A Numerical Study of Abrasive Wear in Tillage Tools due to Soil-Tool Interaction

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Abstract

Abrasive wear of tillage tools by hard soil particles is a major concern in the agricultural industry. Previous efforts to understand the effect that various factors such as the soil composition and the tool material have on tool wear have been primarily experimental in nature. Since a large number of factors influence tool wear during tilling operations, it is impractical to expect the experimental studies to be exhaustive. The finite element method offers an additional tool that can be used in conjunction with experimental studies to further the understanding of wear in tillage tools. In this paper, preliminary results from a numerical study undertaken to study abrasive wear of tillage tools by soil particles are presented. The wear process is modeled as a single sand particle scratching at a prescribed speed on the surface of a tillage tool. The material loss from the tool surface during scratching is estimated using the classical ploughing theory and the concept of the material removal factor. The numerical studies indicate that the material removal factor ranges from 0.55 to 0.7 for sand particles of different sizes and for different indentation depths.

In turn, this suggests that the wear of tillage tools is due to a combination of ploughing and cutting mechanisms with cutting being more dominant than ploughing.

Keywords: finite element method, soil-tool interaction, Abaqus/Explicit, abrasive wear, classical ploughing theory.

1. Introduction

In the agricultural industry, wear of tillage tools is a major concern as it leads to loss of production and an increase in equipment and operational costs (Nalbant, 2011). Experimental work carried out by various researchers to understand the mechanisms and factors governing the wear of tillage tools indicate that the primary wear mechanism in these tools is abrasion between the harder soil particles and the softer tool surface (Bayhan, 2006). In general, tool wear depends on the composition of the soil such as the moisture content, soil particle size and shape, and hardness of the particles (Er, 2006; Horvat, 2008). The major constituents in a typical soil are slime, clay, sand, and gravel. Of these, gravel and sand have been found to be the most responsible for wear losses in tillage tools.

In this work, the abrasive wear of tillage tools due to soil particles during tilling operations is studied numerically by modeling the soil-tool interaction as the scratching of the tool surface by a single sand particle traveling at a prescribed speed. The purpose of the study is to understand the effect of the various parameters such as the particle speed, particle size, scratch depth etc. have on the wear loss. The numerical modeling is carried out using Abaqus/Explicit (v6.9-EF1). The particle shape is taken to be cylindrical with a hemispherical tip of specified radius. The effect of shape on wear losses is not considered in the present work although the shape of the particle can influence wear.

2. The Finite Element Model

The tool is taken to be a rectangular block of size 3.0 mm X 1.2 mm X 1.2 mm and the sand particle (as mentioned in the previous section) is assumed to be cylindrical with a hemispherical tip in shape and the (see Figure 1). These dimensions are similar to those used by Fang et al. (Fang, 2004). The tool material considered is DIN 30MnB5 steel. Since the sand particle is much harder than the steel, the sand particle is taken to be rigid. Numerical simulations are also carried out by treating the sand particle as elastic for one particular particle size. The comparisons between the two sets of results validate the assumption of a rigid sand particle. For this reason, for the rest of this paper, the sand particle is treated as a rigid body.

The rectangular block made of DIN 30MnB5 steel is fixed at the bottom, and the dimensions are chosen large enough so that the faces parallel to the scratch direction do not influence the stresses and displacements in the vicinity of the scratch. The mechanical behavior of steel during the scratch process was taken to be elasto-plastic with linear hardening. The specific properties used are shown in Table 1.

Young's Modulus, *E*	**210 GPa**
Poisson's Ratio, n	**0.3**
Initial Yield Stress	**510 MPa**
Yield Stress at 0.35 Plastic Strain	**710 MPa**
Density, r	**7860 kg/m^3**

Table 1: Material Properties used for DIN 30MnB5 steel.

The scratch process consists of three steps. In the first step, the sand particle makes an indentation of a specified depth in the steel block. In the second step, the particle is given a horizontal speed so that a scratch of a specified depth and length is made in the block. In the third step, the indenter is withdrawn gradually so that elastic recovery takes place in the block. Due to the symmetry present in the model, only half of the sand particle and block system is modeled with symmetry boundary conditions along the symmetry plane (see Figure 1). Furthermore, the rigid sand particle is modeled using discrete rigid elements; whereas, the rectangular block is discretized using C3D8R elements. A biased mesh is used for the block so that a fine mesh is present in the scratch region and a coarse mesh away from the scratch region. The total number of elements used for the block is approximately 90000. The contact between the sand particle and the block is assumed to be frictionless. Our simulations indicate that friction does not have a significant effect on the numerical results, an observation consistent with that of Fang et al., 2005 (Fang, 2005). Furthermore, adaptive meshing is enabled so that the severely deformed area is automatically remeshed frequently. The scratch length is taken to be 1.2 mm. The sand particle travels this distance at a speed of 1.2 m/s which is typical of tractor speeds during tilling operations.

In order to investigate the effect of the indentation depth and the sand particle size on tool wear, different spherical tip diameters and different indentation depths are considered. Specifically, spherical tip diameters of 500 mm, 600 mm, 750 mm, 900 mm, and 1000 mm are considered. For each of these cases, wear losses due to four different indentation depths, namely, 50 mm, 60 mm, 75 mm, and 100 mm, are computed.

