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Un estudio del desgaste erosivo de aceros para herramientas de trabajo en frío

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ARTICLE

A study of the erosive wear of cold work tool steels

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Abstract

In this work, a study of erosive wear was conducted on cold-work tool steels, AISI O1 (Non-deforming, slightly alloyed steel) and AISI D2 (Non-deforming steel with high chromium content) subjected to the impact of silicon carbide particles (SiC), to know their performance against this wear process. An erosion rig based on the ASTM G76-95 standard was employed to complete the testing. Tests were carried out using different impact angles, 30°, 45°, 60° and 90°, with a particle velocity of 24 ± 2 m/s and a particle flux of 63 g/min. The abrasive particles had an angular shape, with a particle size of 420–450 µm. The silicon carbide (SiC) particles were used to accelerate the wear process and evaluate the performance of these materials under severe erosion conditions. Characterization techniques such as hardness tests and optical microscopy were used to know the characteristics of the materials, morphology of the abrasive particles and the wear mechanisms identification. The erosion results showed that AISI O1 steel showed higher erosion rates than AISI D2 steel.

Index terms: erosive wear, ASTM G76, cold work tool steels, erosion rates.

Resumen

En este trabajo, se realizó un estudio del desgaste erosivo en aceros para herramientas de trabajo en frío, AISI O1 (acero no deformable, ligeramente aleado) y AISI D2 (acero no deformable con alto contenido de cromo) sometidos al impacto de partículas de carburo de silicio (SiC), para conocer su comportamiento frente a este proceso de desgaste. Se empleó un equipo de erosión basado en la norma ASTM G76-95 para completar las pruebas. Estas, se llevaron a cabo utilizando diferentes ángulos de impacto, 30°, 45°, 60° y 90°, una velocidad de partícula de 24 ± 2 m/s y un flujo de partículas de 63 g/min. Las partículas abrasivas mostraron una forma angular, con un tamaño de partícula entre 420-450 µm. Se utilizaron partículas de carburo de silicio (SiC) para acelerar el proceso de desgaste y evaluar el comportamiento de estos materiales en condiciones de erosión severa. Se emplearon técnicas de caracterización, como ensayos de dureza y microscopía óptica, para determinar las características de los materiales, la morfología de las partículas abrasivas y la identificación de los mecanismos de desgaste. Los resultados de la erosión mostraron que el acero AISI O1 presentó mayores tasas de erosión que el acero AISI D2.

Palabras clave: desgaste erosivo, ASTM G76, aceros para herramientas de trabajo en frío, tasas de erosión.

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I. INTRODUCTION

Steels used for cold working have certain characteristics such as moderate toughness, high wear resistance and hardness. These alloys are commonly used in cutting, abrasive-charged plastic mold inserts and cold forming (stamping, coining or bending). They are categorized into three groups: carbon tool steels, impact steels and high-carbon steels [1]. In respect to tribological tests on steels for cold working tools, it is possible to mention that AISI D2 steel is one of the most studied; sliding tests have been carried out using a pin-on-disc rig [2], [3], [4] and erosion tests where its resistance to this wear process has been determined [5]. In addition, some studies with this material have evaluated its wear resistance when a coating treatment is applied on this, some coatings used for this are Bo, TiCN and even another coating treatments as AlTiZrN [6], [7]. Other materials used for cold working are AISI O1 and AISI T1 but the existing literature on these materials is limited. However, with AISI O1 steel, some studies have been made to obtain friction coefficient (CoF) on sliding test when the material is coated with bore and nanodeposits of carbon [8]. Andrés & Hernando [9] conducted pin-on-disk tests on AISI O1, showing that abrasive and adhesive wear are the main wear process, when this material is subjected to high loads and speed conditions. On the other hand, the lifespan and friction coefficient of AISI T1 steel have been compared with AISI D2, and obtained that under dry turning test, T1 exhibit lower CoF than D2 but shorter lifespan [10].

