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Stress Evaluation Using Finite Elements in a Manual Agricultural Tool

Evaluación de esfuerzos mediante elementos finitos en una herramienta agrícola de acción manual

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ABSTRACT

This study addresses the imperative need for efficient hand-held agricultural tools, particularly in challenging contexts like hillside agriculture, by focusing on the redesign and evaluation of a manual tillage tool. The objective is to comprehensively assess the stress and fatigue life of a redesigned tool, considering different manufacturing materials such as steels (AISI/SAE 4140, 4130, 1060), A356 aluminum, and nodular cast irons. Employing finite element method simulations and the Von Mises equation, this research confirms an optimal performance within elastic limits for all materials, mitigating the risks of plastic deformation or breakage during normal operation, with Von Mises stresses ranging from 8.39 to 16.30 MPa. All the tools yielded optimal results, meeting the critical requirements for soil penetration resistance, reporting no fatigue failures, and exhibiting useful life values over 1.75 x 1013 years. In terms of ergonomics, A356 aluminum stands out, as it is less heavy and implies a lower effort by the operator, promoting efficient tillage without compromising comfort. This research provides nuanced insights for the design of agricultural tools, emphasizing the harmonious balance between efficiency, longevity, and operator comfort in sustainable practices.

Keywords: handheld tools, elastic limits, fatigue, sustainable agriculture, ergonomics

RESUMEN

Este estudio aborda la imperiosa necesidad de herramientas agrícolas manuales que sean eficientes, especialmente en ámbitos desafiantes como la agricultura en laderas, centrándose en el rediseño y evaluación de una herramienta de labranza manual. El objetivo es evaluar exhaustivamente la tensión y la vida útil ante la fatiga de una herramienta rediseñada considerando diferentes materiales de fabricación como aceros (AISI/SAE 4140, 4130, 1060), aluminio A356 y hierros fundidos nodulares. Empleando simulaciones del método de elementos finitos y la ecuación de Von Mises, esta investigación confirma un rendimiento óptimo dentro de los límites elásticos para todos los materiales, mitigando los riesgos de deformación plástica o rotura durante la operación normal, con tensiones de Von Mises que van de 8.39 a 16.30 MPa. Todas las herramientas presentaron resultados óptimos, cumpliendo con los requisitos críticos de resistencia a la penetración del suelo, sin reportar fallas por fatiga y demostrando valores de vida útil superiores a 1.75 x 1013 años. En términos de ergonomía, el aluminio A356 se destaca por ser menos pesado e implicar un menor esfuerzo por parte del operador, promoviendo una labranza eficiente sin comprometer la comodidad. Esta investigación proporciona percepciones matizadas para el diseño de herramientas agrícolas, enfatizando el equilibrio armonioso entre eficiencia, longevidad y comodidad del operador en prácticas sostenibles.

Palabras clave: herramientas manuales, límites elásticos, fatiga, agricultura sostenible, ergonomía

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Introduction

Currently, the development of efficient and functional handheld agricultural tools is of great significance for advancing the engineering of the agricultural sector. Research works that propose use-based modifications to current designs use are a priority for manufacturing innovative agricultural equipment and tools aimed at the modernization of relatively small rural areas (Toni *et al*., 2017). In this regard, hillside agriculture constitutes a particular case, where high slopes hinder tillage via motorized machines. In this type of land, it is necessary to use highly efficient, manual agricultural tools that generate a low impact on the soil and feature ergonomic designs adjusted to the anthropometric characteristics of the farmer (Sims *et al*., 1998).

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Hoes are among the most commonly employed manual agricultural tools. A hoe is an instrument with a generally curved metal blade that is used to graze, break soils with high hardness, and cut thin roots, among others (González, 2018; Sanahuja, 1971). In addition, it has been reported that mattocks and hoes have been widely used for agricultural tillage since the Neolithic period and by different cultures (Mazoyer and Roudart, 2006). According to Byzantine manuscripts, the hoe was the most widely used tool in the Hesiod era, and it appeared years later in the British Isles during the late Mesolithic. This tool is likely responsible for the emergence of agriculture as we know it. Sanahuja (1971) refers to findings in Iberian deposits and Roman villas in Catalonia, among which some agricultural tools such as mattocks and hoes stand out. When comparing their design against those currently marketed, this author noted little variation in their geometry and manufacture (forged metals). In addition to agricultural use, there are documents that mention the use of hoes as weapons during battles between the Irish and the Spanish (O'Donell and De Estrada, 2014).

Today, there is a variety of hoes, which differ in size, geometry, materials, and use type. Moreover, handheld hoes are regarded as tools of great importance for agriculture and are likely the most widely used in tillage and soil clearing operations worldwide, which is why many farmers depend on them (Sims *et al*., 1998). This may be the main reason why they have evolved to the point of being commercially differentiated by the aforementioned characteristics (Ashburner and Kienzle, 2013). In this context, abrasive wear is an important factor that affects functionality, and, according to Agudelo (2013), it is a significant issue in soil removal and agriculture, increasing the costs associated with energy consumption, repair, part replacement, and the downtime generated by these activities. Agudelo (2013) estimates that the costs generated by friction and wear on agricultural tools, both mechanized and manual, can represent between 0.3 and 3.0% of a country's GDP, and that this situation is more critical in developing countries. Similarly, Yazici (2011) mentions that performing preventive maintenance can save around 337 million dollars a year.

The foregoing justifies undertaking innovation processes in design, materials, use techniques, and ergonomics, among others, in order to achieve greater efficiency in agricultural tillage with hand tools.

