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NUMERICAL ANALYSIS OF FRICTION AND WEAR IN STEEL UNDER ABRASION OF A HARD PARTICLE

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Abstract. *In several manufacturing processes, such as rolling and forging, tool wear and friction between tool and workpiece are factors that affect important characteristics of the final products, like geometry and surface finishing. Thus, it is interesting to investigate in which conditions tool wear is favored and to anticipate the tangential loads that can occur in metal-metal contact. The techniques applied in this type of study include the finite element analysis, which provides the calculation of contact stress distribution, and allows the investigation of a reasonable group of variables, such as geometry of the parts in contact and loads. This work intends to present two-dimensional finite element models that simulate the sliding of a rigid pin over a softer elastic-plastic surface. In each of the analyses, displacements are imposed to the pin, such that it first indents and then slides over the workpiece with constant penetration depth. Displacement of workpiece material is considered throughout the simulations. The main input variable of the analyses is the penetration depth, which influences several outputs of the model, like contact stress distributions and normal and tangential loads that arise from the pre-imposed displacements. Therefore, it is possible to calculate the ratio between tangential and normal loads, commonly defined as friction coefficient. Results indicate a transition in surface behavior as the penetration depths increase.*

Keywords: *Finite element, Friction, Wear, Indentation, Abrasion*

1. INTRODUCTION

In manufacturing processes, such as rolling and forging, tool wear and friction between tool and workpiece are factors that affect important characteristics of final products, like geometry and surface finishing. Despite being harder than the part being formed, the tool is prone to wear, due to impurities in its constituting material and asperities (roughness) of both surfaces in contact. In this sense, one of the main techniques that can be applied to study tool wear is finite element analysis, which allows the evaluation of stress distributions in contact interfaces and propitiates the investigation of a reasonable group of variables, including component geometries and loads (Jhavar, Paul, and Jain, 2013).

Among the possible types of damage in forming tools, wear is one of the most important, because of the direct action in a manufacturing process. The mass loss and debris formation are caused by the contact between tool and workpiece, which are influenced by the mechanical properties of the body and counter-body, especially the hardness, the contact area, and the interfacial and ambient conditions (Hutchings, 1992). In addition, a considerable geometric variation of tools due to wear is observed when hard particles scratch them – a type of wear known as abrasion. According to (Zum Gahr, 1998), the main abrasive mechanisms are: (i-) ploughing or mild regime, in which the plastic deformation is prevailing, leading to prow and pile-up formations without considerable material removal; (ii-) cutting or severe regime, in which chips and grooves appear and result in volume loss; and (iii-) wedge formation, that is a transition step between ploughing and cutting. Considering the ideal case represented by a single abrasive pass, there are several parameters which can affect the wear severity, such as the shape, size and attack angle of the abrasive particle.

Other variable analyzed in terms of abrasion is the tangential to normal force ratio, often referred to as Coulomb friction coefficient. An example of this analysis was conducted in the study developed by Hokkirigawa and Kato (1988), focused on characterization of abrasion mechanisms. In that work, relationships involving the friction coefficient, degree of penetration and hardness of the indented body were discussed, as well as their effects on the ploughing-cutting transitions by means of maps arising from experimental tests.

Abrasive wear can also be associated with the machining processes as orthogonal cutting, for instance. For these analyses, the literature approach takes into account the stress triaxiality effect in the strain to fracture for ductile failure nucleation (Bao and Wierzbicki, 2004). In this case, stress triaxiality is defined as the negative ratio between equivalent hydrostatic pressure and von Mises equivalent stress. Therefore, stress and strain fields occurring in forming processes can be used to calculate both parameters and, thus, to evaluate different damage conditions of the tool material and, consequently, abrasive wear considerations.

Based on this background, the present paper aims to couple damage mechanics and wear, by analysis of how the stress state influence the wear damage due the occurrence of different abrasion mechanisms. The study proposed here is still preliminary, developed by means of a simplified numerical model using finite element method (FEM), but intends to add a contribution to a field, based on an analysis not broadly addressed by other authors.

2. NUMERICAL MODEL

Two-dimensional finite element models were proposed, which simulate an indentation with three different penetration depths (0.3, 0.5 and 0.8 mm), followed by the sliding of a semi-circular pin over a slab. Since plane strain simplification was assumed, the proposed model in fact represents the center region of the contact between a cylinder and a brick. For each simulation, the horizontal displacement imposed in the sliding phase is equal to 1 mm and the depth of penetration is kept constant throughout the solution. The three models have the same characteristics in terms of geometry and material: the pin has a radius of 1.58 mm and the slab is modelled with 15 mm of depth and 50 mm of length. The pin is considered rigid and the slab has elastic-plastic behavior, with properties of a 2024-T351 aluminum alloy, presented by Bao and Wierzbicki (2004) and shown in Table 1 and Figure 1.

