Characteristics of the deformed zone around Vickers indentations in metals

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Abstract. The stress and plastic strain distributions around pyramidal indenter in steel 10 has been investigated by exploring the Vickers hardness of carefully prepared median plane sections through indentations. Experimental results showed that, the maximum strain is observed at a certain depth below the indentation surface inside the hydrostatic compression zone. The minimum permissible ratio between the coating thickness and the indentation depth, which excludes the influence of the substrate on the indentations results obtained by Vickers indenter, is substantiated. The shape and dimensions of plastic deformation zones around Vickers indentations were determined. As a result, between the indentation volume and the deformation zone volume established directly proportional relationship.

1. Introduction
It is well known that indentation measurements have become one of the most important measurement methods to determine the hardness and other mechanical properties of solids, thin films and coatings [1,2]. The Brinell spherical indenter and the Vickers diamond pyramid are most often used as an indenter in hardness testing [3]. Studies the distribution of stress and strain around indentations have aroused the interest of researchers for a long time, for instance, O’Neill, Tabor, Chaudhri and others [4-7].

The hardness measurement allows to obtain a real pattern of the strain and stress distributions around indentations. Experimentally, the flow stress values of different parts of the deformation zone around an indentation in a metal may be determined by measuring their hardness and then comparing the hardness data thus obtained with the Vickers hardness values of specimens of the metal which have been compressed to different amounts of plastic strain.

Also, an equally important task is to determine the shape and size of deformation zones around an indentation, which is considered an important dimensional indicator during indentation process. Johnson proposed a model [8], according to which the areas of space around spherical indentations are formed in the form of hemispheres. Similar results were obtained by A. E. Giannakopoulos and S. Suresh for a sharp indenter [9]. However, the study of deformation zone around indentations is especially important for determining the mechanical properties of thin films and coating because, it is necessary to exclude the substrate influence on the indentation results. Therefore, it is important to obtain a real pattern of the strain and stress distributions around indentations and determine the depth to which plastic deformation extends under indentations.

The main goal of this study is to conduct a comprehensive experimental study of plastic deformation zones around Vickers indentations at different loads, which allows, firstly, estimate the plastic strain.
distribution around pyramidal indenter, secondly, establish the relationship between the indentation volume and the deformation zone volume and finally justify the minimum ratio of the coating thickness to the indentation depth, excluding the influence of the substrate.

2. Materials and experimental process

Indentations were made on an automated Instron Tukon 2500 into low carbon steel (steel 10) samples from which 3 thin sections were made. The indentation loads N (kgf), which applied on each section, were: 60, 100, 150 in the order of their increase. As a result of the experiments, the indentation diagonal d, the indentation depth t and the Vickers hardness HV at each indentation load were determined. The test results are shown in table 1.

| F (kgf) | d (mm) | t (mm) | HV (kgf/mm²) |
|--------|--------|--------|--------------|
| I 60   | 0.958  | 0.136  | 117          |
| II 100 | 1.210  | 0.173  | 113          |
| III 150| 1.514  | 0.216  | 112          |

After the indentation, thin sections were cut along the meridional plane that passes through the center of the indentations. Next, on the incision plane, indentations were made under a load of 0.1 kgf and hardness values of HV0.1 were determined. The indentations were applied in rows, the distance between which was 200 microns, the step between the indentations was also 200 microns. Images of the sectional plane on which the indentations were made are shown in figure 1.

Figure 1. Images of the sectional plane on which the indentations were made.

To obtain graphs "stress σ – hardness HV0.1" and "strain ε – hardness HV0.1", a tensile test was performed on a flat specimen that was made of the same material (steel 10). Testing was carried out on a universal testing machine "Instron 5982". The sample was stretched to different plastic natural strains. At each step of loading σi and εi were calculated using the formulas:

\[ \sigma_i = \frac{F}{S} \]  
\[ \varepsilon_i = \ln \left( \frac{l}{l_0} \right) \]

where F is the load; S - current cross-sectional area; l – current sample length; l₀ – initial sample length.

The hardness HV0.1 at various degrees of plastic deformation is determined. The results of tensile and hardness tests are presented in table 2, where σ is the stress value in the sample; S₀ is the initial cross-sectional area of the sample; Δl is the absolute elongation of the sample; δ is the relative elongation of the sample.

Figure 2 shows the image of the flat stretched specimen and the graphs "σ₁ - HV0.1", "ε₁ - HV0.1" for steel 10.
Table 2. Tensile and hardness tests results.

| F (kgf) | σ = F/S₀ (kgf / mm²) | Δl (mm) | δ = Δl/l₀ | σᵢ = σ(1+δ) (kgf / mm²) | εᵢ | HV 0.1 (kgf / mm²) |
|---------|----------------------|---------|-----------|------------------------|-----|------------------|
| 768.8   | 26                   | 4       | 0.089     | 27.9                   | 0.085 | 129              |
| 947.4   | 32                   | 7       | 0.140     | 36.5                   | 0.131 | 171              |
| 1059.5  | 35                   | 8       | 0.189     | 41.7                   | 0.173 | 193              |
| 1096.1  | 36                   | 12      | 0.267     | 46.2                   | 0.236 | 211              |

Figure 2. Flat stretched specimen (a) and (b) graphs "σᵢ - HV0.1" and "εᵢ - HV0.1" for steel 10.

