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# Numerical analysis of the influence of friction conditions on the pile-up effect in Vickers hardness measurements

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**Abstract.** Vickers indentation load-depth curve may be used to determine basic mechanical properties of metallic materials such as hardness, yield stress, modulus of elasticity, and elastic and plastic work. The pile-up phenomenon observed during indentation causes underestimation of the projected contact area and the diagonal dimensions of the impression in different hardness measurement scales (nano-, micro-, and macro-). The aim of this paper is to conduct a numerical analysis of the effect of friction conditions on the pile-up phenomenon during testing of DC04 steel sheet. The mechanical properties of the sheet metal used for the modelling purpose were first characterized by tensile tests on samples cut along the rolling direction (0°), transverse to the rolling direction (90°) and at an angle of 45° to the rolling direction. The numerical computation was conducted using ABAQUS, which is one of the powerful finite element-based programs. A wide range of variation of friction coefficients, i.e. 0-0.3 has been used in the analysis. It has been observed that the results of indentation of anisotropic materials are significantly affected by friction. The difference in the pile-up height measured at rolling direction of sheet metal and transverse to the rolling direction decreases with the reduction of the maximum displacement of the indenter. For higher values of the coefficient of friction, the higher the value of the indenter displacement, the lower becomes the increase in the pile-up height value.

## 1. Introduction

Mechanical properties of metallic materials are important features that determine their applicability to the specific bulk metal forming process or to the construction of a particular element type. For this reason, metals are subjected to different types of tests which aim is to establish the ability to transfer the load without damage [1, 2]. Due to the static, dynamic or cyclical nature of various loads, a number of test methods have been developed to determine the mechanical properties of materials, such as yield stress, ultimate tensile strength, modulus of elasticity, hardness, and strain hardening parameters. Hardness testing is a non-destructive test that can be carried out directly on structural elements and can be carried out in nano-, micro- and macro- scales according to the specimen sizes. The measurements in static conditions, especially in the nano- and microscale give reasonable results. The use of dynamic-plastic or dynamically elastic devices for measuring hardness causes significant errors to the results of testing thin-walled elements. Indentation hardness significantly depends on the elastic-plastic properties

of material which on elastic recovery of the bulk deformed material [3]. Furthermore, the hardness measurement accuracy may be disturbed by surface roughness of the material tested [4, 5].

Hardness may be defined as a measure of the resistance of the metal when pressing the indenter tip or a measure of the resistance of the metal against the permanent deformation resulting from the indentation. A hardness test consists of indenting the material for a specified time and at a given load on a smooth metal surface, which results in a localized permanent deformation in the shape of a dimple impression. The prevalence of static hardness measurements may be easily explained by establishing the relationship between hardness test results and the results of other tests of mechanical properties carried out in a very small volume of material. In order to study the mechanical properties of materials, i.e. Berkovich, Brinell, Rockwell and Vickers hardness, many indentation based studies have been conducted using diverse parameters such as the load applied, material dimensions and shape of the indenter.

Pile-up or sink-in of the material (Figure 1) around the indenter-tip is a phenomenon which leads to a significant error in the determination of material properties [6, 7]. These phenomena cause significant underestimation during indentation of the impression diagonals and the true contact area of impression. As shown by Bolshakov and Pharr [8], the true contact area may be overestimated by 60%.
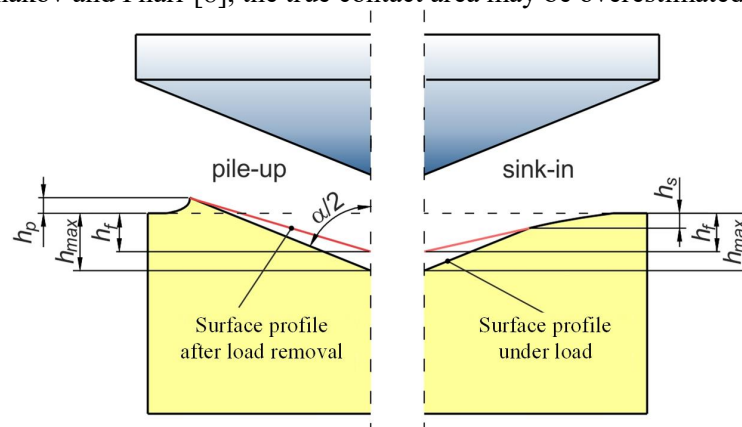


