NUMERICAL AND EXPERIMENTAL ANALYSIS OF THE ABRASIVE WEAR OF TWO STEELS USED IN TILLAGE TOOLS
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ANÁLISIS NUMÉRICO Y EXPERIMENTAL DEL DESGASTE ABRASIVO DE DOS ACEROS UTILIZADOS EN APEROS DE LABRANZA

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ABSTRACT
This study combines computer simulation using the Discrete Element Method (DEM) with field experiments to assess the resistance to abrasive wear of AISI 1010 and AISI C1064 steels in tillage tools. It was found that the wear on AISI 1010 was over 50% higher than on AISI C1064. The DEM model accurately predicted wear $(e = 0.005g, R^2 = 99.8\%)$*, regardless of operational conditions and steel characteristics. The mean absolute errors of the simulation compared to field tests were 0.01937 g for AISI C1064 and 0.08619 g for AISI 1010.*

RESUMEN
Este estudio combina simulación computacional con el Método de Elementos Discretos (DEM) y experimentos de campo para evaluar la resistencia al desgaste abrasivo de los aceros AISI 1010 y AISI C1064 en herramientas de labranza. Se encontró que el desgaste en AISI 1010 fue más del 50% mayor que en AISI C1064. El modelo DEM predijo con precisión el desgaste $(e = 0.005g, R^2 = 99.8\%)$*, independientemente de las condiciones operativas y características de los aceros. Los errores absolutos medios de la simulación respecto a las pruebas de campo fueron 0.01937 g para AISI C1064 y 0.08619 g para AISI 1010.*

INTRODUCTION
The development of agriculture worldwide has been achieved due to different characteristics, among which stand out the modification and creation of some tillage tools based on designs that guarantee a higher quality of work, the reduction of energy consumption and the damage to the soil that brings with it the loss of fertility and low levels of agricultural production. In Cuba, among the soils of greatest economic importance are those classified as Yellow Ferrite, according to the New Version of the Genetic Classification of Soils in Cuba *(Hernández et al., 2015)* and as Ultrasol, according to the USDA Soil Taxonomy *(Soil Survey Staff, 2010).* In most cases, these soils are used for the production of tobacco, vegetables, grains, as well as roots and tubers, and for the development of livestock. They are considered to be highly abrasive soils, i.e. they cause considerable wear of tillage tools, due to the presence of iron and quartz particles, whose ratio (SiO_2/F_2O_3) is predominant, reaching values that oscillate between 10 and 15%, constituents that justify their abrasive character. These particles lead to abrasive wear, which increases energy consumption and makes soil preparation, conditioning and cultivation more expensive *(Herrera et al., 2010).*

This phenomenon has been widely studied due to the large losses caused in the mechanised tools used in the different tasks of agricultural processes. It is generally quantified by measuring the loss of material, and currently experimental *(Pérez et al., 2010; López, 2011; González, 2012; Jia y Zhou, 2012; Rojek, 2014; Singh et al., 2017; Obrad et al., 2018; Chen et al., 2018; Bedolla et al., 2018)* and numerical methods have been used for its study. Among the numerical ones, the Distinct or Discrete Element Method (DEM) has the most application for the study of abrasive wear *(Graff, 2010; Rojek, 2014; Perazzo et al., 2016; Hoormazdi et al., 2018; Chen et al., 2018; Ucgul et al., 2017, Graff, 2010, Bedolla et al., 2018; Montes, Herrera, López, Pérez, & Torres, 2023; Zolotarevskiy, Gallo, Pereira, & Barnett, 2022; Zhang, Fu, Ren, Liu, Lin, Zhang & Zhang, 2024).* The advantage of the latter over traditional methods is that it allows predicting the behaviour of a given phenomenon, and also decreases the time required for testing.