This work presents an evaluation of the stress generated by impact load on a manual tillage tool, considering different manufacturing materials and using the finite element method (FEM) in computational simulations. In particular, the employed hoe, modeled for furrowing work, features an improved geometric design, and it was manufactured with materials resistant to wear and impact, *i.e.*, AISI/SAE 4140, 4130, and 1060 steel; A356 aluminum castings; and nodular cast irons with different surface treatments (annealed and normalized). It should be noted that some of the materials mentioned above have already been used for the manufacture of agricultural tools and have been referenced by various authors in different patents. As per a patent on the construction of vertical plows (Balvanz and Eldora, 2019), AISI/SAE 4140 steel is used to make moldboards in the plows and is implemented in the construction of backhoes with high resistance to wear (Gegel, 1998). Yu and Bhole (1990) report the high resistance of AISI/SAE 4130 steel, hence its great usefulness in the manufacture of plow tools. Teko *et al*. (2018) have reported this material in regard to the construction of blades for sugar cane harvesters. As for AISI/SAE 1060 steel, De Almeida Luz (2019) reports their use in furrowers. A356 aluminum has been reported in the manufacture of machine elements such as pistons, engine blocks, and car wheels (Ahmed *et al*., 2016; Charco, 2017; Fernanda *et al*., 2018). Finally, Bednář *et al*., (2013) have used nodular cast irons to manufacture tools for subsoilers, given that this material has a high resistance to abrasive and erosive wear and is regarded as a ductile iron (Enríquez Berciano and Tremps Guerra, 2012).

For stress evaluation via the FEM, a maximum power of 300 W (Botta, 2003) was considered as a critical value, which is reached upon the impact between a fertile soil and a tool, considering the dynamic movement of the latter as resembling a particle that hits the former for a short period of time. The simulations were carried out using the ANSYS software, taking the Von Mises equation in three dimensions as a reference, to determine the elastic stress concentration sites of each of the materials used for manufacturing the tools. *Stress* is denoted as the uniaxial tensile stress that generates a combination of maximum distortion energy, considered as the actual combination of applied stresses, expressed in a two-dimensional or three-dimensional manner (Cruz-Avilés *et al*., 2018; Norton, 2011).

Most manual farming tools available in the market are designed considering the force they can apply to the soil, their producibility, and their efficiency, but the comfort of the operator is rarely taken into account. It has been reported that most of the agricultural workforce suffers from, pain in the neck, shoulders, arms, and trunk (Benos *et al*., 2020; Yusuf and Yusuf, 2006). Thus, designing a tool that allows for the dissipation of forces, enables proper cultivation, and reduces the effort required by the operator, would contribute to greater efficiency in farming tasks, without compromising the workers' quality of life.

Therefore, the objective of this research was to evaluate the stresses and lifecycle of a manual agricultural tool through the FEM, analyzing tools of different materials when subjected to impact loads.

Materials and methods

Manual tool modeling in computer software

Using the SolidWorks software, the redesign of a conventional hoe (quadrangular) was modeled. Through image processing, a final 3D model with the same dimensions and geometry as the actual tool used in the soil preparation process was obtained. To create the design, photographs of the tool were taken from the side, top, and front views. Measurements of length, width, and height were taken, and, based on them, the photographs were scaled in the software to generate a model (Figures 1 and 2).

Figure 1. Manual tool taken as a reference for modeling in SolidWorks
Source: Authors

Figure 2. SolidWorks model of the manual tool
Source: Authors

Mechanical properties and materials used for the simulation

To perform the FEM stress simulations, the following groups of materials were considered: nodular cast irons (annealed and normalized), low-alloy steels with medium-carbon content (AISI/SAE 4140 and 4130), carbon steel (AISI/SAE 1060), and cast aluminum (A356).

The FEM analysis considered an impact between the tip of the manual tool and the soil, simulating the energy that a farmer would exert during tillage. Through calculations using Newton's third law (action and reaction), the simulation results were found to be equivalent, *i.e.*, the force exerted by the tool against the soil was of the same magnitude as that exerted by the soil on the tool, but in the opposite direction. Regarding the magnitude of the impact force, the critical value reported by Botta (2003) was considered. This author concluded that, during a normal working day, a person exerts a force of approximately 60 N, at a speed of 1.1 m/s (equivalent to 66 W), albeit stating that, for some instants, an operator can impart a power close to 300 W on the agricultural tool. This value was taken as a reference in our simulations, which were performed using the ANSYS 2019 R2 V19.4 software. The mechanical module was employed, which required entering the characteristics and properties of each material. Molten aluminum (A356) was modeled based on information on physical properties obtained from Mott (2009) and Matweb (2016). The data for the nodular cast iron were obtained from Agudelo (2013), Angus (1976), and Herring (2018). In the case of steels, information from Matweb (2016) and Budynas and Nisbett (2015) was employed. The mass of the materials was calculated based on the density values obtained in the aforementioned sources and the volume provided by SolidWorks, *i.e.*, 9.2977×10^{-5} m^3. Based on the constant velocity, a static structural analysis was performed.

Table 1 presents the mechanical properties and the mass calculations considered for each hand tool material. This information was used in Equation (1) to model the dynamics of the impact during tillage, considering the tool as a particle.

$$\int \underline{F} dt = m \triangle \vec{v} \tag{1}$$

Table 1. Mechanical properties of the materials used for the impact force calculations and the FEM stress simulation

Material	Mass (kg)	Elastic modulus (GPa)	Poisson's ratio	Density (kg/m^3)	Elastic limit (MPa)	Tensile strength (MPa)
AISI/SAE 4140	0.73	205.00	0.29	7850.00	675.00	1020.00
AISI/SAE 4130	0.73	205.00	0.29	7850.00	460.00	731.00
AISI/SAE 1060	0.73	205.00	0.29	7850.00	427.00	779.00
Annealed nodular cast iron	0.66	168.33	0.29	7120.00	275,79	413.69
Normalized nodular cast iron	0.66	168.33	0.29	7120.00	482.63	689.48
A356 aluminum permanent mold cast	0.25	72.40	0.33	2670.00	179.00	255.00

Source: Agudelo (2013), Angus (1976), Budynas and Nisbett (2015), Herring (2018), Matweb (2016), Mott (2009)

Where:

- F: impact force due to weight (N)
- dt: differential time for impact (s)
- $m\Delta\vec{v}$ mass variation due to the speed of the tool during the impact (kg-m/s)

By solving the integral in Equation (1), the formula for the linear motion of an impacting particle was obtained, as shown in Equation (2).

$$F\left(\Delta t\right) = mv_f - mv_i \tag{2}$$

Where:

- m : mass of the tool (kg)
- v_i : initial speed of the tool (m/s)
- v_f : final velocity just before impact (m/s)

To obtain the impact force, the initial velocity (v_i) was set as 0, considering that the tool starts from a resting position. Following Botta (2003), a final speed of 1,1 m/s was assumed, as well as an impact time 0.001 s. For similar situations, the analysis of Marcon (2018) was taken into account, where the maximum impact time used was 10 ms. However, for the impact to be more critical, a minimum value was taken, *i.e.*, approximately one thousandth of a second.

