting from shot peening, was specified. A method of residual stress determination proposed by Oppel, based on Knoop microhardness distribution, was applied. An analysis of residual stress of 1.4539 austenitic steel welded joints, made with the use of TIG method and additionally strengthened with shot peening of the surface, showed good agreement of the results obtained both with the $\sin^2\psi$ method and based on the microhardness measurement. The highest compression stress has occurred in a so-called Belayev point, approximately of 35 ÷ 40 μm from the surface.

**Keywords:** residual stress, welded joints, TIG, Knoop microhardness, shot peening
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## 1. Introduction

The aim of the tests, presented in the article, was to define residual stress obtained based on microhardness measurements with the Knoop method. Application of the Knoop microhardness measurements to determine the transverse $\sigma_1$ and the longitudinal $\sigma_2$ residual stress was proposed by Oppel [1]. The results of analytical calculations, according to this method, were compared to the residual stress specified with the use of x-ray diffraction with the $\sin^2\psi$ method [2].

Paper [1] reveals that already in 1932 Kokubo noticed an influence of tensile stress in the elastic range on reduction of the material hardness [3]. These observations were confirmed by George Sines and R. Carlson, as well as by Fink and Van Horn [4]. They proved that changes in the hardness in the surface layer occurred as a result of the hardening process. An absolute value of residual compressive stress was higher than the introduced tensile stress. Changes in the total state of stress could be, therefore, defined as gradual reduction of compressive stress.

The Knoop method shows the biggest sensitivity to stress with the Knoop microhardness measurements if a longer diagonal of the imprint is perpendicular to the direction of stress.

Shot peening is a process resulting in obtainment of a favourable distribution of residual stress, in particular, compressive stress, in the processed material due to a phenomenon of elastic-plastic stroke in the shot blasting material — processed object's contact point [2].

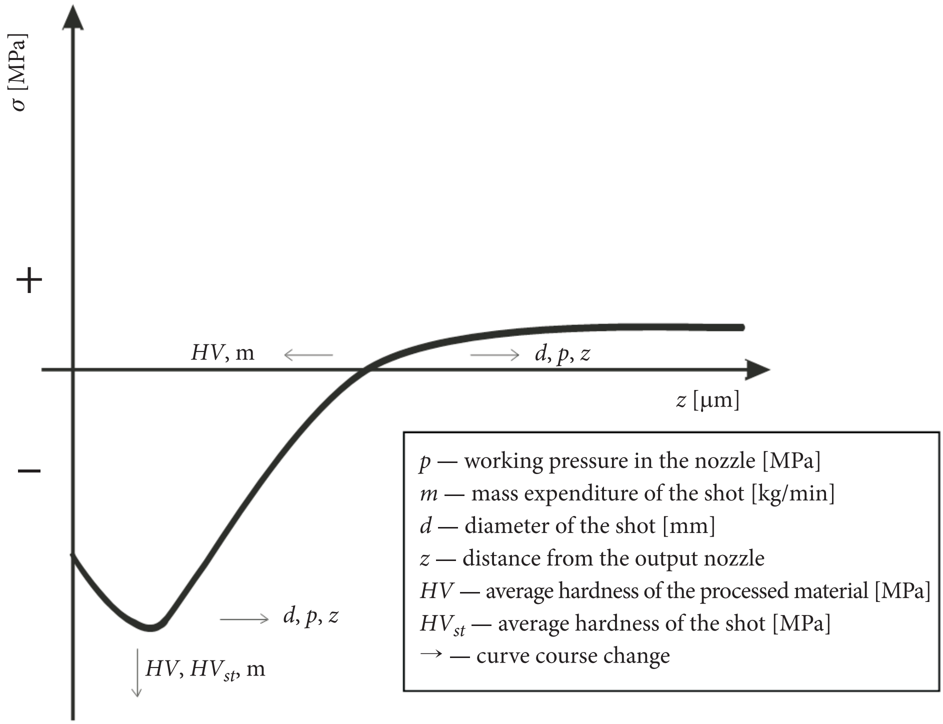
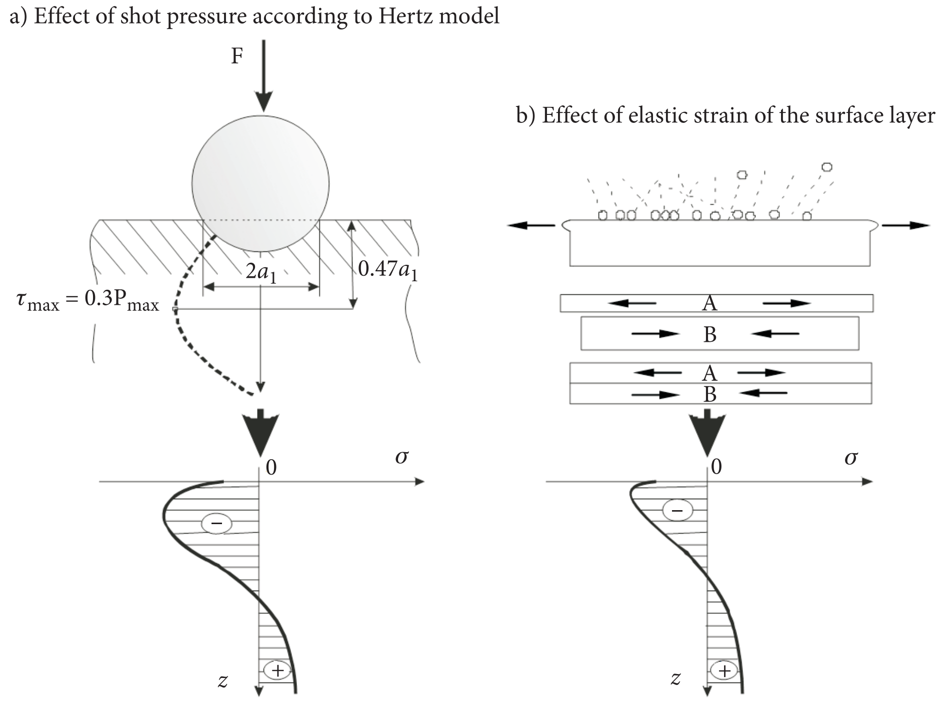