The models developed in DEM in the aforementioned research, for the simulation of problems related to geomaterials, take as input data the parameters related to the microstructure of these materials *(Graff, 2010; Rojek, 2014; Perazzo et al., 2016; Hoormazdi et al., 2018; Chen et al., 2018).* Microstructural parameters, as usual, can be estimated by simulation from macrostructural properties, which are determined by conventional tests performed in soil mechanics laboratories, or from tests performed directly in the field *(Pérez et al., 2010; López, 2011; Obrad et al., 2018; Bedolla et al., 2018).* The definition of one or the other microstructural parameter depends on the software to be used. Among the software suitable for DEM simulation is the Yet Another Dynamic Engine (YADE), a non-commercial software available as free software on the Internet that has been applied to the study of soil and its interaction with tillage tools.

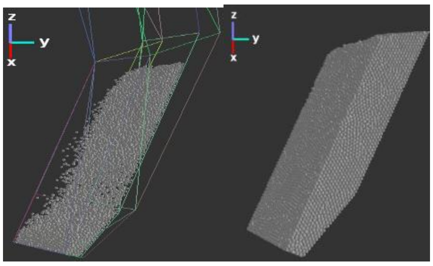
Based on the above, the aim of this paper is to determine the abrasive wear resistance of AISI 1010 and AISI C1064 steels used in tillage tools.

MATERIALS AND METHODS

Methodology for the simulation of the abrasive wear of tillage implement parts using the Discrete Element Method (DEM)

Development of the virtual method. For the simulation of abrasive wear under these conditions, a 3D virtual model was developed, which can be found in Sánchez, (2015). In it, the tilling process was idealised from the representation of a homogeneous soil block (1) with which the tools (2) interact; these tools have the same dimensions and geometries as those used in the experimental abrasive wear tests under operating or field conditions *(Sánchez et al., 2018)*. A soil block with the dimensions of $0.3m$ length, $0.12m$ height and $0.12m$ width was generated. It consisted of a total of 22942 randomly distributed spherical particles. The diameter of the particles ranged from 0.002 to $0.0007m$, and the density was $12235\ g/cm^3$ (Sánchez, 2015).

For the case of the tillage tools, 3D sketches with geometries equal to the tools were initially created to be used in the experimental trials and then a particle packing was generated inside the sketch. For this, a hexagonal assembly to gravity deposit the particles inside the sketches was used (Figure 1a). Finally, the lines from the sketches were removed and the virtual model of the tools with particles formed itself (Figure 1b). The rectangular tools were formed with a total of 19800 spherical particles of $0.0005m$ diameter.



a b

Fig. 1 - Process of elaboration of virtual tool.

a) Process of filling the virtual tool, b) virtual tool after its elaboration

Establishment of boundary conditions. The movement of the soil particles *(Sanchez, 2015)*, is limited in the normal direction of the lateral planes that delimit the block (3); but nevertheless the soil particles could move freely (translation and rotation) in all axes within the blocks. The tool (y-axis) was set to a velocity movement similar to that obtained in experiments under operational or field conditions. The rest of the directions were limited to the tool movement. The simulation was completed in 25 h of the tool in the soil block.

Procedure for DEM simulation of tillage tool wear. The DEM simulation of wear was performed using the method previously developed and validated in laboratory conditions by *Sanchez, (2015)*. Tool wear was simulated through mass or particle loss, in which the effect of the resulting force on the tool particles that originates from the resistance that the soil exerts on the tool during tillage was taken into account. Wear was quantified by integrating mass loss over time (Equation 1).

$$P_{mass} = \int \dot{P}_{mass}\, dt \tag{1}$$

In the simulation the tool was allowed to travel only a distance of $0.25m$ total length of the soil block to avoid the effect of the edge of the container back wall increasing soil pressures on the tools and causing unnecessary particle removal. In the model a function was programmed to impose a penalty to stop the movement of the tool when it completes the intended path. The simulation results were compared with those obtained in experimental tests under operational or field conditions.

Microstructural parameters of the soil and tool

These parameters used as input data for the simulation were estimated through the simulations of the direct and direct modified cuts trials. (Table 1).