In accordance with the above, the impact force for each hoe was calculated with the following values, as represented in Equation (3).

$$F = \frac{mv_f}{\left(\Delta t\right)} = \frac{\left(mass\ of\ hoe\right)\left(1.1\frac{m}{s}\right)}{0.001s} \tag{3}$$

During the impact, it was considered that the operator applied a force of 272.73 N. This value was added to that obtained in Equation (3) and tabulated as the total force for each material (Table 2).

Table 2. Impact force of a hoe on the soil for each tool material

Material	Force (N)	Fy (N)	- Fz (N)
AISI/SAE 4140	1075.58	1036.47	287.44
AISI/SAE 4130	1075.58	1036.47	287.44
AISI/SAE 1060	1075.58	1036.47	287.44
Annealed nodular cast iron	1000.92	964.52	267.49
Normalized nodular cast iron	1000.92	964.52	267.49
Aluminum A356	545.80	525.95	145.86

Source: Authors

Simulation and finite element model

In the FEM simulations, a mesh size of 2 mm was selected for optimal and precise results. 207 799 nodes and 132 830 tetrahedral elements were obtained, as this type of mesh allows for a better adjustment of the tool's geometry, adapting to changes in shape and to smaller areas. In general, the mean quality was 0.7617, and reductions in this regard were caused by sudden changes in geometry. However, considering that the tool has a complex shape, the reported values are good, as they are closer to 1, which denotes the highest quality (Seeni *et al.*, 2020). Additionally, the aspect ratio was 2.3041 – a good-quality mesh has an aspect ratio between 1 and 5. The Jacobian ratio obtained was 0.9984, with the ideal value being 1 (SolidWorks, 2022). In addition, greater precision can be obtained with a larger number of nodes (Dutt, 2015; Molino *et al.*, 2003). The static module of the ANSYS finite element software was used for modeling and calculating the maximum Von Mises stress after assigning a type of material to the studied tools. Then, the boundary conditions were selected, *i.e.*, the type of stress, corresponding to the force exerted by the farmer when using the furrowing hoe; and the impact force of each material, concentrated on the tip of the tool, using approximately one third of the total area (2.9 x 10^{-3} m^2). This procedure is illustrated in Figure 3. Here, the area in red receives the impact. The direction follows the rib (tangential to the tool and perpendicular to the soil), which is considered the most critical factor. The tool stub is centered on the z-axis, implying that the forces are distributed in the y- and z-axes (Table 2). Regarding the distribution, a tool angle of 15.5° was taken into account. The magnitude of the force applied by each material is presented in Table 2. Each material was simulated with these parameters.

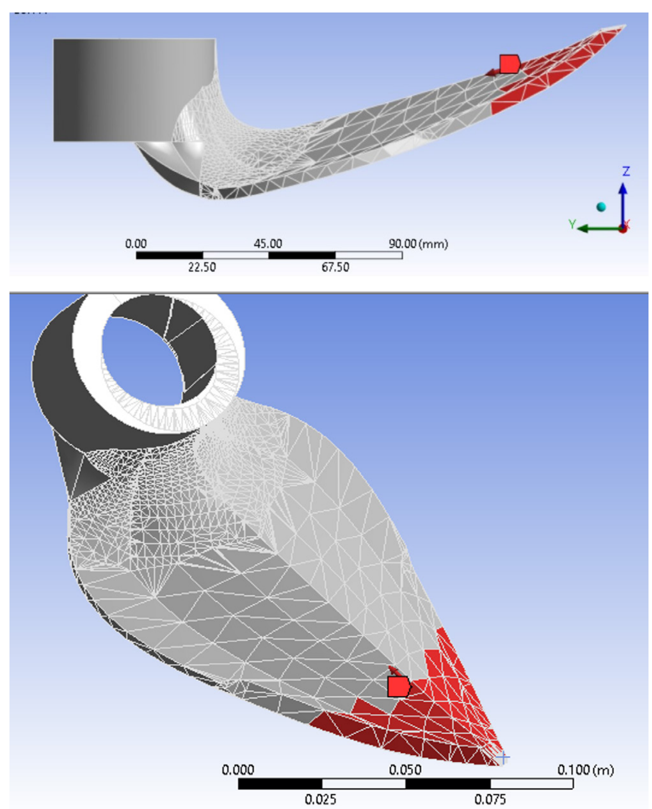

Figure 3. Zone of greatest influence of the impact force on the soil
Source: Authors

It is important to note that, internally, the software calculates the Von Mises stresses that can produce failures due to deformation or breakage. For a deformation of the material to occur, it is necessary to equal or exceed the elastic limit stress in tension for each material. In the event of a break, the maximum stress at break must be equaled or exceeded.