Fig. 1. Course of residual compressive stress changes from shot peening parameters [5, 6]

An important aim of shot peening is generating a new state of the surface layer in the processed material resulting from a phenomenon of elastic-plastic stroke in the shot blasting material — processed object's contact point as well as origin of a favourable distribution of residual stress, in particular, compressive stress [5, 6]. Generation of residual compressive stress in the surface layer of the steel is dependent on the applied shot peening conditions, namely, on mass, velocity and gradation of processing pellets, as well as on duration of processing (Fig. 1).

“As a result of operation of dynamic loads on the metal, placement of atoms in crystalline meshes exceeds the minimal level of kinetic energy, which hinders building an original mesh and causes a disturbance state while inducing origin of stress in the material around the slides line. Only part of atoms is in their original position, the rest is new positions, which is a main cause of origin of residual stress inside the material” according to [5].



a) Effect of shot pressure according to Hertz model

b) Effect of elastic strain of the surface layer

Fig. 2. Scheme of stress origin resulting from shot peening according to Hertz model (a) and strain model [6] (b)

Presently, distribution of residual stress in the welded joints is determined with numerous, usually expensive, experimental methods. An option could be determination of residual stress with the method developed by Oppel, based on the Knoop microhardness.

## 2. Research methodology

Diffraction records for determining residual stress were performed on Brucker D8 Discover x-ray diffractometer operating in the geometry of a point beam ($\varphi \approx 1.5$ mm) with PSD VANTEC2 position sensitive detector located at the Faculty of Materials Science and Engineering, Warsaw University of Technology (Fig. 3b). The conditions of records were as follows: tension — 40 kV, current — 40 mA, step — $\Delta 2\Theta 0.03$, counting time of one measuring point — 200 s. Distribution of the transverse $\sigma_1$ and the longitudinal $\sigma_2$ residual stress in the weld axis was tested (Fig. 3a). To determine the distribution of subsurface residua stress, welded joints were electrochemically etched for 2, 4, 15, and 30 min in order to remove subsequent surface layers. One of the methods for measuring residual stress of the metal, i.e., such stress which occurs in material as a residue after removing all loads, is the $\sin^2\psi$ method consisting in measuring a change of inter-layer distances in a metal crystallographic mesh as a *sinus* function of an inclination angle in respect to a specimen flat surface. The obtained experimental inter-layer distances $d_{hkl}$ and x-ray elastic constants for the tested material constitute input data for a software calculating values of residual stress. A decisive limitation of this method for industry tests is a specimen size limited by the possibilities of placing the specimen in the grip.