The erosion phenomenon causes serious economic losses in several industries, for that reason is a topic extensively studied. The erosion process is a time dependent phenomenon influenced by three main groups factors: impact conditions, properties of the eroding particles and properties of the eroded surface [11], in which two mechanisms occur depending on the characteristics of the eroded material: micro-cutting if it is a ductile and deformation for brittle materials [12], [13]. The cutting mechanism is more severe when particles impact the surface at lower impact angles, causing micro-ploughing and irregular indentations (scratches), in so far as deformation mechanism refers to particles impacting at perpendicular angles, causing mainly cracking formation and plastic deformation [14], [15].

Because there is little information on erosion tests of cold work tool steels, such as AISI O1 and AISI D2, the aim of this paper is to evaluate the performance of these materials against this significant wear process. Due to their chemical composition, these alloy steels could be very useful in applications where erosive wear is a problem that requires innovative solutions.

II. EXPERIMENTAL DETAILS

A. Test procedure

The materials used for the tests were AISI O1 and AISI D2 steels in the as-received condition. The surface morphology was obtained using a Radical 1200 model microscope (see Fig. 1a-b). These materials are very interesting and can be extremely useful for manufacturing mechanical components subjected to severe wear and multiple mechanical stresses. This is because they have chemical compositions, with elements such as tungsten, vanadium, and molybdenum as shown in Table 1, which improve their mechanical properties and therefore increase their mechanical strength and toughness [16, 17]. The materials were delivered in the form of standard steel slabs (25mm wide and 3mm thick) and then cut carefully with a hacksaw crosswise to obtain the sample dimensions, 50 mm X 25 mm X 3 mm in thickness, to fix in the sample holder of the erosion rig [13]. Then, hardness tests were conducted using a Microhardness Tester LECO LM 700. Five hardness values were acquired for each tested material in accordance to ASTM E384-17 [18] and an average value was calculated. The hardness of AISI O1 and AISI D2 was 363 HV and 343 HV, respectively. The applied load to the Vicker's indentor (square-based diamond pyramid) was 1000 gf, whereas the dwell time was 15

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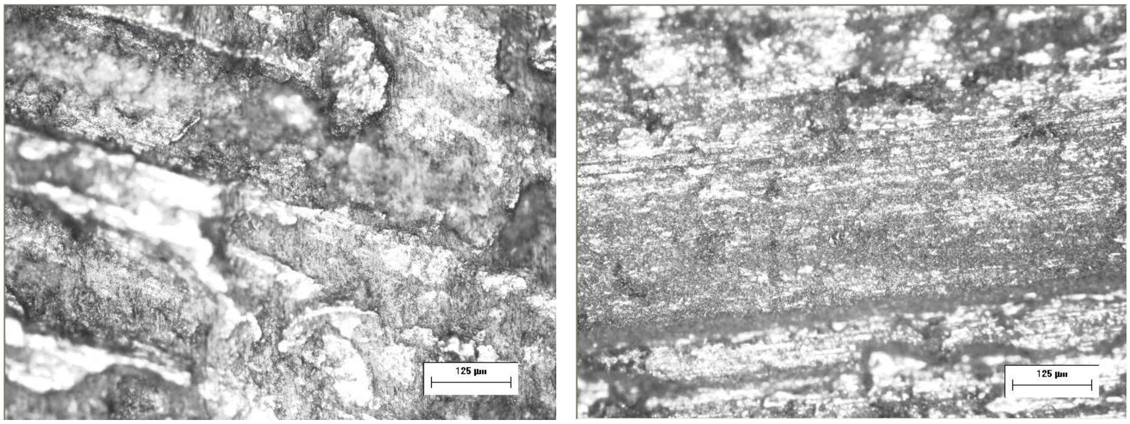
sec. In respect to abrasive particles, silicon carbide was employed to accelerate the erosion damage on the surfaces. The morphology of angular silicon carbide particles, is shown in Fig. 2 [19].