The Von Mises stress can be expressed as in Equation (4) for a three-dimensional system using the XYZ components (Budynas and Nisbett, 2015).

$$\sigma' = \frac{1}{\sqrt{2}}\left[\left(\sigma_x-\sigma_y\right)^2+\left(\sigma_y-\sigma_z\right)^2+\left(\sigma_z-\sigma_x\right)^2+6\left(\tau_{xy}^2+\tau_{yz}^2+\tau_{zx}^2\right)\right]^{\frac{1}{2}} \quad (4)$$

Where:

- σ' : Von Mises stress
- σ_x : normal stress in the x-direction
- σ_y : normal stress in the y-direction
- σ_z : normal stress in the z-direction
- τ_{xy} : shear stress in the xy plane
- τ_{yz} : shear stress in the yz plane
- τ_{zx} : shear stress in the zx plane

In order to compare the values obtained from the simulation against those of the manual calculations, the simplified Von Mises equation was used:

$$\sigma' s = \sqrt{\frac{\left(\sigma_1-\sigma_2\right)^2+\left(\sigma_2-\sigma_3\right)^2+\left(\sigma_3-\sigma_1\right)^2}{2}} \quad (5)$$

Where:

- $\sigma' s$: simplified Von Mises stress
- $\sigma_1 = \sigma_x$: normal stress in the x-direction
- $\sigma_2 = \sigma_y$: normal stress in the y-direction
- $\sigma_3 = \sigma_z$: normal stress in the z-direction

The percent error is presented in Equation (6).

$$\%E = \frac{FEM\,Value - Manual\,Value}{Manual\,Value} * 100 \quad (6)$$

Lifecycle simulation

Using the ANSYS software, a simulation of the tool's lifecycle was carried out, based on the fatigue parameters for each of the materials, in addition to using the Von Mises stresses generated in the previous simulations and the geometry of the tool. We predicted the number of cycles that the tool could withstand under the conditions provided by the stress analysis, considering a reversible stress and Goodman relation. For an eight-hour workday and a work efficiency of 70%, the number of cycles in a conventional ploughing day was determined, finally obtaining the number of days that the tool can work before failing due to fatigue.

Results and discussion

The Von Mises theory, also known as the *maximum distortion energy theory*, offers a versatile framework for understanding the behavior of diverse materials across various service conditions. These conditions encompass factors such as stress application rates, impact severity, and working temperatures, as well as specific design characteristics like material properties, defects, and geometry. This theory posits that yielding and failure occur when the total deformation energy per unit volume reaches or surpasses the energy corresponding to the material's yield strength (Budynas and Nisbett, 2015; Vanegas Useche, 2018). According to Pérez-González *et al*. (2011) the Von Mises criterion is a good option for materials with a ductile tendency, but it is not suitable for materials with a brittle tendency (in such materials, they recommend using another one, such as the Christensen criterion). The materials used in this research exhibit a ductile tendency, as it is common to find rock fragments in agricultural soils, where a sudden impact can more frequently lead to cracks or catastrophic failures in the material. In the case of the materials under study, the Von Mises equivalent stress values, calculated based on normal stresses, consistently remained below the yield strength of each material. This observation indicates that the actual stresses experienced during impact did not surpass the material's elastic limit, highlighting that the material's performance primarily resides within its elastic zone.

The computational results reveal that the geometric design of the tool's tip facilitates stress distribution and concentration in localized areas, effectively dissipating the deformation energy generated during operation. While the computational graphs demonstrate stress concentration in small regions relative to the tool's size, none of the materials exceeded their yield limits or elastic strength. This reaffirms that the materials predominantly operate within their elastic zones.

Table 3. Von Mises elastic stresses for each tool material

Material	Von Mises Stress (MPa)	Elastic limit (MPa)
AISI/SAE 4140	16.30	675.00
AISI/SAE 4130	16.30	460.00
AISI/SAE 1060	16.30	427.00
Annealed nodular cast iron	15.17	275.79
Normalized nodular cast iron	15.17	482.63
Aluminum A356 permanent mold cast	8.39	179.01

Source: Authors

For the steels, stress magnitudes between 69.67 x 10^{-4} and 16.30 MPa were obtained (Figure 4). In general, the concentration of Von Mises stresses in the conic area where the cape is installed was evident for each type of material, mainly due to the change in the geometry of the tool and the presence of the moment generated by the cape during agricultural work. Particularly, the highest stress magnitudes were obtained in the area of the nerve, as it has a greater contact with the soil and due to the change in section from its pointed geometry, implying areas with high stress concentrations. This is similar to the results of Cazin *et al.*, (2020), who found that the maximum efforts occurred in joints and geometry changes.

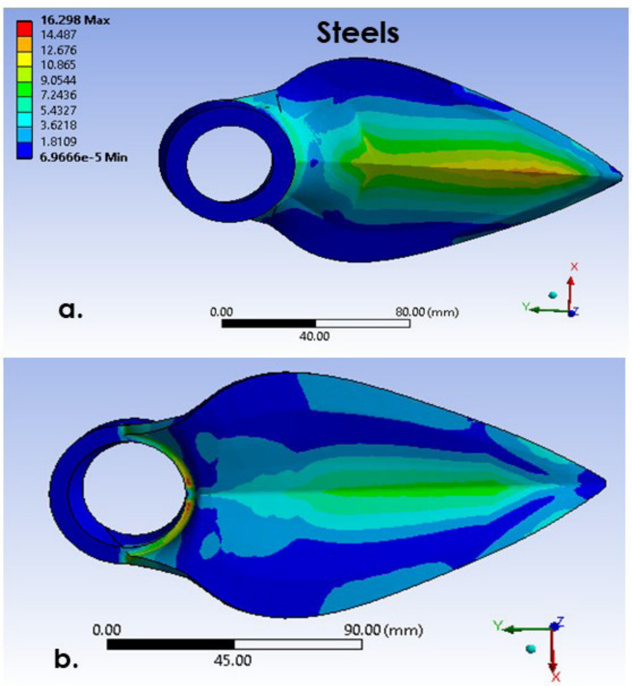

Figure 4. Von Mises stress calculated for steel tools**.** Views: a) front, b) back.
Source: Authors

The nodular steel tools simulated (Figure 5) reported values between 64.85 x 10^{-4} and 15.17 MPa, with a behavior similar to that of steels regarding the stress concentration areas. These values, although slightly lower (by 7%) than those of steels, do not represent great differences in the Von Mises stress calculated in this study. However, given the nature of the materials, they could eventually exhibit a different wear behavior, which was not within the scope of this study.