**Figure 1.** Cross section of the indentation profile.
*Definition of abbreviations in the figure: $h_f$ - final displacement of the indenter after complete unloading, $h_{max}$ - maximum displacement of the indenter, $h_p$ - pile-up height, $h_s$ - sink-in depth, $\alpha$ - angle between the two opposite faces of indenter ($\alpha = 136°\pm0.5°$)*

Many studies have devoted to the formation of pile-up/sink-in. For instance, several studies [9-11] have shown that these phenomena can be correlated to the elastic and plastic regimes of deformation, such as the ratio of the final indentation depth $h_f$ to maximum indentation depth $h_{max}$ or the strain hardening exponent *n*. An empirical method of approximating the pile-up contact perimeter has been developed by Kese and Li [12] who concluded that correlating pile-up to various material and loading conditions can be invaluable in appropriately accounting the effect of pile-up on hardness. Zhou and Yao [13] suggested accounting the plastic work and plastic deformation volume to accounting the pile-up. It is well known that the Oliver and Pharr method [14] can overestimate the hardness value of metallic materials that plastically deform due to piling up around the indentation. Some of authors proposed a correction to this standard Oliver and Pharr method to account for errors in hardness measurement due to pile-up effect. In general, imaging-based hardness corrections for pile-up or sink-in formation are based on the consideration that the contact area depends on the tip-area function.

Cabibbo et al. [15] used scanning probe microscopy (SPM) measurements and analytical methods to analyse indentation hardness. As it has been concluded, the SPM-based method showed a quite good quantitative and qualitative literature data agreement. In the work of Burik et al. [16] pile-up correction of mechanical properties was based on the ratio of pile-up height measured by atomic force microscopy (AFM) and contact depth. Bandara et al. [17] conducted 2D and 3D numerical simulations of nano-indentations to understand the behaviour of pile-up formation. They concluded, however, that the pile-

up height increased linearly relative to the load, while the rate (slope) increases with the amount of strain hardening. Zhang et al. [18] found numerically that high temperature hardness does not change with the change of load when pile-up of material during indentation is ignored. Tang et al. [19] conducted the finite element (FE) analysis to examine the pile-up effect on the accuracy of sharp indentation testing. They concluded that the effect of pile-up becomes significant when $h_f/h_{max} > 0.85$. The pile-up effect depends on the anisotropy of the material tested and, in general, the anisotropic pile-up or sink-in patterns were, so far, studied in relation to single crystals [20-22].

The aim of this study is to build a finite element based model and investigate the relationship between the frictional conditions and the amount of the pile-up effect during testing of anisotropic material. Three dimensional (3D) numerical models have considered to account for real strain hardening properties and anisotropic yield criterion of the sheet metal tested. The remaining part of the article is divided into 4 Sections. Section 2 presents the material used for the study and the mechanical properties of the steel sheet determined through tensile test. The numerical modelling work is reported in Section 3 followed by the discussion of the results in Section 4. Finally, Section 5 presents the conclusions drawn from the study.

## 2. Material

The test material was a 2-mm-thick steel DC04 sheet commonly used in the automotive industry. Table 1 presents basic mechanical properties of the sheet determined according to the EN ISO 6892-1 standard. The samples for the tensile tests were cut along the rolling direction (0°), transverse to the rolling direction (90°) and at an angle of 45° to the rolling direction. Three specimens were tested for each sample orientation and basic mechanical parameters were determined.