Table 1

Parameters employed as input data for the simulation

Parameters	E_m	$\nu_m(-)$	$c_m\ (kPa)$	$\phi_m\ (°)$
Soil	1796.85	0.36	6	32.24
Parameters	E_{s-mm}	$\nu_m\ (-)$	$c_m\ (kPa)$	$\delta_{s-mm}\ (°)$
Interphase soil-metal				
AISI 1010	2.300	0.36	8.19	30.44
AISI C1064	2.800	0.36	8.19	30.44
Parameters	E_{mm}	$\nu_{mm}\ (-)$	C_N	C_T
AISI 1010	$1{\cdot}10^{+10}$	0.29	$1{\cdot}10^{+20}$	$1{\cdot}10^{+20}$
AISI C1064	$2.1{\cdot}10^{+10}$	0.29	$1{\cdot}10^{+20}$	$1{\cdot}10^{+20}$

Simulation of the wear and tear of tillage implements. The simulations were carried out on a desktop computer with the following characteristics: Processor: Intel Pentium, Hard Disk: 250 GB, RAM: 4 GB and three USB ports. The simulation was completed in five passes of the tools through the soil block, covering a real simulation time of 5 h.

Methodology for the characterisation of the test conditions and determination of the operating conditions of the tractor-crop tillage unit.

This research was carried out in the production areas of the Empresa de Cultivos Varios Manacas *(Sánchez et al., 2018)*, located in Santo Domingo municipality, Villa Clara province, Cuba. In this enterprise, Yellow Ferritic soils predominate, which are considered highly abrasive, causing great wear on tillage tools. For the development of this experiment, the set made up of the Yumz-6m tractor and a Tiller type cultivator with 11 working bodies was used, which can be consulted in *Sánchez et al. (2018)*.

Methodologies for the characterization of operation conditions.

To determine the operating conditions, the following variables were quantified: ambient temperature, soil moisture, soil bulk density, tillage forward speed, mass loss and working time.

Room temperature

This variable was measured using a digital thermometer and the procedure for its determination can be found in Sánchez et al. (2010). Data were taken every 30 minutes, during the duration of the wear experiments in order to know the variation of this variable during its development.

Soil humidity (w).

It was carried out using the gravimetric method, following the procedure established in the Cuban standard NC ISO 67:2000. The samples were weighed with the precision balances indicated in *Sánchez et al. (2010)*. The equipment indicated in *Sánchez et al. (2010)* was used to take the samples, and five points were chosen at random in the diagonal of the test plot as shown in (Figure 2a), three soil samples were taken in each one at three different depth levels (Figure 2b).

Apparent soil density (γd)

The procedure described in the Cuban standard NC ISO 3447:2003, which is based on the Kopecky ring method, was followed, as shown in *Sánchez et al. (2010)*. The determination of the mass of the soil samples was carried out with a balance of $10 \pm 0.01kg$ accuracy, which can be consulted in *Sánchez (2015)*. Sampling was carried out at the same points where the samples were taken for moisture determination (Figure 2), so the number of samples was the same as for the previous test.