In the case of the A356 aluminum tool, the calculated Von Mises stress ranged from 40.46 x 10^{-4} to 8.39 MPa (Figure 6), which is significantly lower than the values obtained for steels and iron castings. The main reason for this difference is that the aluminum hoe is significantly lighter than the others, as well as the impact force exerted on the tip of the tool. The maximum values are observed in the nerve and the area of connection with the end of the furrowing hoe, maintaining a behavior similar to that of the other materials, as a result of the geometry of the tool and the stress concentration areas. In addition, the tillage conditions and the impact model are similar for all the studied materials.

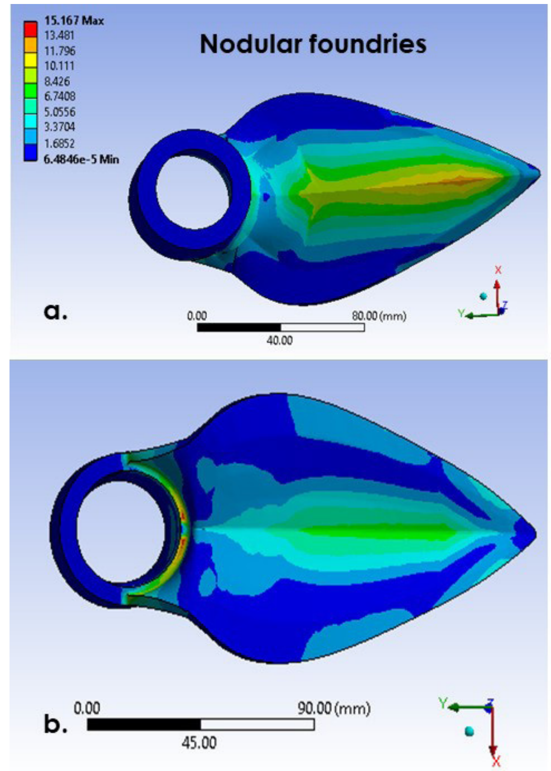

Figure 5. Von Mises stress calculated for the nodular foundry tools. Views: a) front, b) Back.**Source:** Authors

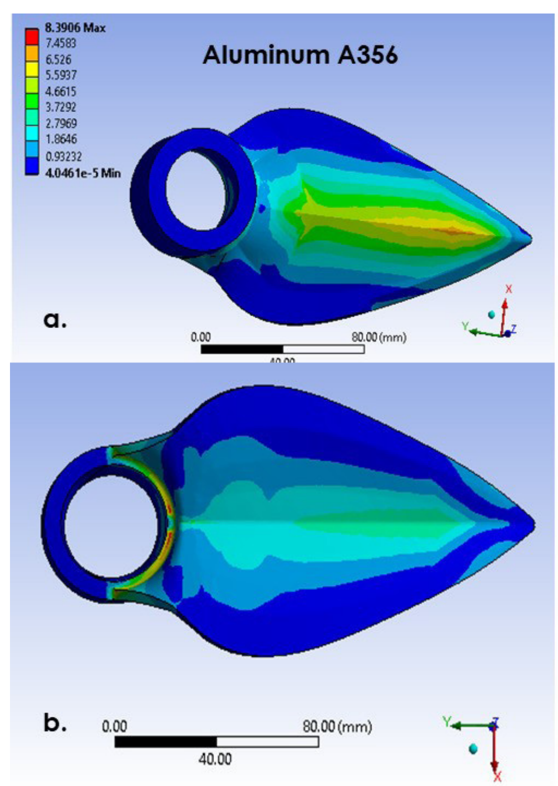

Figure 6. Stress generated in the aluminum tool. Views: a) front, b) back.
Source: Authors

As per Von Mises theory, the elastic limit of the material and the maximum stress generated must be compared. In Table 3, it is evident that none of the furrowing hoe materials exceeds the creep limit, *i.e.*, no tool material will fail under the established working conditions, which are similar to those proposed by Leslie and Aguila (2014) for the FEM analysis of a multiple chisel plough, where the tool did not any exhibit failures caused by exceeding the elastic limit. This leads to the hypothesis that the tool materials' useful life could be long and lack plastic deformations. Consequently, the tools' lifecycle may be influenced by tribological factors such as wear.

Table 4 presents the results obtained in the simplified von Mises stress analysis, in addition to the percent error.

Table 4. Simplified Von Mises elastic stresses for each tool material

Material	Simplified Von Mises stress σ′ (MPa)		%E
	Manual	FEM	
AISI/SAE 4140	4.93	5.27	6.90
AISI/SAE 4130	4.93	5.27	6.90
AISI/SAE 1060	4.93	5.27	6.90
Annealed nodular cast iron	4.58	4.90	6.99
Normalized nodular cast iron	4.58	4.90	6.99
Aluminum A356 permanent mold cast	2.50	2.69	7.60

Source: Authors

Note that the percentage errors are below 8%. This indicates a satisfactory outcome of the simulation, and this error can be attributed to the geometry and distribution of the areas during the simplified calculations.

According to the previous analysis and given that the tool is unlikely to fail by exceeding its elastic limit, a fatigue analysis was carried out to determine the number of lifecycles to which the different tool materials could be subjected before exhibiting damage to their microstructure. Figures 7, 8, and 9 present the lifecycles for the steel, iron, and aluminum foundries, respectively. These analyses were performed while assuming constant loads, without any variability during different agricultural tasks. However, it should be indicated that lifecycles can be affected because of the interaction between the tool and a heterogeneous and anisotropic material, such as agricultural soils. Furthermore, it is known that fatigue is not a critical factor of failure in this type of tool, as discussed below.

As shown in Figure 7, the number of lifecycles for the tool under load conditions is very high. In the case of AISI/SAE 4130 steel, there is a stress concentration zone similar to that obtained in the Von Mises simulation, with values of up to 7.65 x 10^{29} lifecycles before exhibiting failures, particularly in the area adjacent to the nerve and on the cape, representing the notching areas subjected to higher concentrations of stress. Additionally, it is important to note that, for the AISI/SAE 1060 and 4140 steels, a clear visual reference is not given since they have higher tensile strength and lifespan.