**Table 1.** Mechanical properties of the DC04 steel sheet.

| Orientation | Yield stress $R_{p0.2}$ (MPa) | Ultimate tensile stress $R_m$ (MPa) | Strengthening coefficient $K$ (MPa) | Strain hardening exponent $n$ | Lankford coefficient $r$ |
|---|---|---|---|---|---|
| 0° | 182.1 | 322.5 | 549.3 | 0.214 | 1.751 |
| 45° | 196 | 336.2 | 564.9 | 0.205 | 1.124 |
| 90° | 190 | 320.9 | 541.6 | 0.209 | 1.846 |
| Average value | 191.2 | 328.95 | 555.17 | 0.208 | 1.461 |

The values of the strain hardening parameters, i.e. the strength coefficient $K$ and the strain hardening exponent $n$, were determined by approximation of the experimental stress-strain curve by the Hollomon power law relationship:

$$\sigma_p = K \cdot \varphi_i^n \tag{1}$$

where $\sigma_p$ is the yield stress and $\varphi_i$ is equivalent plastic strain.

Although the values of the determination coefficient R2 of the experimental data in equation (1) were above 0.985, it is well known that Hollomon equation does not fit accurately the experimental data in the range of small amounts of plastic deformations. So, in the numerical models, the real strain hardening curve has been included. Figure 2 shows exemplary stress-strain relations. It is observed in this figure that the stress-strain relation curves for rolling direction (0°) and transverse direction (90°) overlap.
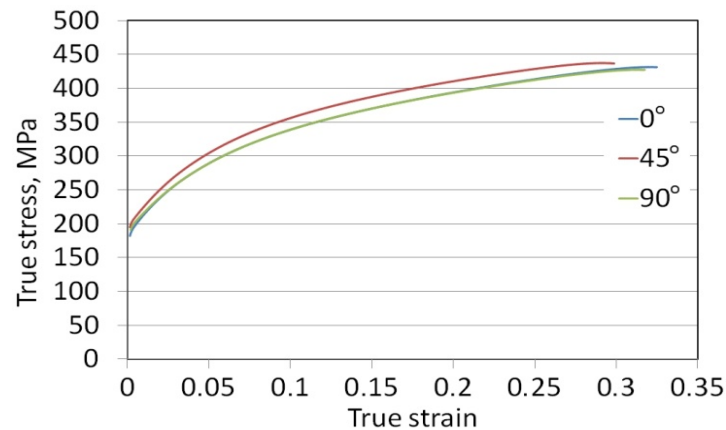
**Figure 2.** Exemplary true stress-true strain curves for the DC04 sheet.

## 3. Numerical modelling

The numerical modelling of Vickers pyramid indentation test has been performed in FE-based ABAQUS software. 3D model of the indenter and workpiece were analysed. Due to the plane symmetry of the indentation process, a quarter model with appropriate symmetric boundary conditions was used(Figure 3). The hardness of diamond indenter is much greater that the hardness of the workpiece. So, the geometry of the indenter is represented by plane that was meshed using rigid elements. The maximum displacement of the indenter $h_{max}$ into workpiece was set to four values: 0.0025 mm, 0.005 mm, 0.075 mm and 0.1 mm.

To select the appropriate element size, especially in the area of contact of the indenter with workpiece, the mesh sensitivity analysis was conducted. The indenter surface has been meshed by 8375 4-node 3-D bilinear rigid quadrilateral elements since ABAQUS allows only these options for rigid elements. All rotations and displacements of the indenter surface in X and Y direction (Figure 3) were fixed, while the displacement of nodes laying on the base of the sheet metal model were fixed only in Y direction. Furthermore, the displacement of nodes laying on the YZ plane and XY plane were fixed in X and Z direction respectively. The workpiece was modelled with a 46202 8-node linear brick with the capability of representing large deformations and material and geometrical non-linearity. A finer mesh at the contact region and a gradually coarser mesh further away from the contact area were used to reduce the computational time and increase the computational accuracy.
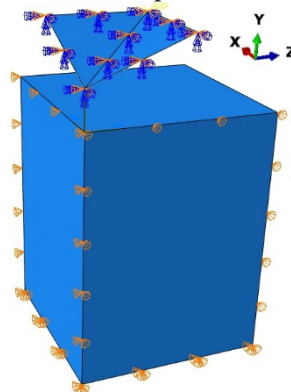


**Figure 3**. Finite element mesh in the numerical simulation.

The workpiece material is treated as elastic-plastic. The elastic behaviour of sheet material has been specified using the following parameters: Young's modulus $E = 210$ GPa and Poisson's ratio $v = 0.3$. The plastic behaviour of the steel sheet was described by the Hill(1948) [23] quadratic yield function, commonly used to describe the yielding of anisotropic steel sheets [24].