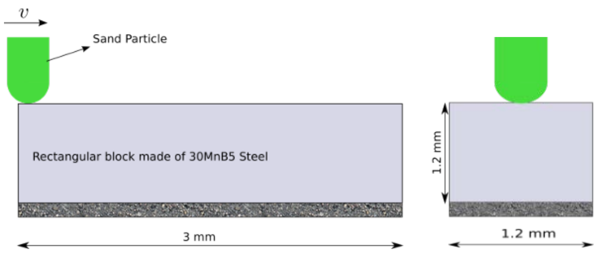

Figure 1. A 2-D schematic of the scratching of the tool surface by a sand particle: (left). side view, (right). front view.

3. Wear Loss Calculations

In general, the wear loss in tillage tools is due to microploughing, microcutting and microfatigue. Since the focus of this work is only on a single sand particle scratching in a single-pass, the microfatigue mechanism is not considered. In addition, the microcutting mechanism is considerably more complex to model due to various issues involved in contact conditions, material separation laws, etc. For materials that exhibit significant plastic deformation, microploughing is considered to be an important mechanism of wear loss (Fang, 2005). For these reasons, we consider only the microploughing mechanism where there is no material separation, and the material under and around the sand particle deforms plastically and is pushed to the sides to form a groove. The wear loss calculations are accomplished by using the concept of the material removal factor f_{ab} defined as (Gahr, 1987; Fang, 2004).

$$f_{ab} = 1 - \frac{A_{p1} + A_{p2}}{A_g}$$

where A_{p1} and A_{p2} are the areas of pile-up on the left and right sides of the groove. The total amount of material displaced from the groove is denoted by A_g . We point out that a similar approach has been taken by Fang et al. in a series of papers on two-body wear (Fang, 2001, 2004 and 2005).

When the factor f_{ab} equals zero, the pile-up area is the same as the groove area and therefore, the primary mechanism of wear is completely microploughing. On the other hand, when f_{ab} equals unity, the pile-up area is zero, and therefore, the primary mechanism of wear is microcutting. For values of f_{ab} in between zero and unity, both the mechanisms are present with higher values of f_{ab} indicating more propensity towards microcutting. Since material separation is not included in the present work, a non-zero value of f_{ab} can be interpreted to mean that a fraction of the displaced material by plastic deformation is ahead of the sand particle, and it is this mass that eventually is separated from the rest of the tillage tool to form wear debris.

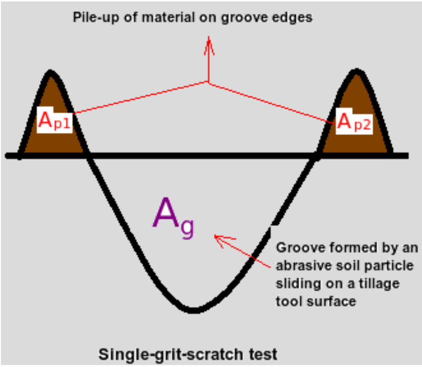

Figure 2. A sketch of a cross-section during scratching of a surface by an abrasive particle.

In the next section, we use the aforementioned definition of the material removal factor to calculate wear losses in tillage tools due to scratching by a single sand particle. Results from our numerical studies on the effect of particle diameter and indentation depth on the material removal factor are presented.

4. Results

The wear loss per unit scratch length is typically calculated by multiplying the material removal factor f_{ab} by the groove area A_g (Gahr, 1987). For the numerical results presented in this section, we use this approach to calculate the wear losses in tillage tools. Our results indicate that the except for a short initial period of the scratch, this factor is essentially constant for the complete length of the scratch.

In Figure 3, the snapshots of a scratch simulation at four different times are shown. The first shows the contact between the particle and the surface being established. The second snapshot shows the particle-block system at the end of the indentation step. The third snapshot shows the system at the end of the scratching process. Finally, the fourth snapshot shows the system after the loading is removed.

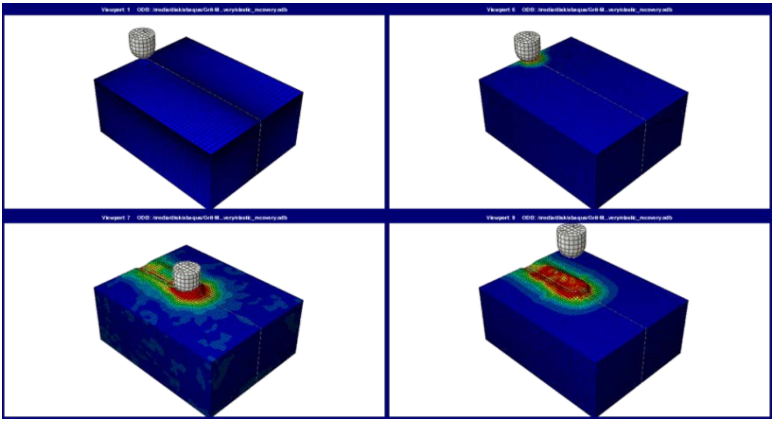

Figure 3. Finite element modeling of the scratching of the steel surface by a sand particle: (a). initial indentation to establish contact between the block and the particle, (b). end of the indentation step and beginning of the scratching process, (c). end of the scratching process and (d). unloading of the block.