3. Results and discussion
Regression analysis hardness data showed that, they are well fitted by the expressions:

\[ σᵢ = 0.222HV0.1 - 0.9991 \]  \hspace{1cm} (3)
\[ εᵢ = 0.0171e^{0.0122HV0.1} \]  \hspace{1cm} (4)

Patterns strain and stress distributions around indentations were obtained by using equation (3) and equation (4) and hardness test results. Figure 3 shows the distribution patterns of σᵢ and εᵢ around indentations made by pyramid Vickers at different loads.
Figure 3. Patterns strain and stress distributions around indentations obtained by the pyramid at different loads $F$: a, $b \sim 60$ kgf; c, d $\sim 100$ kgf; e, f $\sim 150$ kgf.

In the deformed metal volume under the indentations there are two main zones, the hydrostatic core and the plastic deformation zone (figure 4). In the hydrostatic core, compressive forces act in all directions. As it was established, the stress and strain values in this zone approach the true tensile strength volume.

Figure 4. The shape and size hydrostatic core and the plastically deformed zone under the indentations obtained at different loads: a - 60 kgf, b - 100 kgf, c - 150 kgf.

From figure 4 it has been established that the hydrostatic core under the indentations has a shape close to hemispherical, and its radius $R_{HC}$ increases with increasing load $F$. Center sphere is located at the top of the pyramidal indentations at a distance from the surface $\approx t$ (the indentation depth), where maximum values of stresses and strains appear. The shape of plastic deformation zone under the indentations turned out to be close to spherical, which is agree with Hill-Johnson and Giannakopoulos and Suresh models. It should be noted that the radius of plastic deformation zone $R_{PD}$ increases with increasing applied load on indenter. This radius $R_{PD}$ can be determined both experimentally from patterns strain distribution and by formula D. Kramer.

According to D. Kramer [10], the radius of plastic deformation zone under the indentations $R_{UPD}$ is calculated from:

$$R_{UPD} = \sqrt[3]{\frac{3P}{2\pi\sigma_T}}$$

(5)
where P - an applied load on indenter, σT - yield strength.

Also, the indentation volume V and the plastic deformation zone volume VPD (experimental volume), VUPD (calculated volume) were calculated by the following formulas:

\[ V = 8.16t^3 \]  
\[ V_{UPD} = \frac{2\pi R_{UPD}^3}{3} - 8.16t^3 \]  
\[ V_{PD} = \frac{2\pi R_{PD}^3}{3} - 8.16t^3 \]

Between V and VUPD, as well as between V and VPD were established directly proportional relationships:

\[ V_{UPD} = 101.7V + 0.17 \]  
\[ V_{PD} = 92.569V + 1.714 \]

The relationships described by equation (9) and equation (10) are presented in the form of a graph in figure 6.

![Figure 5](image)

**Figure 5.** The relationship between VUPD, VPD and V.

The ability to estimate the plastic deformation zone volume, which is an important dimensional indicator, under the indentations is the main practical result of equations (9) and (10).

Also the ability to substantiate the ratio between the total plastic deformation depth T and indentation depth t at different loads is another important result. The main results of determining the geometrical parameters of the indentations and the deformed zone under the pyramidal indentations are presented in table 3.

**Table 3.** The geometrical parameters of the indentations and the deformed zone around the pyramidal indentations at different loads for steel 10.

| Load, (kgf) | t, (mm) | d, (mm) | RHC, (mm) | RPD, (mm) | RUPD, (mm) | T, (mm) | Φ=T/t | VPD, (mm³) | VUPD, (mm³) | V, (mm³) |
|------------|---------|---------|-----------|-----------|-----------|---------|-------|-----------|-----------|---------|
| 60         | 0.137   | 0.958   | 0.204     | 1.2       | 1.014     | 1.337   | 9.75  | 3.59      | 2.16      | 0.0209  |
| 100        | 0.173   | 1.210   | 0.392     | 1.4       | 1.31      | 1.5     | 10.24 | 5.7       | 4.66      | 0.0421  |
4. Conclusion

The revealed patterns the distribution of hardness, stress and strain in the deformed metal under the indentations obtained by the Vickers pyramid showed that the plastic deformation zone has a spherical shape, which is agree with Hill-Johnson and Giannakopoulos A. E. – Suresh S. results. However, the centres of these spheres displaced downward as the indentation load increases. It was observed that the maximum strain is located at a certain depth below the indentation surface inside the hydrostatic compression zone. It was shown that there is a directly proportional relationship between the indentation volume and the deformation zone volume. Studies and tests have established that the ratio between the coating thickness and the indentation depth, which excludes the influence of the substrate on the indentation results made by Vickers Indenter, must be at least 10.

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