(a) (b)

Fig. 1. Micrographs of tested materials, (a) AISI O1, (b) AISI D2.

TABLE 1.
CHEMICAL COMPOSITION OF THE TEST MATERIALS.

Materials	% Wt.						
	C	Si	Mn	Cr	V	W	Mo
AISI O1	0.85-0.95	0.20-0.40	1-1.3	0.40-0.60	-	0.40-0.60	
AISI D2	1.50	0.40	0.40	12	0.80	-	0.95

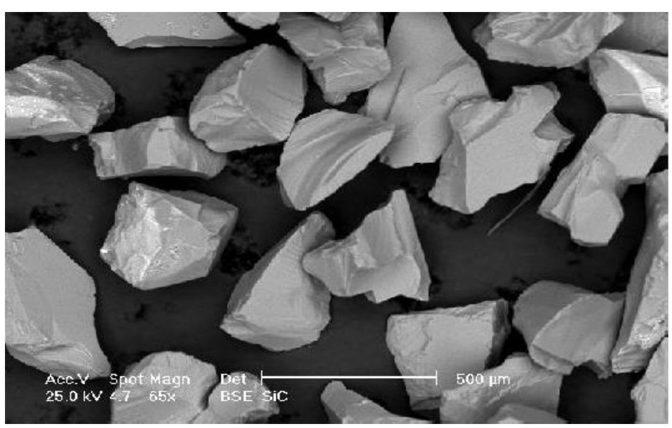


Fig. 2. Morphology of silicon carbide particles [19].

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The erosion tests were performed using a sand blasting erosion equipment, based on ASTM G76-95 [20]. The testing conditions are summarized in Table 2. The mass loss values were determined as follows, the samples were weighed before each test to obtain an initial weight and removed every 2 min, cleaned by using acetone and weighed again, using an analytical balance (accuracy of ± 0.0001 g). The micrographs of the eroded surfaces were analyzed using optical microscopy to identify the wear mechanisms at two incident angles, 30º and 90º.

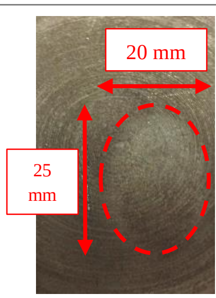
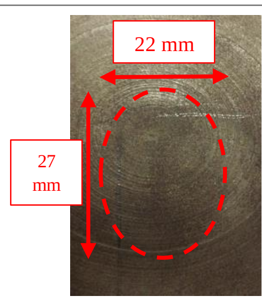
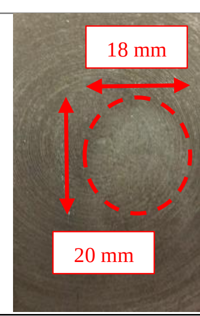
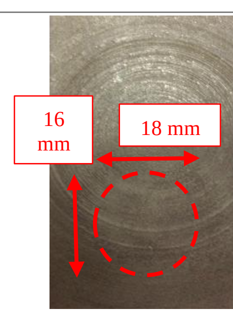
TABLE 2.
TESTING CONDITIONS.

Parameters	Values
Time	10 min (each sample was removed every 2 min to determine the mass loss)
Impingement angles	30°, 45°, 60° and 90°
Particle velocity	30 ± 2 m/s
Particle flux	63 g/min
Distance	10 mm (between samples and end of stainless steel nozzle)
Nozzle dimensions	4.7 mm internal diameter, 6.3 mm external diameter and 260 mm length
Room temperature	35°C-40°C

III. RESULTS

A. *Wear scars*

Fig. 3 shows the wear scars produced on the tested materials at different incidence angles. The wear area is extended as the impact angle decreases ($\alpha \leq 45º$). The wear scar is roughly elliptical at 30° and 45°, while it is nearly circular at 60° and 90°. This is related to the impact geometry, which modifies the specimen orientation when it is positioned to be impacted at different impingement angles. Although the wear scars on AISI D2 steel showed a larger damage area, it was not the material with the highest wear rate. In contrast, AISI O1 steel exhibited smaller wear scars but showed the most erosion damage.