The Hill(1948) formulation is an extension of the isotropic von Mises function, and can be expressed in terms of rectangular Cartesian stress components as:

$$\bar{\sigma} = \sqrt{\left(F(\sigma_{22} - \sigma_{33})^2 + G(\sigma_{33} - \sigma_{11})^2 + H(\sigma_{11} - \sigma_{22})^2 + 2L\sigma_{23}^2 + 2M\sigma_{31}^2 + 2N\sigma_{12}^2\right)} \qquad (2)$$

where $\bar{\sigma}$ is the equivalent stress, and indices 1, 2, 3 represent the rolling, transverse and normal directions to the sheet surface. Constants F, G, H, L, M and N define the anisotropy state of material and they are determined based on the Lankford's coefficients and yield stresses in specific directions of the sheet metal according to the formulas which have been described, for example in [25].

The contact properties have been described by Coulomb friction model using the following friction coefficients: 0.1, 0.2 and 0.3. Moreover, the frictionless conditions were assumed for the purpose of studying only the effect of material anisotropy on the pile-up effect. ABAQUS integration implicit code has been successfully applied for the static simulation of the indentation process. To solve geometrical and material non-linear problem, the incremental-iterative Newton-Raphson method is used.

## 4. Results and discussion

The pile-up height values were measured along the rolling direction (RD) and transverse (TD) to the rolling direction starting from the impression tip (Figure 4). The variations of the displacement of the nodes laying in the RD (Figure 5) and TD directions may be divided into three areas: (i) straight line corresponded to the edge of indenter, (ii) pile-up effect and (iii) the horizontal straight line where the material is not subjected to the plastic deformation.
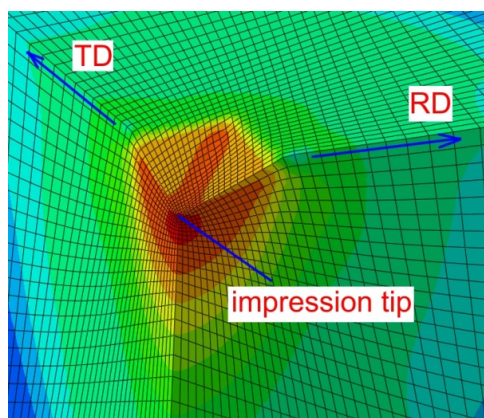


**Figure 4**. Schematic of measurement of the pile-up height in two orthogonal directions
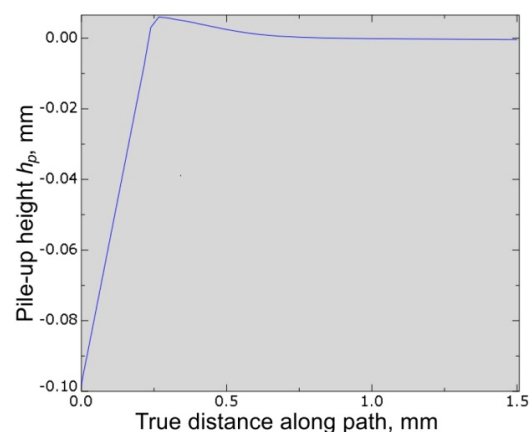


**Figure 5**. Exemplary variation of the pile-up height along the RD ($\mu = 0.3$, $h_{max} = 0.1$ mm)

The increase in the friction coefficient $\mu$ value causes a reduction of the pile-up height $h_p$ for all analysed impression depths (Figure 6). In the case of frictionless conditions, a pile-up height increases nearly linear with the maximum displacement of the indenter $h_{max}$. For higher values of the coefficient of friction, the higher the value of the indenter displacement, the slower is the increase in the pile-up height value.