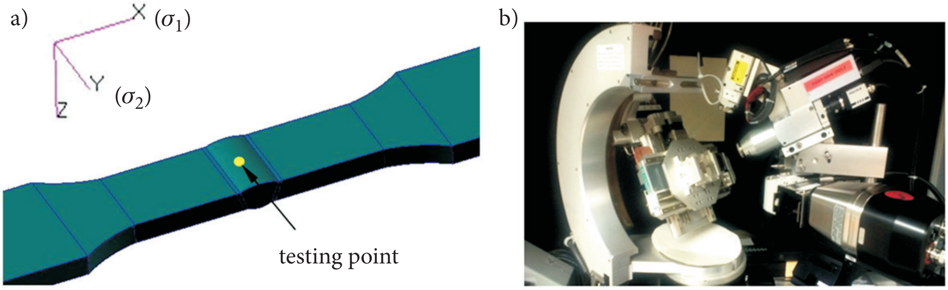


Fig. 3. The transverse $\sigma_1$ and longitudinal $\sigma_2$ residual stress measuring point (a), x-ray diffractometer (b)

## 3. Research object

1.4539 steel (percentage: C: ≤0.02; Si: ≤0.70; Mn: ≤2.00; P: 0.030; S: ≤0.010; N: ≤0.15; Cr: 19.0÷21.0; Cu: 1.20÷2.00; Mo: 4.0÷5.0; Ni: 24.0÷26.0) joints made with TIG method and additionally strengthened by surface shot peening were tested.

Tests of structure in the area of the 1.4539 steel joint welded with TIG method (Fig. 4 a and b) after shot peening revealed deformation of austenite grains caused by a squeeze of the surface layer up to the depth of approximately 250 μm. In the photo of the microstructure, a dashed line indicates the depth of a strengthened surface layer of elements after shot peening, whereas the symbol S indicates a weld microstructure.

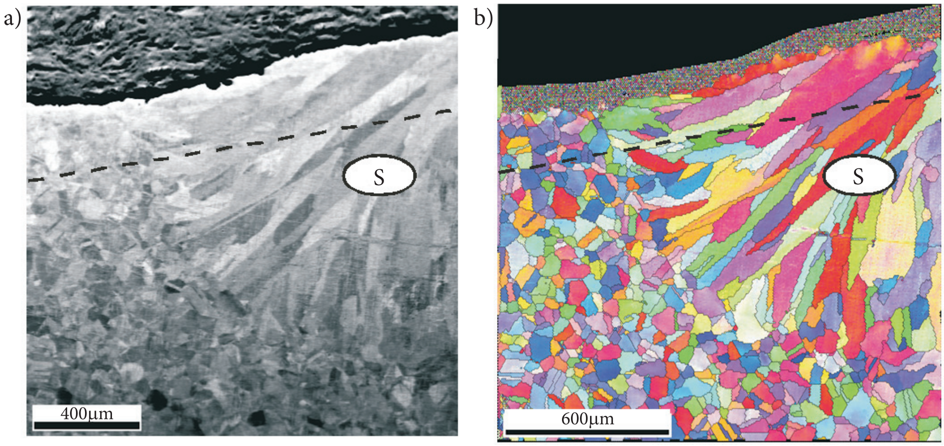


Fig. 4. Microstructure of a surface layer after shot peening the area of a joint welded with TIG method (a) made with the use of FSD detector (a) and EBSD (b) FEI Quanta 3D FEG scanning microscope [2]

## 4. Development of residual stress distribution based on changes in knoop microhardness

The method for measurements of the Knoop hardness consisted in application of a diamond pyramid penetrator whose opposite edges create in pairs the angles of 173° 30' and 130°. The imprints are in the form of an extended rhombus with a diagonals ratio equal to 7.114:1, whereas the imprint depth is 1:30 of its longest diagonal (Fig. 5, 6).

The Knoop microhardness is expressed by formula (1)

$$H_K = 14,228\frac{F}{L^2} \tag{1}$$

where: $F$ — the force a penetrator is pressed into the material with kN,
$L$ — the length of a longer diagonal of the imprint [mm]. During the tests, the loading force was 300 g.