Materials	30º	45º	60º	90º
AISI O1				

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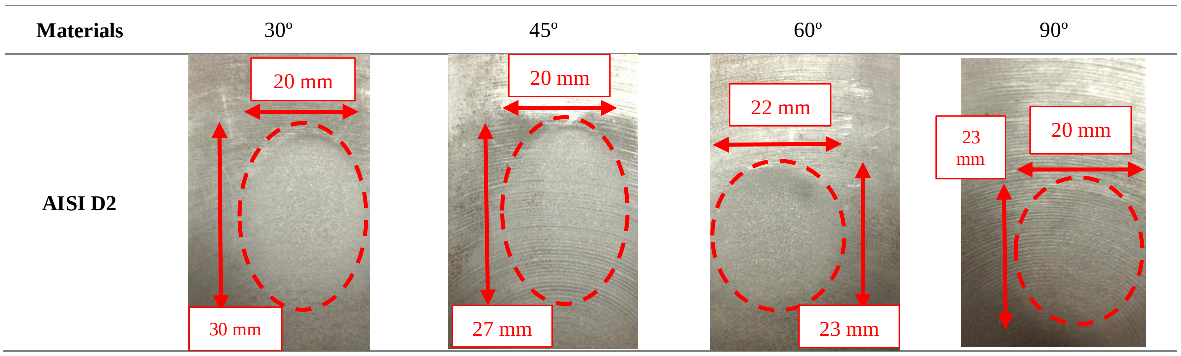
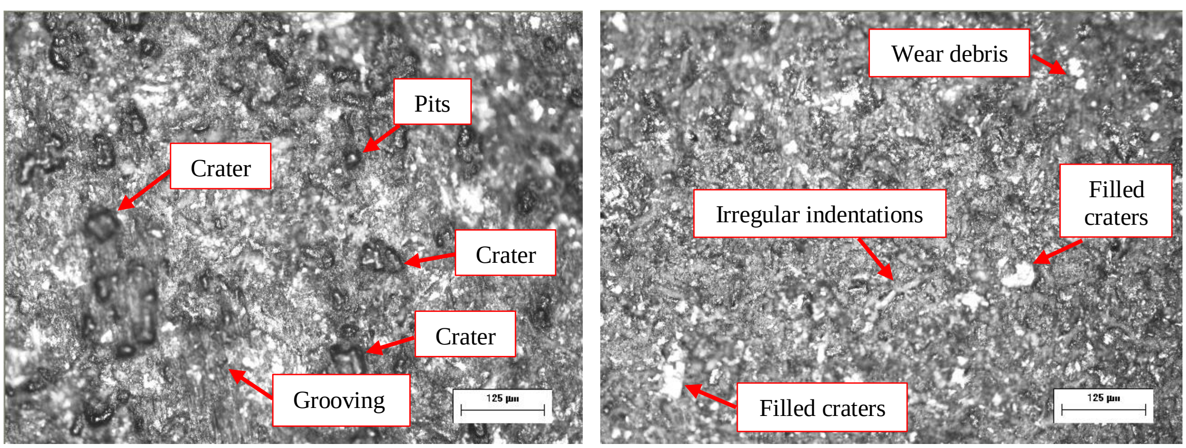