The groove formed by the scratch is shown in Figure 4 from two different angles. The formation of the ridges along the sides of the groove due to severe plastic deformation is clearly evident in this figure.

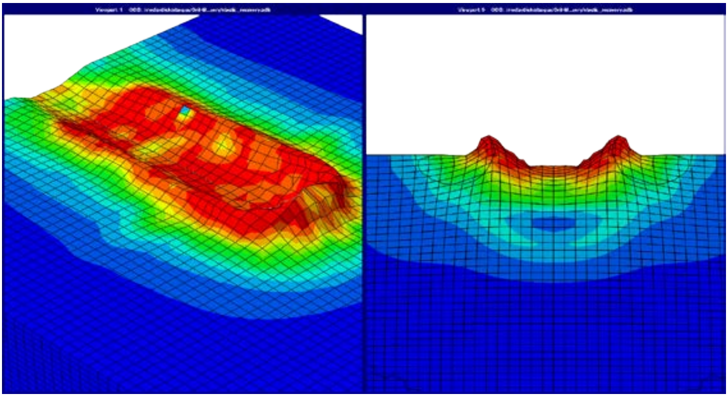

Figure 4. Ridge formation along the sides of the groove due to scratching of the steel surface by a sand particle.

The groove area A_g and the ridge areas (A_{p1} and A_{p2}) are computed from the contours of the groove and ridges using the nodal displacements. Our calculations show that these areas vary very little along the groove once the particle is sufficiently away from the boundary where the initial contact between the particle and the steel surface is established. For this reason, the material removal factor f_{ab} and the groove area are assumed to be constants factors along the scratch length. The dependence of f_{ab} on the sand particle diameter when the indentation depth is 10% of the diameter is shown in Figure 5. In Figure 6, the variation of f_{ab} with indentation depth for five different values of the sand particle diameter is shown. Although Figure 5 shows an increase in the value of f_{ab} with the sand particle diameter, Figure 6 shows that, for some ratios of the indentation depth to particle diameter, the variation of f_{ab} with the indentation depth may or may not be monotonically increasing or decreasing. However, our results indicate that the value of f_{ab} lies in the range of 0.55 to

0.7 indicating that the dominant mechanism of wear may be cutting and less ploughing. These values are consistent with the experimental results which indicate that f_{ab} is typically around 0.7.

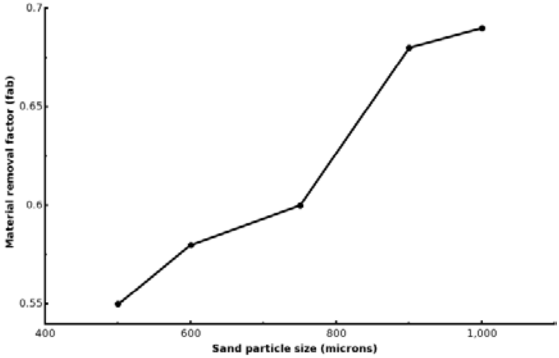

Figure 5. The variation of the material removal factor f_{ab} with the sand particle diameter when the indentation depth is 10% of the particle diameter.

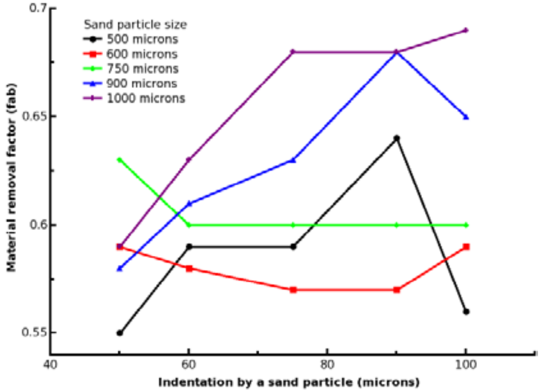

Figure 6. The variation of the material removal factor f_{ab} with the indentation depth for five different sand particle sizes.

The results produced in Figures 5 and 6 are for soil particle sizes ranging from 500 microns to 1000 microns. Since a typical soil is not homogeneous and consists of particles of sizes ranging from a few microns to a few thousand microns, further numerical investigations need to be carried out to understand the influence of the larger soil particles such as gravel.

5. Conclusions

The numerical results presented in this paper suggest that both the indentation depth and the soil particle size influence the wear behavior of tillage tools due to abrasion by soil. Based on the values of the material removal factor obtained in the present work, it can be concluded that the abrasive wear is due to both ploughing and cutting mechanisms with the latter being slightly more dominant than the former. However, there does not appear to be a clear pattern in the dependence of the material removal factor on the indentation depth or particle size. This is in contrast to the results reported in the literature that suggest that wear losses initially increase and reach a constant value as the particle size is increased. Additional numerical studies with particle sizes (different from those considered in this study) are currently being carried out to verify this claim.

6. Bibliography

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