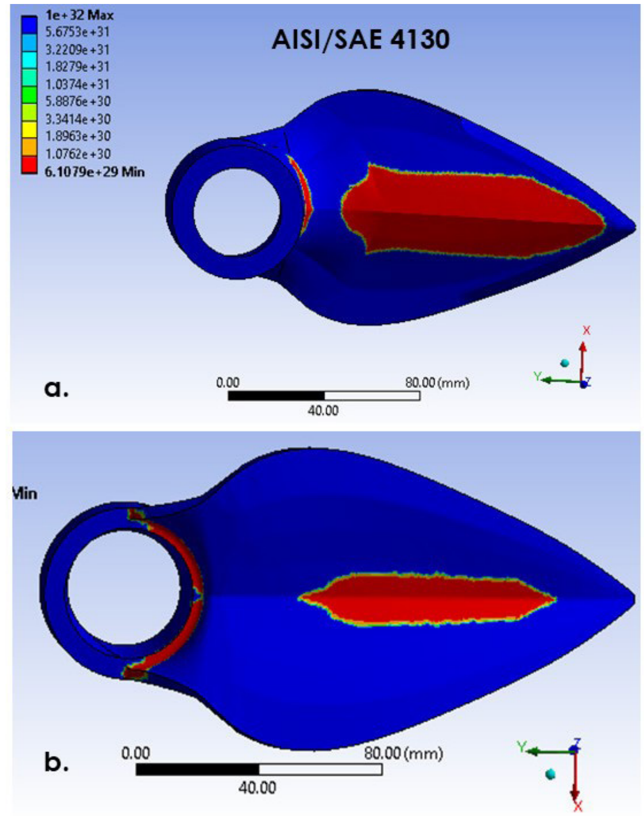

Figure 7. Simulated lifecycles of the 4130 steel tool. Views: a) front, b) back.
Source: Authors

The opposite occurs with iron castings, although the normalized nodular casting has a higher tensile strength than the annealed one. However, the fatigue properties of the latter are better, implying that the tool material subjected to the standardization process exhibits a greater susceptibility to failure due to fatigue. Those differences lead to the hypothesis that the microstructure of iron foundries influences fatigue cycles due to the heat treatment of the tool. However, the number of cycles necessary for fatigue to occur is very high; given the analyzed conditions, it takes about 3.06 x 10^{29} cycles for the tool to fail.

Figure 8 shows a higher stress concentration zone in the standardized nodular casting tool, implying a difference in the number of lifecycles when compared to that shown in Figure 7 for AISI/SAE 4130 steel, whose fatigue resistance is greater. The latter also has a better distributed tool geometry.

In the fatigue simulation, the A356 aluminum tool has the lowest fatigue lifecycles, since it is made of the material with the lowest tensile strength and has the lowest ductility coefficient. However, Figure 9 shows that, except for the stress concentration area, the lifecycles are similar to those of the other tools (1 x 10^{32} cycles). It is worth noting that A356 aluminum is the material that supports the lowest load.

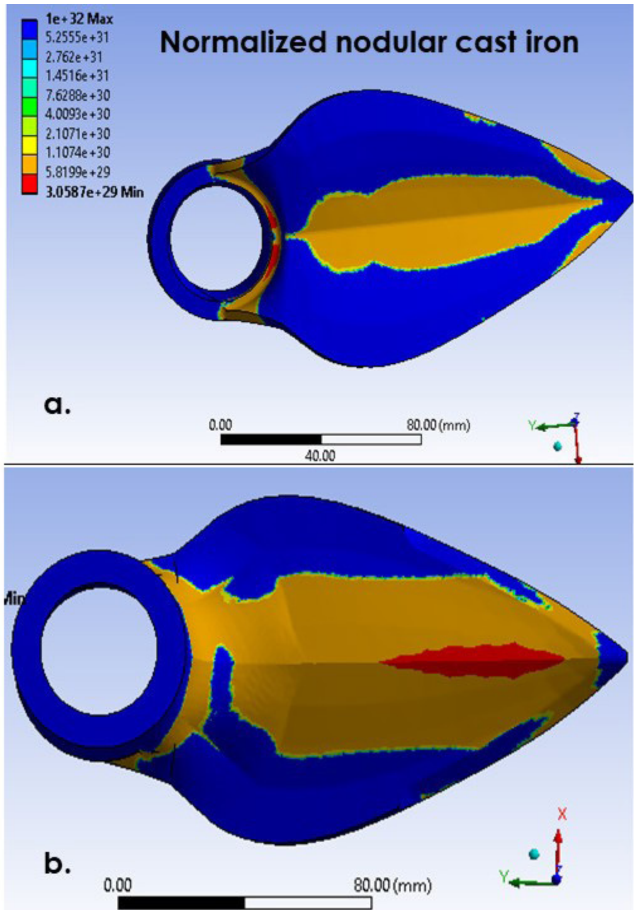

Figure 9. Simulated life cycles for the A356 aluminum tool. Views: Views: a) front, b) back.
Source: Authors

The application of loads below the creep limit on agricultural tools generates changes in the internal microstructure of each material. When this process occurs repeatedly under different conditions, it can damage the tool over time, as it is subjected to fluctuating and variable stresses. This type of failure is called *high cycling failure*, and it occurs when the stresses are very far from the creep limit. In the case of the studied metals, the number of lifecycles needed for failure is very high. This could only be demonstrated after the tools have been operated for much of their useful life and/or by performing specific microstructure and even nanostructure tests (Espejo and Hernández, 2017).

Table 5 presents the parameters calculated regarding the number of days that the A356 aluminum tool could withstand under traditional working conditions. This material was selected because, according to the fatigue results, it is the one with the most critical fatigue lifecycles.

Note that, under normal working conditions, the tool would have a very long lifespan, in the order of thousands of years. Thus, the critical factor for a damage to the tool is determined through other mechanisms, such as abrasive wear given the soil-tool interaction, but not through fatigue.