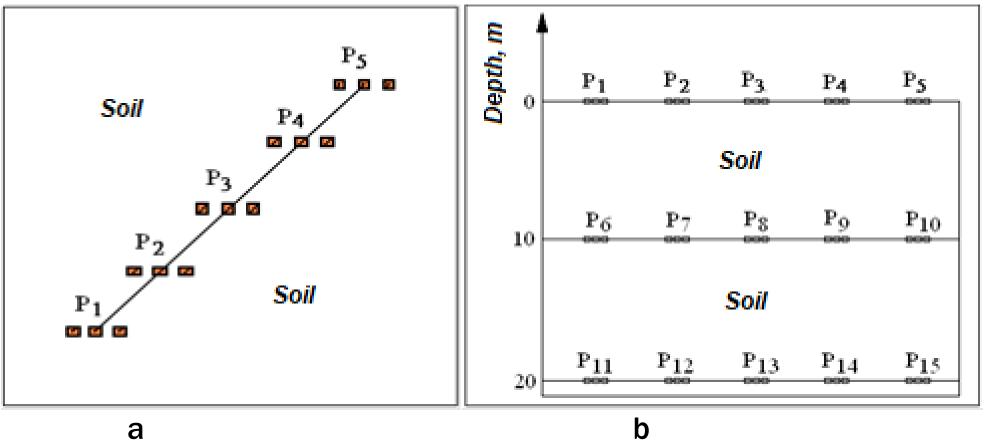


Fig. 2 - Collection of samples for the determination of humidity and soil density.
a) Points for the collection of the humidity and density samples, view in the plant of the parcel;
b) Points for the collection (from P1 to P15), lateral view of the parcel.

Methodologies for determining the operating parameters of the assembly. Determination of the feed rate of the assembly.

As a previous step to the determination of this variable, the length of the experimental plot was measured in order to know the distance travelled by the tool. During the experiment, the time in which the assembly travelled that distance was measured using a stopwatch. The calculation of the forward speed of the tool was carried out using equation 2.

$$V_T = \frac{D_R}{T_E} [m/s] \quad (2)$$

where:

D_R - distance travelled, [m];
T_E - time of the experiment, [s].

Methodology for the experimental determination of the wear under field conditions.

The tillage implements used in the experiments are those of the company where the experiments were carried out. Their geometry is shown in figure 3.

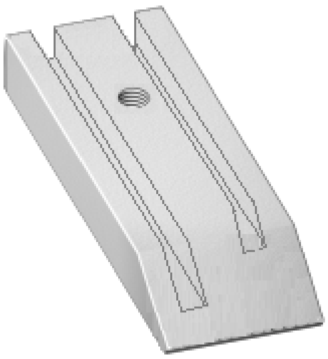


Fig. 3 - Geometry of the tool used in the experiments (Isometric view)

The main characteristics of the used tools or tillage tools are shown in table 2.

Table 2

Characteristics of the tools object of study

Type of part	Type of material	Nominal mass, g	Hardness, HB	Roughness, μm
Rectangular	AISI 1010	802.4	110	12.5
Rectangular	AISI C1064	725.51	165	12.5

Under these conditions, the mass loss of the AISI 1010 and AISI C1064 steel tools was determined with rectangular geometries, moving the assembly at the second speed of the tractor and the duration of the experiment was 24 h. The tools were weighed every 5 h of work. With these objectives in mind, an experimental design was carried out with two randomised treatments (Table 3) and four replicates.

Table 3

Design of experiment for the determination of the wear in field conditions

Treatments	**Speed, $km \cdot h^{-1}$**	**Geometry**	**Material**
T1	Second speed	Rectangular	AISI 1010
T2	Second speed	Rectangular	AISI C1064

Methodology for the statistic processing of results

The statistical processing of the wear determination experimental results under operating or field conditions, the simulation results and the comparison between them was carried out with the statistical processor STATGRAPHICS Centurion XV, using the analysis of simple regressions, comparison of means and Kolmogorov-Smirnov tests, with the purpose of finding the existing relationships between the study variables.

RESULTS AND DISCUSION

Results of the simulation of abrasive wear as a function of the type of material (AISI 1010 and AISI 1046). The results of the simulations show that during the interaction of the tillage tool with the soil, the tool of both materials wears and changes its shape progressively with increasing working time (Figure 4); this has been widely described in scientific literature *(Ucgul et al., 2015; Skirkus and Jankauskas, 2015)*. The wear is due to the loss of mass that results in the deformation over time of the machining tool losing its cutting edge completely. This directly contributes to increased energy demand and decreased quality of workmanship. The trend of increasing wear over working time was previously reported by *(Ucgul et al., 2017; Kostencki et al., 2016; Wang et al., 2016; Sun et al., 2018)*.