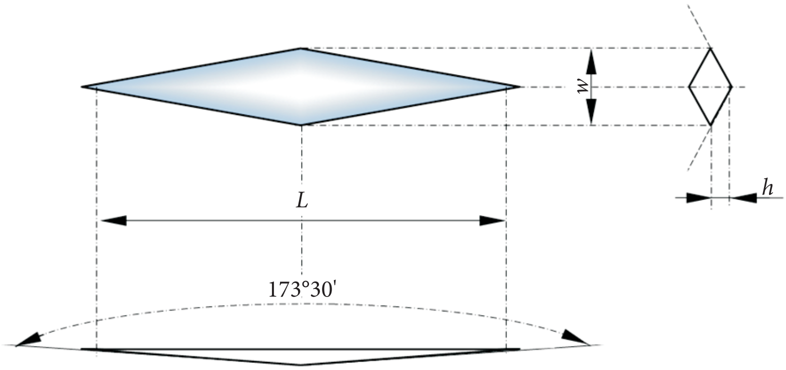


Fig. 5. Scheme of Knoop penetrator imprint cross section

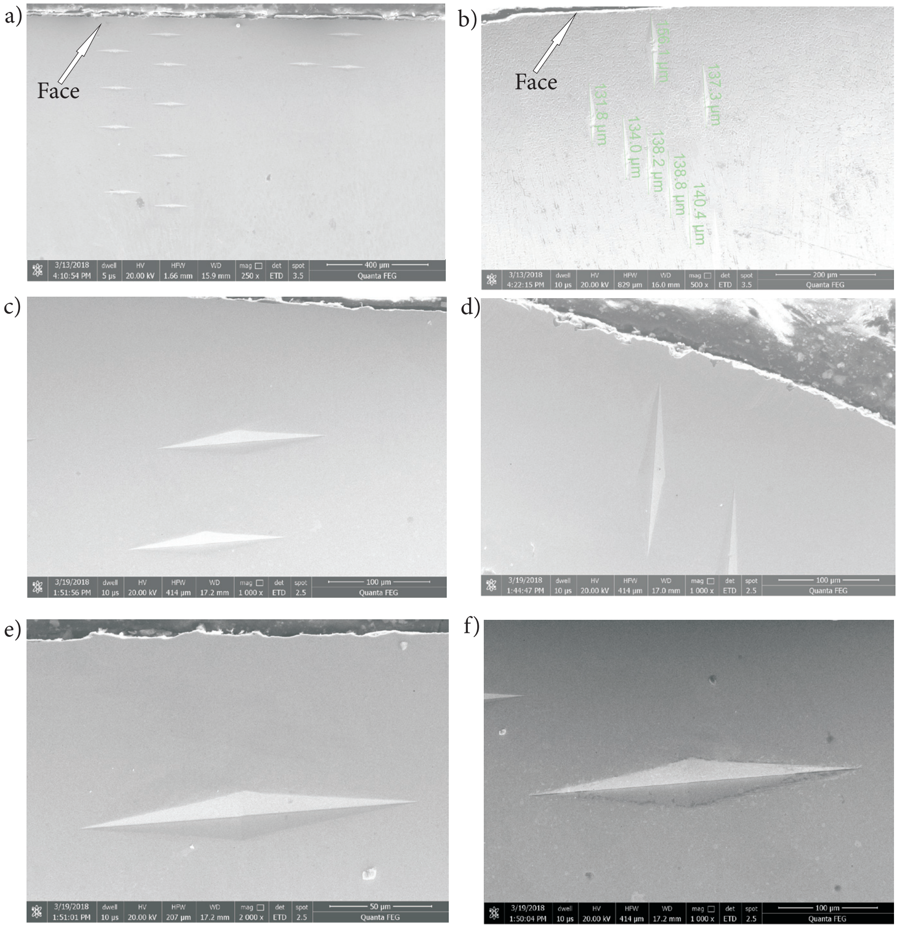


Fig. 6. Examples of imprints performed during measurement of Knoop hardness distribution into the surface layer: parallel to the joint face surface $H_{K1}$ (a, c, e f), perpendicularly to the joint face surface $H_{K2}$ (b, d)

A relative increment of the Knoop microhardness is designed with $\Delta H_1$ and $\Delta H_2$

$$\Delta H_1 = \frac{H_{K1} - H_{K1o}}{H_{K1o}}, \ \Delta H_2 = \frac{H_{K2} - H_{K2o}}{H_{K2o}} \tag{2}$$

where: $H_{K1}$, $H_{K2}$ — microhardness of the weld after the strengthening process of surface measured with the Knoop method, and
$H_{K1o}$, $H_{K2o}$ — microhardness of the specimen weld measured with the Knoop method after release of the structure.