Table 1. Physical and Mechanical Properties of 2024-T351 alloy

Density (kg/m³)	2,780
Elastic Modulus (GPa)	73.1
Poisson ratio	0.33

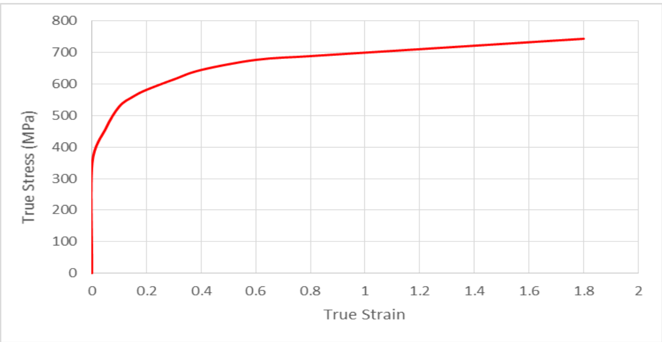

Figure 1. Stress-strain curve for the aluminum alloy considered as the slab material (adapted from Bao and Wierzbicki, 2004)

Solution was conducted in Abaqus/Explicit, version 6.12. The choice of an explicit solution was made considering the intense deformation of the slab expected in the scratching, which would lead to numerical instabilities and difficulties in convergence. The pin was meshed with 1,448 elements, while 92,150 elements were used in the slab. For both parts, 4-node quadrilateral elements were selected, and adaptive remeshing was applied to the slab, maintaining mesh quality during formation of prows and avoiding instabilities that could arise if elements deformed excessively. Because of the plane strain assumption, no material deformation outside the plane represented in the numerical model is allowed. Nodes at the base of the slab were constrained in all directions and interactions between pin and slab were considered frictionless, as the friction coefficient is one of the outputs of the simulations. Figure 2 summarizes the numerical model.

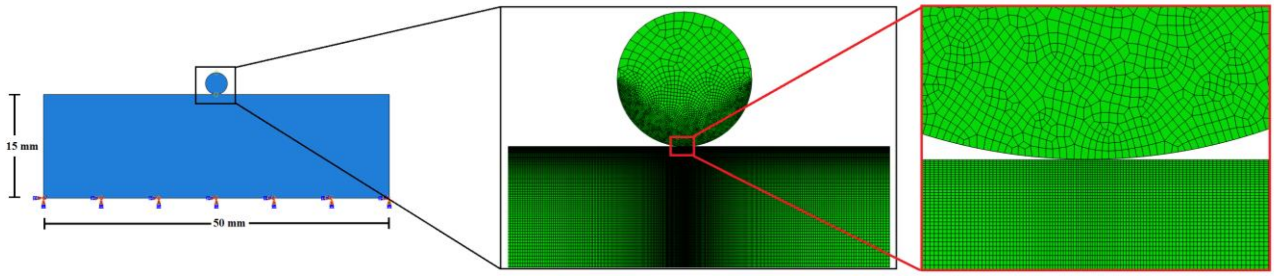

Figure 2. Numerical model developed for the study. In detail, finite-element mesh of pin and slab

3. RESULTS

Figure 3 presents the evolution of Coulomb friction coefficient (COF) with scratch length for each penetration depth. In all cases, it can be seen that the COF increases as the indenter scratches the slab, because the amount of material accumulated in front of the indenter becomes larger. Although not verified in the simulations, there seems to be a tendency for stabilization of COF values with further scratching, as the increase rate of this variable decreases with the scratch distance. For higher indentation depths, this accumulation of material in the prow is more pronounced, resulting in larger COFs.