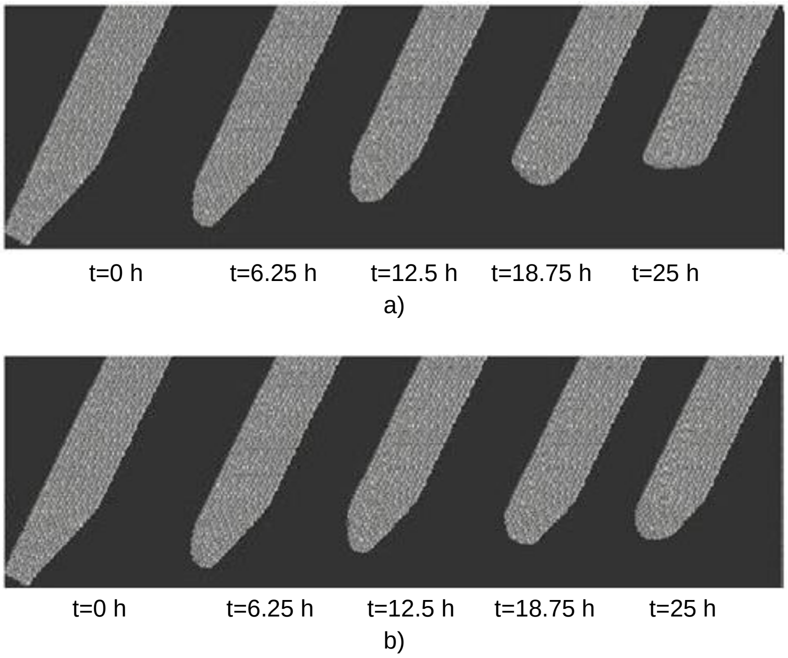


Fig. 4 - Evolution through time of the profiles of the tools during the tillage.
Results of the simulation ($V = 7.38\ km \cdot h^{-1}$). a) Steel AISI 1010; b) AISI C 1064

The comparative analysis of the mass loss obtained in the simulations for each type of steel showed a tendency to increase in magnitude as the clean (uninterrupted) working time increased, reaching total values of 314.03 and $79.08g$, for AISI 1010 and AISI C1064 steel tools, respectively (Figure 5). The trend and values obtained in the simulation were similar to those found by other researchers, either by simulation *(Graff, 2010; Rojek, 2014)* or experimentation in controlled or field conditions directly *(Graff, 2010; Rojek, 2014; Hoormazdi et al., 2018; Chen et al., 2018; Ucgul et al., 2017, Graff, 2010, Bedolla et al., 2018)*.

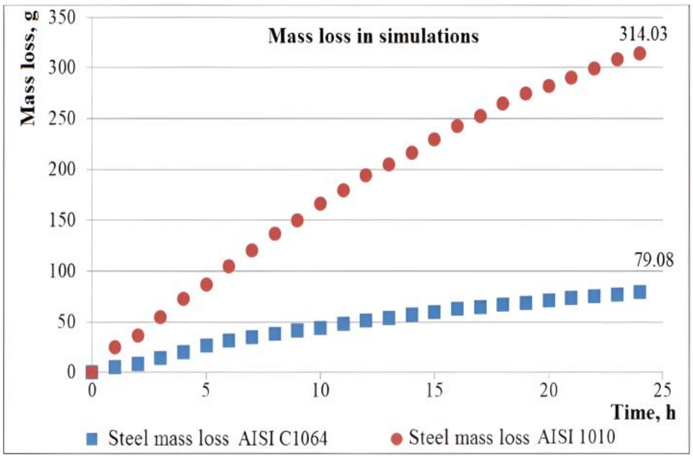


Fig. 5 - Mass loss of the tools depending on the simulation time

Simple regression analysis of the mass loss results in the simulations showed that there is a linear relationship between the mass loss of AISI C1064 steel and the clean working time with $R^2 = 0.9698$ (Figure 6).