Table 5. Fatigue parameters

Parameter	Value	Units
Impacts/day	18 144	Cycles/day
A356 aluminum lifecycles	7.60 x 10^{19}	Cycles
Lifespan of A356	8.38 x 10^{14}	Weeks
	2.09 x 10^{14}	Months
	1.75 x 10^{13}	Years

Source: Authors

From a perspective of ergonomics and the principle of lowest energy expenditure by the operator, the furrowing hoe with the best performance is the one designed with aluminum casting; its lower weight implies the lowest impact force, hence the lower energy requirements. The stress required for penetrating the soil should be considered, since the tool must withstand the soil's resistance without failing. Jaramillo (2014) reports that a soil resistance value greater than 35.5 kg/cm^2 (3.48 MPa) constitutes the limit for root development in a great proportion of crops. Still, considering the load necessary to break the soil in very critical situations, none of the tools exceeds its elastic limit, indicating that the agricultural soil does not offer sufficient resistance to cause the tool to fail due to impact load. Therefore, based on the stress and fatigue analysis, all the studied materials have a potentially long useful life, in addition to the fact that all of them exceed the critical agricultural soil stress, allowing for an adequate decompaction. If worker ergonomics are considered, A356 is the recommended furrower material. However, to select the optimal material, it is necessary to perform an abrasive wear analysis, given that, although there is no fatigue failure, the loss of useful life can be caused mainly by the abrasion generated by agricultural soils, especially those with a higher concentration of sand particles, which in turn causes the loss of shape and mass of the tool (Singh *et al.*, 2020). Abrasive wear is considered to be one of the most serious issues in agricultural tools, reporting losses of up to 40 million dollars in countries such as Australia, which are associated with the replacement of tools due to wear by continuous use (Malvajerdi, 2023). Thus, we suggest conducting future research focused on the abrasive wear of each of the materials studied herein, in order to enhance the selection process.

Conclusions

The Von Mises stress calculated for the six manual tool materials, which were simulated using the ANSYS software, did not exceed the elastic limit. Therefore, under normal operating conditions, plastic deformation is unlikely, as well as the breakage of the materials, due to impact against the soil. Finite element analysis determined that the material with the highest Von Mises stress was AISI/SAE 4140 steel (16.30 MPa), and the lowest value was reported by A356 aluminum (8.39 MPa).

Through the ANSYS fatigue analysis, it was predicted that the tools would not exhibit fatigue failures and would feature a great number of operating cycles, with the most critical value reported for A356 aluminum, corresponding to a useful life of 1.75 x 10^{13} cycles. Meanwhile, the lowest critical value regarding fatigue was observed in AISI/SAE 1060, steel with 1 x 10^{32} cycles. Hence, all the materials are suitable for tool design, offering a long lifespan and meeting the stress requirements for completing their tasks.

As for ergonomics, A356 aluminum exhibits a good behavior, given that it is less heavy and, consequently, the efforts generated are lower, enabling an efficient tillage while ensuring the operator's comfort.

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References

Agudelo, P. (2013). *Estudio de desgaste de recubrimientos duros en una herramienta de arado tipo cincel* Master's thesis, Universidad Nacional de Colombia. https://repositorio.unal.edu.co/handle/unal/20967

Ahmed, A., Wahab, M. S., Raus, A. A., Kamarudin, K., Bakhsh, Q., and Ali, D. (2016). Mechanical properties, material and design of the automobile piston: An ample review. *Indian Journal of Science and Technology, 9*(36). https://doi.org/10.17485/ijst/2016/v9i36/102155

Angus, H. T. (1976). Mechanical, physical and electrical properties of cast iron. In Cast Iron: Physical and Engineering Properties (2nd ed., pp. 34–160). Elsevier. https://doi.org/10.1016/B978-0-408-70933-0.50007-4

Ashburner, J. E., and Kienzle, J. (2013). *Agricultural hand tools in emergencies: Guidelines for technical and field officers*. FAO Plant Production and Protection Paper.

Balvanz, J., and Balvanz, R. (*2019*). *Vertical tillage tool. U.S. Patent No. 10,314,221 B2*. https://patents.google.com/patent/US10314221B2/en

Bednář, R., Votava, J., Červinka, J., and Fajman, M. (2013). Suitability of technical materials for machinery subsoilers for soil tillage. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 61*(1), 9–16. https://doi.org/10.11118/actaun201361010009

Benos, L., Tsaopoulos, D., and Bochtis, D. (2020). A review on ergonomics in agriculture. part II: Mechanized operations. *Applied Sciences (Switzerland), 10*(10), 3484. https://doi.org/10.3390/app10103484

Botta, G. (2003). *Guía de clases maquinaria agrícola, Licenciatura en Negocios Agropecuarios*. Universidad de La Pampa, Facultad de Agronomía.

Budynas, R. G., and Nisbett, J. K. (2015). *Diseño de ingeniería mecánica de Shigley* (10th ed.). McGraw Hill.

Charco, J. L. (2017). *Fabricación de un prototipo de block de motor de combustión interna de dos tiempos por manufactura aditiva indirecta con una aleación de aluminio al silicio* [Undergraduate thesis, Escuela Politécnica Nacional]. https://bibdigital.epn.edu.ec/handle/15000/18849

Cruz-Avilés, A., Ortiz-Domínguez, M., Suarez-López, Y., RiveraLanderos, E. A., Lechuga Canto, C. B., Muños-Sánchez, Y., Santana-Robles, F., and García-Pérez, C. (2018). Teoría de falla bajo carga estática. *Ingenio y Conciencia Boletín Científico de La Escuela Superior Ciudad Sahagún, 5*(10), 3319. https://doi.org/10.29057/ess.v5i10.3319

De Almeida Luz, W. (2019). *Desgaste em ferramentas de máquinas agrícolas: revisão bibliográfica* [Thesis, Universidade Tecnológica Federal Do Paraná]. http://repositorio.roca.utfpr.edu.br/jspui/bitstream/1/14778/1/LD_COEME_2019_2_05.pdf

Dutt, A. (2015). Effect of mesh size on finite element analysis of beam. *International Journal of Mechanical Engineering, 2*(12), 8-10. https://doi.org/10.14445/23488360/IJME-V2I12P102

Enríquez Berciano, J. L., and Tremps Guerra, E. (2012). *Fabricación de fundición nodular*. Fundidores. https://oa.upm.es/14450/1/Fundición_nodular.pdf

Espejo, É., and Hernandez, H. (2017). *Análisis de fallas de estructuras y elementos mecánicos* (1st ed.). Universidad Nacional De Colombia.