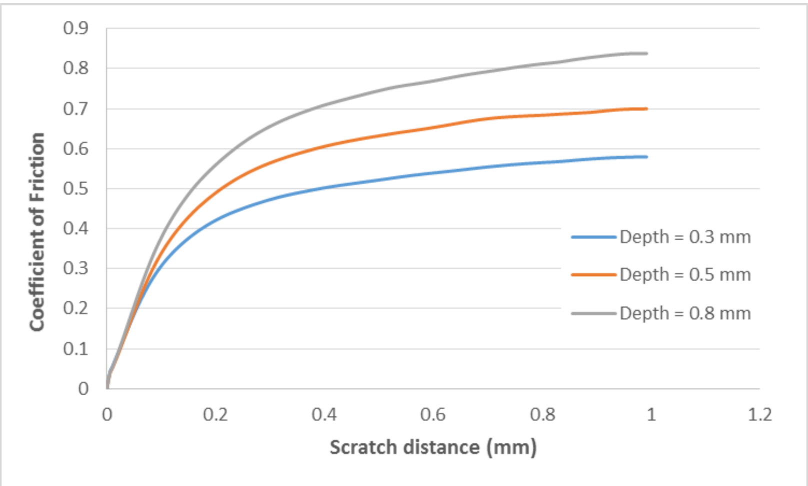

Figure 3. Evolution of coefficient of friction for each indentation depth

The COFs obtained from the numerical analyses are supposed to be related to the wear regime verified in the simulations. Among other authors, Hokkirigawa and Kato (1988) showed that larger values of friction coefficient for the same indenter geometry and material are associated with more severe wear regimes. Therefore, there is a direct relation between COF and abrasion mechanisms, which was investigated in this study. Bao and Wierzbicki (2004) conducted a series of upsetting tests, which showed that aluminum alloy specimens failed by shear fracture upon compression, a result that is expected, as no void formation can occur in compression. Thus, as the material ahead of the indenter is in compression in the current study, with high negative triaxialities being observed, it is expected that failure also occurs by shear fracture. In this sense, results presented in Figure 4 show that high values of maximum shear stress develop in the prow in all cases, more intense and concentrated in a smaller area for deeper penetrations of the indenter. Such result indicates more tendency of cutting for larger indentation depths, leading to a more severe wear regime as more material is cut away from the slab. As the depth of indentation and cutting is directly related to the COF, as shown in Figure 3 and by Hokkirigawa and Kato (1988), a relation between wear regime and friction coefficient can be established, with higher COFs being associated with more severe wear regimes.

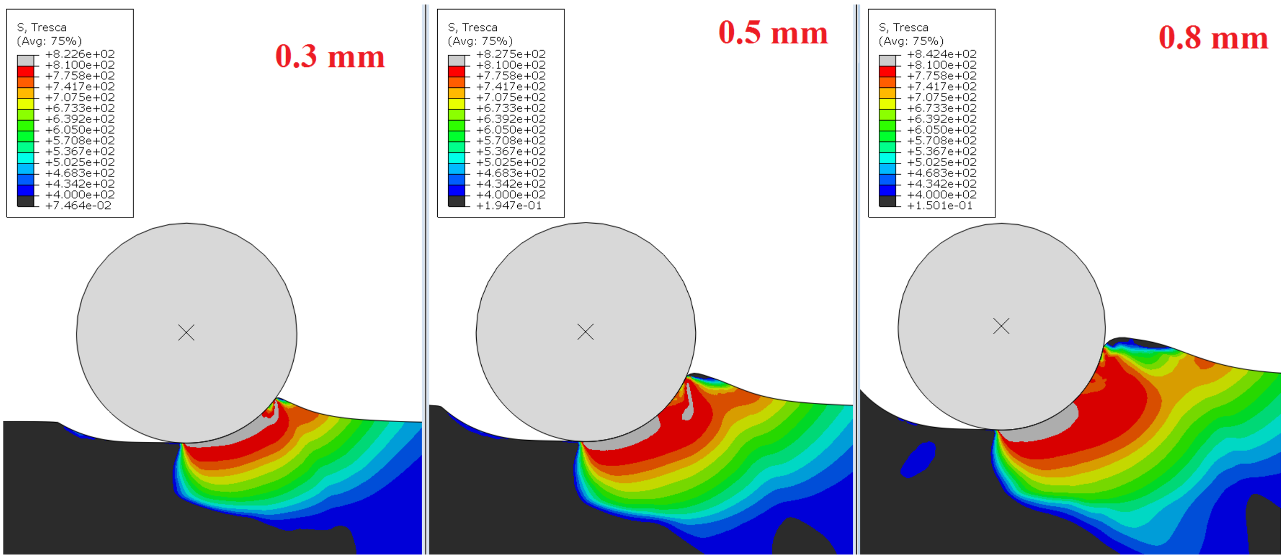

Figure 4. Distribution of maximum shear stresses in the region of indentation for the cases studied (values in MPa)

For the three cases, it is also possible to verify a plastic, tensile-stressed region behind the indenter. The combined action of the local plasticity and positive triaxiality makes this region prone to the occurrence of ductile failure, what is verified in the tail of the indenter in actual scratch tests. This result can also be confirmed by substitution of the stress triaxiality and equivalent plastic strain in the map proposed by Bao and Wierzbicki (2004) for the same material used in this work, as shown in Figure 5. Black points represent the surface nodes displayed in color in the contour shown at the left. All the points are above the line drawn through the blue points, indicating a tendency to observe tensile ductile failure.