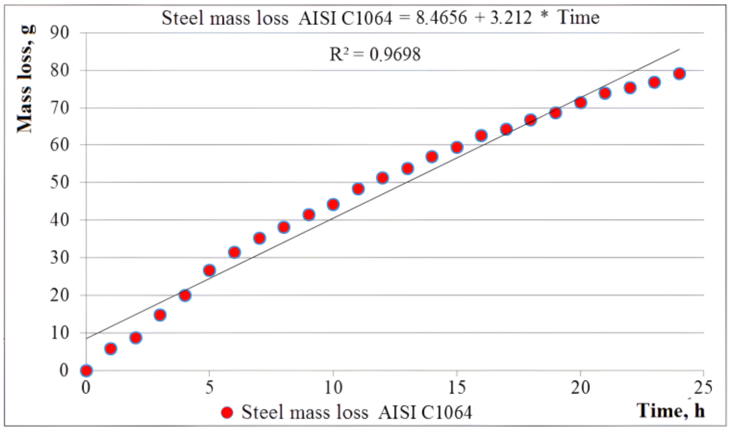


Fig. 6 - Analysis of simple regression of the dependence of the mass loss in the simulation on Steel AISI 1010 in respect to the clean work time

On the other hand, simple regression analysis of the mass loss in the simulations on AISI 1010 steel showed that there is also a linear relationship between its mass loss and the clean working time, with $R^2 = 0{,}9863$ (Figure 7).

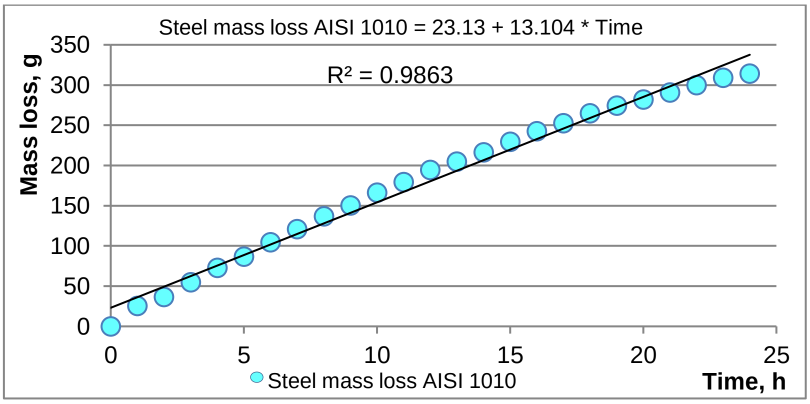


Fig. 7 - Analysis of simple regression of the dependence of the mass loss in the simulation on Steel AISI 1010 in respect to clean work time

The results of experiments in field conditions show that during the interaction of the tillage tool with the soil, the tool of both materials wears and changes the edge geometry progressively with increasing working time (Figure 8), this has been widely described in the scientific literature. *(Graff, 2010; Rojek, 2014; Hoormazdi et al., 2018; Chen et al., 2018(Ucgul et al., 2017, Graff, 2010, Bedolla et al., 2018)*.

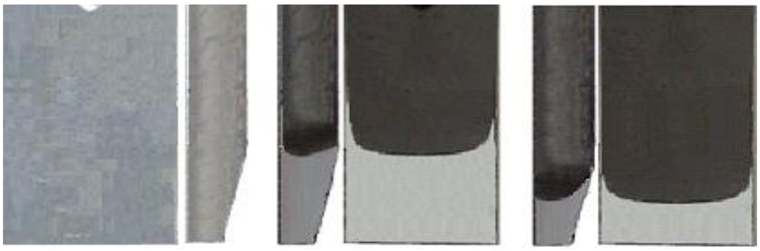


Fig. 8 - Variation of the geometries of the tools in field experiments.
a) and b) before the trial T=0 h; c) and d) tool after the trial T=24 h (steel AISI 1010);
e) and f) tool after the trial T=24 h (steel AISI C 1064)

The comparative analysis of the mass loss obtained in the experimentation under field conditions for both steels showed a tendency to increase its magnitude as the clean (uninterrupted) working time increased, reaching total values of $304.02g$ for the AISI 1010 tool steel and $79.81g$ for the AISI C 1064 steel (Figure 9). Both the trend and the values obtained in the experimentation under field conditions were similar to those found by other researchers under similar conditions *(Graff, 2010; Rojek, 2014; Hoormazdi et al., 2018; Chen et al., 2018, Ucgul et al., 2017, Graff, 2010, Bedolla et al., 2018)*.