Fernanda, T., Gatamorta, F., and Oliveira, M. (2018). A *Influência das Condições Ambientais na Porosidade de rodas de ligas leves*. https://doi.org/10.26678/ABCM.CONEM2018.CON18-1018

Gegel, G. A. (1998). *Earthworking machine ground engaging tools having cast-in-place abrasion and impact resistant metal matrix composite components (Patent No. 5,743,033)*. Google Patents.

González Cobas, J. (2018). Lexicografía y sistematicidad. Acerca de los nombres que designan instrumentos agrícolas. *Revista de Lexicografía, 22*, 135-150. https://doi.org/10.17979/rlex.2016.22.0.3324

Herring, D. (2018). *Heat treatment of cast irons*. Industrial Heating. https://www.industrialheating.com/articles/94644-heat-treatment-of-cast-irons

Jaramillo, D. F. (2014). *El suelo: origen, propiedades, espacialidad* (2nd ed.). Universidad Nacional de Colombia, Sede Medellín.

Leslie, J. F. M., and Aguila, M. V. G. (2014). Análisis del comportamiento resistivo del implemento de trabajo del multiarado MAU-250. *Acta Agronomica, 64*(1), 22-29. https://doi.org/10.15446/acag.v64n1.42849

Malvajerdi, A. S. (2023). Wear and coating of tillage tools: A review. *Heliyon, 9*(6), e16669. https://doi.org/10.1016/j.heliyon.2023.e16669

Marcon, P. (2018). *Agent of deterioration: Physical forces*. Government of Canada. https://www.canada.ca/en/conservation-institute/services/agents-deterioration/physical-forces.html

Matweb (2016). *Online Materials Information resource*. http://www.matweb.com/

Mazoyer, M., and Roudart, L. (2006). *A history of world agriculture*. Earthscan. http://base.dnsgb.com.ua/files/book/Agriculture/History-of-Agriculture/A-History-of-World-Agriculture.pdf

Molino, N., Bridson, R., and Fedkiw, R. (2003). *Tetrahedral mesh generation for deformable bodies*. https://graphics.stanford.edu/papers/meshing-sig03/meshing.pdf

Mott, R. L. (2009). *Resistencia de materiales* (vol. 5). Pearson Educación.

Norton, R. (2011). *Diseño de máquinas: un enfoque integrado* (4th ed.). Pearson Educación.

O'Donell, H., and De Estrada, D. (2014). Presencia irlandesa en la milicia española. *Revista Internacional de Historia Militar, 92*, 555844. https://dialnet.unirioja.es/servlet/libro?codigo=555844

Pérez-González, A., Iserte-Vilar, J. L., and González-Lluch, C. (2011). Interpreting finite element results for brittle materials in endodontic restorations. *BioMedical Engineering OnLine, 10*(1), 44. https://doi.org/10.1186/1475-925X-10-44

Sanahuja, E. (1971). Instrumental de hierro agrícola e industrial de la época ibero-romana en cataluña. *Pyrenae, 7*, 61-110. https://core.ac.uk/download/pdf/39114287.pdf

Seeni, A., Rajendran, P., Hussin, M., and Ismail, F. (2020). Errors and uncertainties in simulation of steady, viscous flow past a circular cylinder at re = 20 using a systematic approach. *INCAS Bulletin, 12*(3), 203-217. https://doi.org/10.13111/2066-8201.2020.12.3.17

Sims, B. G., O'Neill, D. H., Walle, R. J., Ellis-Jones, J., Rivera Rosero, A., and Jirón Estrada, J. (1998). Ergonomic evaluation of hand-hoes for hillside weeding and soil preparation in Honduras. *Ceiba, 39*(2), 183-189.

Singh, J., Chatha, S. S., and Sidhu, B. S. (2020). Abrasive wear behavior of newly developed weld overlaid tillage tools in laboratory and in actual field conditions. *Journal of Manufacturing Processes, 55*, 143-152. https://doi.org/10.1016/j.jmapro.2020.03.040

SolidWorks (2022). *Mesh quality checks*. https://shorturl.at/qzEKO

Teko, D. R., Rouge, B., and Cormier, J. (2018). *Base cutter blade* (*Patent No. US 2018/0139901 A1*). https://patentimages.storage.googleapis.com/fc/a4/9d/21d94e1962fdee/US20180139901A1.pdf

Toni, S., Corrêa, C. C., de Souza, D. C., Muzeka, G., and Rossa, Ü. B. (2017). Enxada iracema, cavador tatuí e subsolador vangador de solo como novas ferramentas agrícolas como promotoras de tecnologias as propriedades rurais. *Anais Da Mostra de Ensino, Pesquisa, Extensão e Cidadania* (*MEPEC*), *2*, 83-87. https://publicacoes.ifc.edu.br/index.php/MEPEC/article/view/229

Vanegas Useche, L. V. (2018). *Diseño de elementos de máquinas*. Universidad Tecnológica de Pereira. https://doi.org/10.22517/9789587223019

Yazici, A. (2011). Wear behavior of carbonitride-treated ploughshares produced from 30MnB5 steel for soil tillage applications. *Metal Science and Heat Treatment, 53*, 46-51.

Yu, H.-J., and Bhole, S. D. (1990). Development of a prototype abrasive wear tester for tillage tool materials. *Tribology International, 23*(5), 309-316. https://doi.org/10.1016/0301-679X(90)90004-9

Yusuf, H., and Yusuf, D. (2006). *Ergonomics of selected hand tools for soil tillage in Nigeria* [Conference paper]. International Conference on Engineering Research & Development: Impact on Industry. https://www.researchgate.net/publication/365762299%0AErgonomics