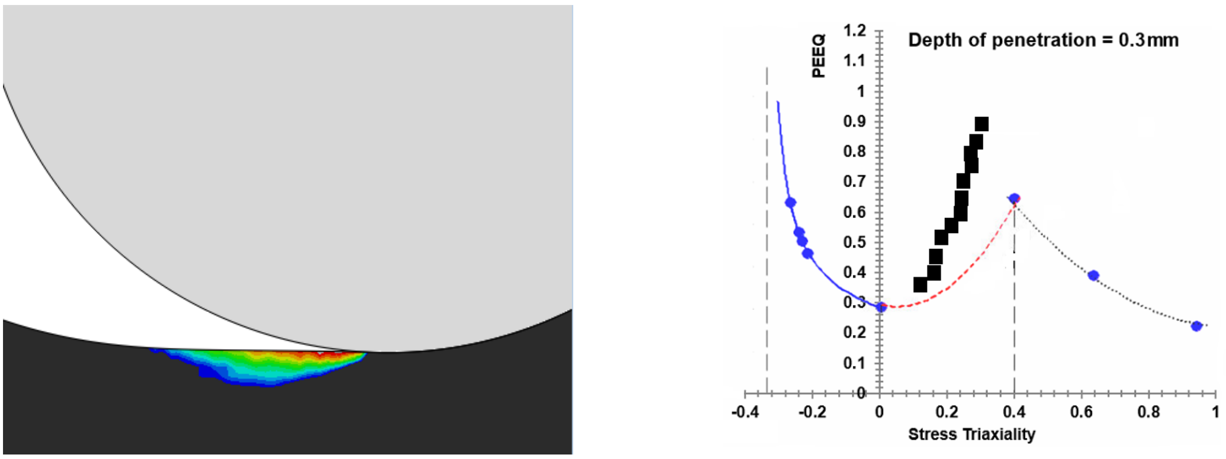

Figure 5. Region of positive triaxialities behind the indenter (left, in color) and distribution of surface nodes in triaxiality x plastic strain map (right, adapted from Bao and Wierzbicki, 2004)

In terms of plastic strain, simulations indicated that values for larger penetration depths are higher than shallow ones. Moreover, maximum values tend to move from the tip of the prow towards the region right below the center of the indenter for deeper penetrations. Both patterns are related with cutting of material during scratching, as the plastic strain in the surface below the indenter can be raised to a point when more energy is needed to further deform the material than to nucleate a new surface – what eventually leads to local failure in the slab.

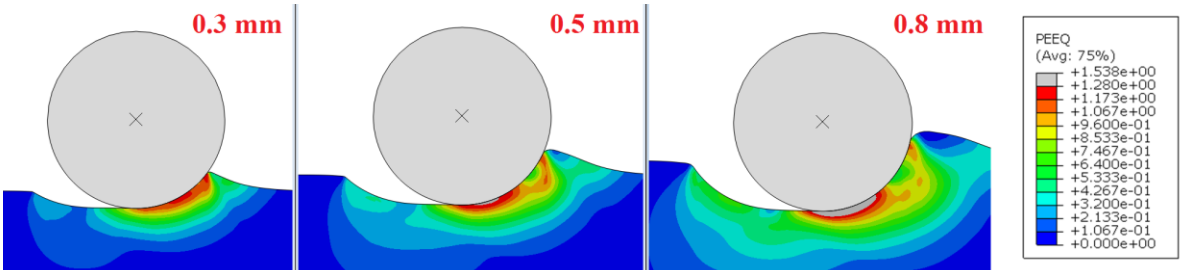

Figure 6. Distribution of equivalent plastic strains in the region of indentation for the cases studied

4. CONCLUSIONS

The current work presented a first attempt to relate damage mechanics and wear, by means of 2D finite element simulations of indentation and scratching of an aluminum alloy by a rigid indenter. Main conclusions drawn are:

- Values of coefficient of friction gradually raise as the indenter scratches the slab, with COF tending to different values as the scratch is developed.
- Higher values of COF were obtained for larger indentation depths, and are directly related to more severe wear regimes, as shear stresses and plastic strains are higher in the base prow for deeper scratches, indicating possibility of cutting by local shear.
- In opposition to the compressive behavior of the prow, the region just behind the indenter develop mainly tensile stresses, which are responsible for the nucleation of defects observed in actual scratch tests.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Bao, Y., and Wierzbicki, T. 2004. “On Fracture Locus in the Equivalent Strain and Stress Triaxiality Space.” *International Journal of Mechanical Sciences* 46(1): 81–98.

Hokkirigawa, K., and Kato, K.. 1988. “An Experimental and Theoretical Investigation of Ploughing, Cutting and Wedge Formation during Abrasive Wear.” *Tribology International* 21(1): 51–57.

Hutchings, I M. 1992. *Tribology: Friction and Wear of Engineering Materials*. Edward Arnold.

Jhavar, S., C. P. Paul, and Jain, N. K.. 2013. “Causes of Failure and Repairing Options for Dies and Molds: A Review.” *Engineering Failure Analysis* 34: 519–35.

Zum Gahr, K. H. 1998. “Wear by Hard Particles.” *Tribology International* 31(10): 587–96.

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