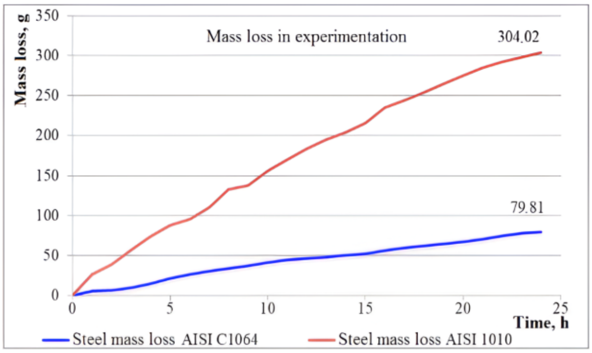


Fig. 9 - Mass loss of the tools depending on the experimentation time

The lowest mass losses were found in the AISI C 1046 steel (Figure 9), this result being consistent with the nature of this type of material which is composed of elements of higher wear resistance, as the carbon content reaches 0.61% and the manganese content 1.06%.

Statistical comparison of the tool wear results obtained in the experiments, using a Kolmogorov-Smirnov test, showed that there are significant differences between the mass loss experienced by both steels during working process, with a reliability level of 95% (Figure 10).

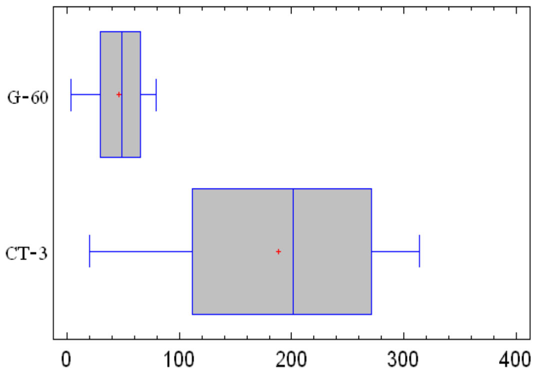


Fig. 10 - Results of the comparison of the mean mass loss of the tools (Kolmogorov-Smirnov), during the tillage in operation conditions

The comparative analysis of the mass loss obtained in the experimental tests and the simulations showed that the wear curves of the simulations follow the same trend shown in the experimental tests, i.e. the mass loss increases with increasing time for the two steels investigated (Figure 11). This same trend was found by *Graff (2010), Rojek (2014), Kostencki et al. (2016), Perazzo et al. (2016), Bedolla et al. (2018)*.

A similarity in the magnitudes of mass loss was also found, being very accurate for the case of AISI C 1064 steel (Figure 11).

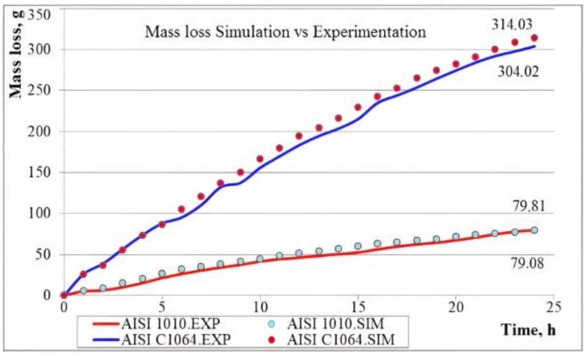


Fig. 11 - Mass loss of the tools in the simulation and experiment according to time function

The simple regression analysis of the mass loss results on AISI C 1064 steel showed a linear relationship between the mass loss obtained in the simulation with respect to the experiment with a reliability level of 95%, with $R^2 = 99.13$ % (Figure 12). Similar results were reported by *Perazzo et al. (2016)*, but on another type of steel.