Work [1] describes the relations, presented by Oppel, which allow for calculating the $\sigma_1/E$ ratio, according to formula (3), and for determining values of biaxial residual stress from Figure 7 defined based on the results of microhardness increment (Table 1).

$$\frac{\sigma_1}{E} = a\left(\Delta H_1 + \Delta H_2\right) \tag{3}$$

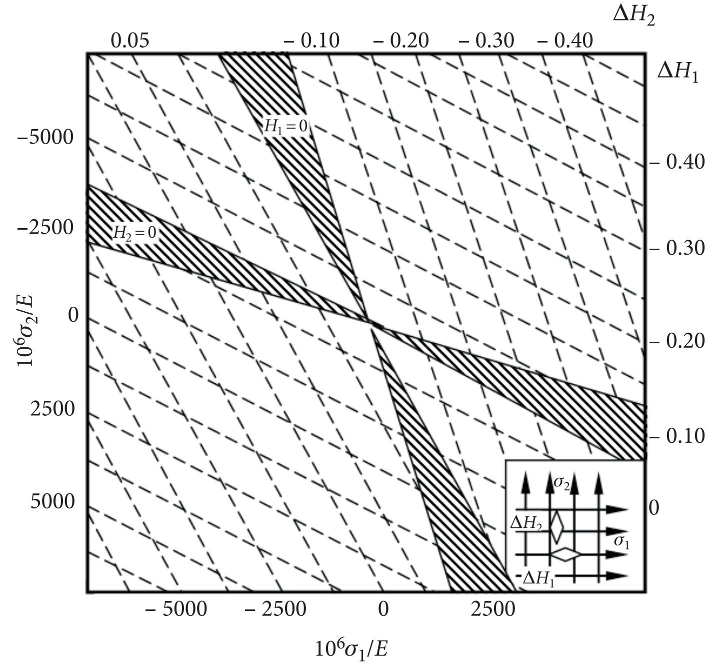


Fig. 7. Nomogram for determining stress developed by Oppel based on measurement of microhardness changes [1]

Table 1

Comparison of residual stress results determined with a method proposed by Oppel and with the use of x-ray diffractometer

| residual stress determined with the method proposed by Oppel | | | | | | | | | residual stress determined with the use of x-ray diffraction with $\sin^2\psi$ method | |
|---|---|---|---|---|---|---|---|---|---|---|
| levels of imprints from the surfaces | $H_{K1}$ | $H_{K1o}$ | $\Delta H_1$ | $\sigma_1$ | $H_{K2}$ | $H_{K2o}$ | $\Delta H_2$ | $\sigma_2$ | $\sigma_1$ | $\sigma_2$ |
| 1 | — | — | — | — | — | — | — | — | -350 | -420 |
| 2 | — | — | — | — | — | — | — | — | -92 | -385 |
| 3 | 200 | 200 | -0.11 | -76 | 200 | 224 | -0.101 | -170.5 | 23 | -194 |
| 4 | 214 | 203 | -0.04 | -201 | 203 | 234 | -0.13 | -150 | -219 | -329 |
| 5 | 217 | 224 | 0.029 | -20 | 224 | 230 | -0.03 | -350 | -136 | -278 |
| 6 | 189 | 224 | -0.13 | -131 | 224 | 230 | -0.03 | -320 | | |
| 7 | 224 | 220 | 0.00 | -125 | 220 | 227 | -0.03 | -130 | | |
| 8 | 208 | 217 | -0.07 | -120 | 217 | 227 | -0.04 | -136 | | |
| 9 | 203 | 217 | -0.05 | 10 | 217 | 227 | -0.04 | -156 | | |
| 10 | 217 | 217 | 0.03 | 1 | 217 | 0.93 | -0.90 | -60 | | |

## 5. Discussion

The results of tests on the transverse $\sigma_1$ and longitudinal $\sigma_2$ residual stress in the weld axis, obtained with the $\sin^2\psi$ x-ray method, as well as obtained based on analysis of the Knoop microhardness changes according to Oppel method are presented in the graph form (Fig. 8). There were observed two areas of the biggest change in compressive stress, one at the surface (1), whereas the other under the surface, probably at the point of the biggest strain of the material after shot peening (2). Discrepancy in a margin of an error between experimental measurements of residual stress and a theoretical analysis may result from specificity of x-ray tests which receive a 'measurement signal' from the depth of approximately 10.0 ÷ 12.0 μm averaging residual stress of the second type $\sigma^S$ between the neighbouring grains. This method, so-called $\sin^2\psi$ method, is based on the diffraction lines shift occurring in the conditions of material stress with a crystalline structure.