In the RD direction, greater values of pile-up height were observed (Figure 6a) compared to the TD direction (Figure 6b). This phenomenon may be linked to the differences in the values of Lankford's coefficients of the material and in the yield stress. The value of the yield stress in the RD direction is lower than in the TD, thus the material is more susceptible to flow in the RD direction.
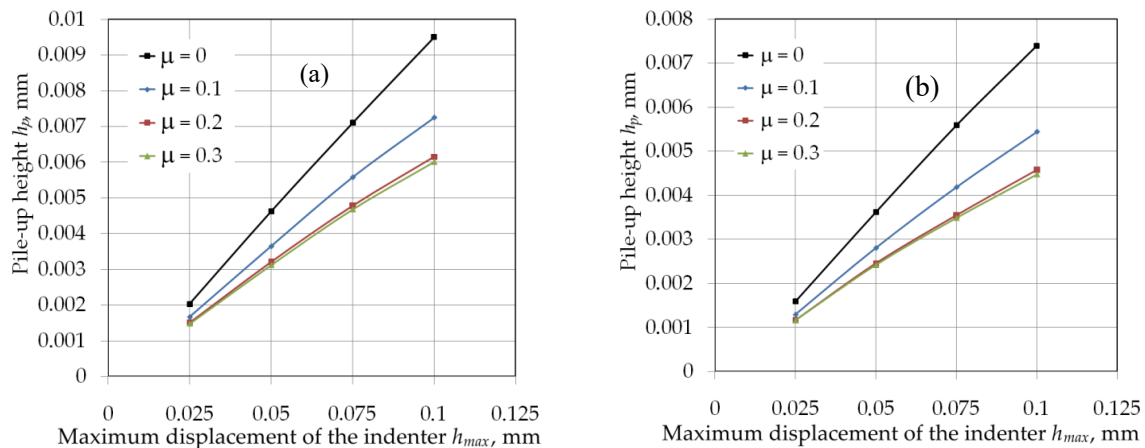
**Figure 6**. Variation of the pile-up height along (a) rolling direction (b) transverse direction

The difference in the pile-up height measured at RD and TD decreases with the reduction of the maximum displacement of the indenter $h_{max}$ (Figure 7). A similar effect has been observed for the indentation depths $h_{max}$ = 0.05 mm and 0.075 mm (not presented in Figure 7). Anisotropic pile-ups have important effects on the diagonal dimensions of the impression and evaluation of the contact area from indentation load–displacement curves. Thus, the area is always underestimated while the hardness is always overestimated. Moreover, elastic properties of the anisotropic material cause the non-uniform stress recovery of the material near the pile-up.
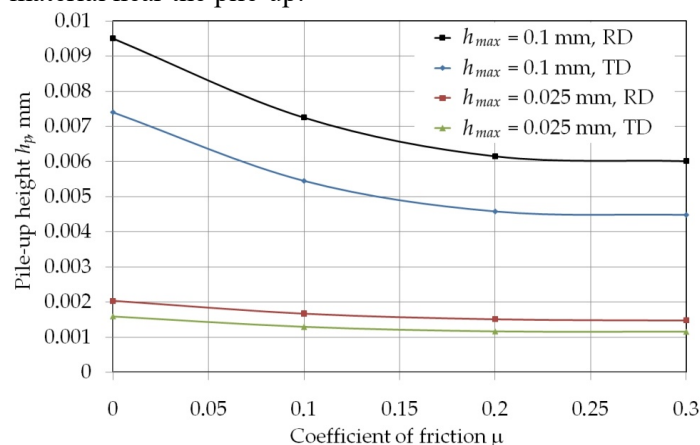


**Figure 7**. Effect of the friction coefficient on the pile-up height

## 5. Conclusions
In this paper, the frictional conditions and anisotropic material properties were addressed through determining a pile-up height. The results of 3D numerical simulations of the indentation that have been accounted for the material anisotropy and real strain hardening properties, allow to draw the following conclusions:
- In the case of anisotropic elastic-plastic sheets exhibiting plane anisotropy, the flow of the material around the tip, and formation of the pile-up around the tip, is non-uniform.
- The height, and as a consequence, the volume of the pile-up around the indenter depends on the friction coefficient value and the maximum indentation depth.
- The difference in the pile-up height measured at RD and TD, decreases with the reduction of the maximum displacement of the indenter $h_{max}$.

- The friction between indenter and specimen can significantly affect the contact area and piling-up or sinking-in which is in good agreement with the results of comprehensive computations conducted by Guo et al. [26].

**Acknowledgement**

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