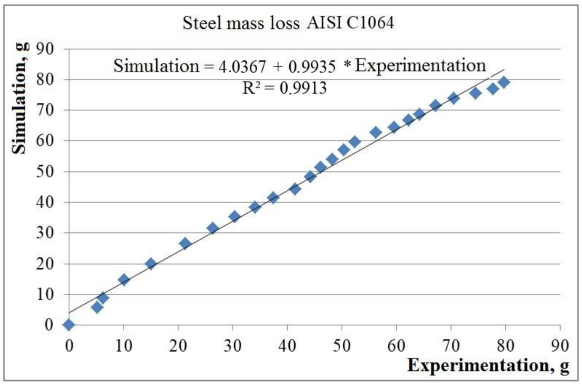


Fig. 12 - Analysis of simple regression of the dependency of the mass loss in the simulation on Steel AISI C1064 regarding the experimental one

On the other hand, the results of the simple regression analysis of mass loss in AISI 1010 steel show a linear dependence of the mass loss obtained in the simulation with respect to that obtained experimentally, with a reliability level of 95% (Figure 13). This same relationship was obtained by *Perazzo et al. (2016)* on steels with different properties.

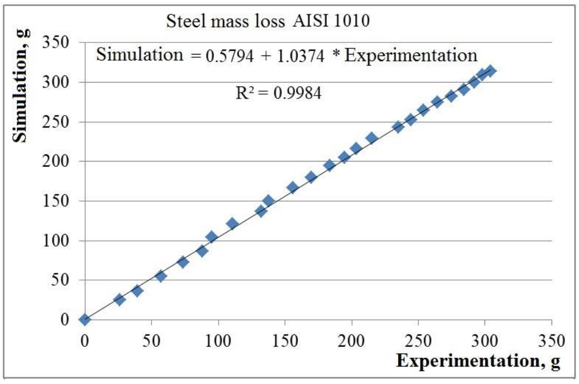


Fig. 13 - Analysis of simple regression of the dependency of the mass loss in the simulation on Steel AISI 1010 regarding the experimental one

Finally, a simple regression analysis of the validation results showed that there are statistically significant relationships between simulation and experimental mass loss for a 95% confidence level (Figure 14). The regression equation showed that there is a linear relationship between simulated and experimental mass loss $(R^2 = 0.998 \; and \; e = 0.005g)$. Similar results were obtained by *Graff (2010), Rojek (2014) and Kostencki et al. (2016)*.

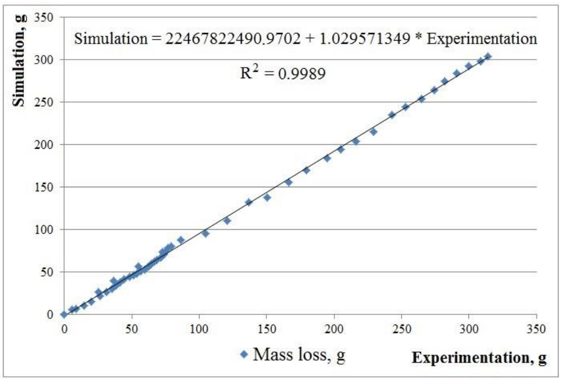


Fig. 14 - Analysis of simple regression of the dependency of the mass loss in the simulation regarding the experimental one

CONCLUSIONS

The results of the simulations, as well as the experiments, showed that the mass loss and geometry changes were much higher than 50% in AISI 1010 steel compared to AISI C1064.

The model developed in DEM is able to accurately predict the wear experienced in the tillage tools, independently of the characteristics of the steels and the operating conditions $(R^2 = 0.998\ and\ e = 0.005g)$.

The high degree of correlation between the values of mass loss predicted by the abrasive wear model and those determined experimentally under operating or field conditions $(r = 0.99)$, is another indicator of the validity of the model developed for the simulation of the wear of the working parts of the tillage tools under the conditions studied.

The mean absolute errors of the simulation with respect to the field tests reached 0.01937 g for AISI C1064 steel and 0.08619 g for AISI 1010.

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