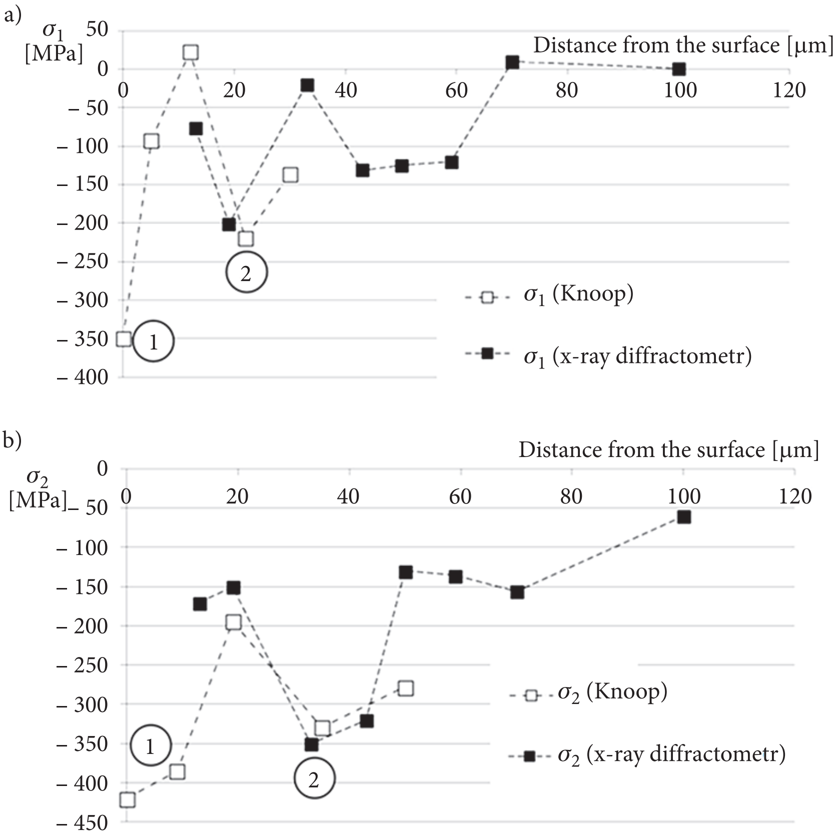


Fig. 8. Course of subsurface transverse $\sigma_1$ and longitudinal $\sigma_2$ residual stress of the second type $\sigma^S$ in the axis weld determined experimentally with an x-ray diffractometer and with analytical method based on Knoop microhardness

## 6. Conclusions

Analysis of two methods for determining residual stress, both with an x-ray method and analytically based on the Knoop microhardness changes with Oppel method in 1.4539 austenitic steel show good agreement. Both the methods required relevant preparatory procedures  and preparing the specimens. Due to economical reasons, the analytical method is more favourable and may be a complement for comparison of the obtained results. The experimental tests, as well as the theoretical analysis prove occurrence of a characteristic strain point (Belayev point) for joints made with TIG and shot peened at the depth approximately 35 ÷ 40 μm under the surface.

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## Analiza naprężeń własnych w połączeniach ze stali austenitycznej 1.4539 wykonanych metodą TIG

**Streszczenie.** W artykule porównano wyniki badań naprężeń własnych wyznaczonych na podstawie pomiarów mikrotwardości Knoopa i doświadczalnie przy użyciu dyfraktometru rentgenowskiego. Określono rozkład naprężeń własnych w spoinie po umocnieniu warstwy wierzchniej w wyniku kulowania. Zastosowano metodę wyznaczania naprężeń własnych zaproponowanych przez Oppela na podstawie rozkładu mikrotwardości Knoopa. Analiza naprężeń własnych połączeń spawanych ze stali austenitycznej 1.4539 wykonanych metodą TIG dodatkowo umocnionych przez kulowanie powierzchni wykazała dobrą zgodność wyników uzyskanych za pomocą metody $\sin^2\psi$ oraz na podstawie pomiaru mikrotwardości. Największe naprężenia ściskające występowały w tzw. punkcie Bielajewa ok. 35 ÷ 40 μm od powierzchni.

**Słowa kluczowe:** naprężenia własne, połączenia spawane, TIG, mikrotwardość Knoopa, kulowanie
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