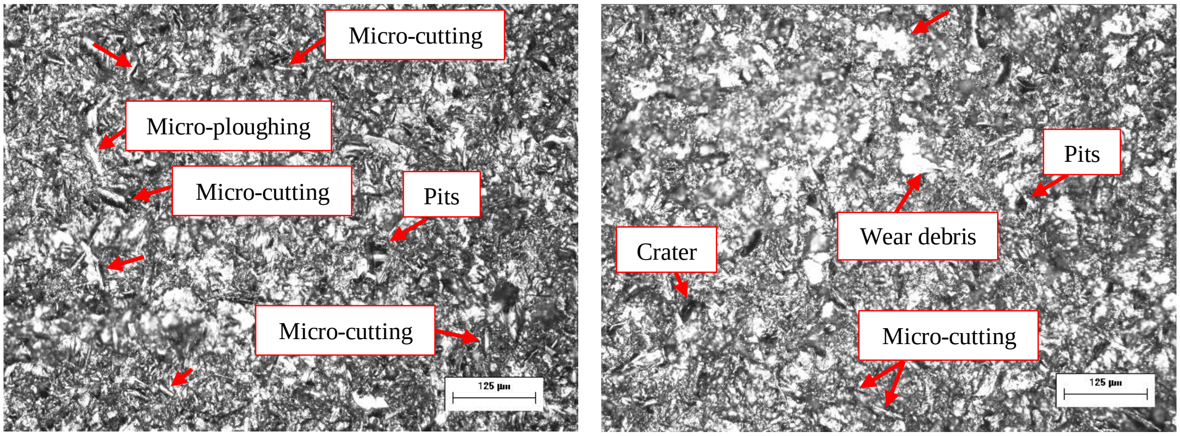
Fig. 3. Wear scars on AISI O1 and AISI D2.

B. *Wear mechanisms analysis*

Micrographs of the wear caused on the tested materials at 30° and 90° are shown in Fig. 4a-d. Typical wear mechanisms can be identified here, such as craters of varying sizes, micro-cutting, and some holes filled with wear debris on the surfaces of AISI O1 steel. Furthermore, wear mechanisms such as micro-cutting, micro-ploughing, pitting, and various random scratches are observed on the surfaces of AISI D2 steel, which performed very similarly at each incidence angle. These micrographs provide a broader perspective on why AISI O1 steel exhibited the highest erosion rates at each impact angle compared to those obtained on AISI D2 steel. This is due to the number of craters observed on the surfaces at 30° and 90°, which resulted in a greater amount of material removal compared to AISI D2, since the micrographs on this steel showed that the silicon carbide particles only caused micro-cutting actions, scratches and irregular indentations, which led to displacement of the material and not to detachment, which considerably reduced the wear damage.



(a) (b)

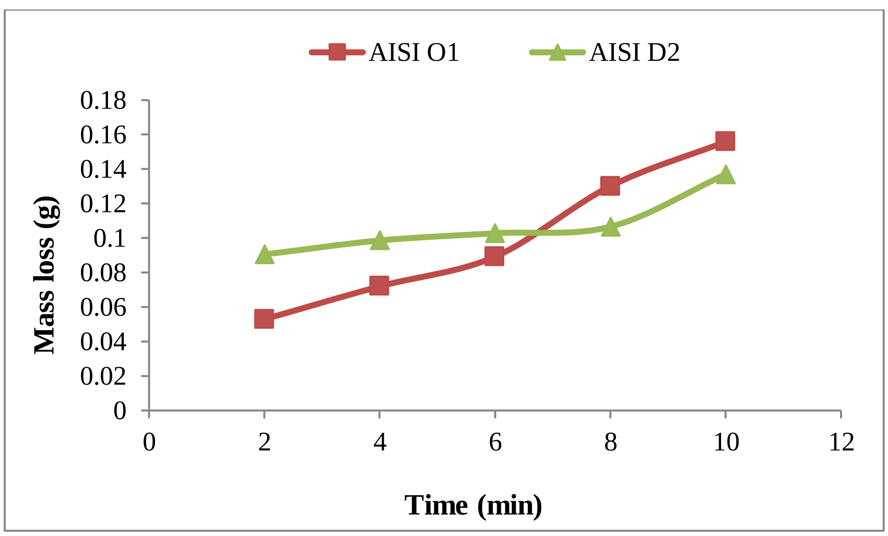


(c) (d)

Fig. 4. Erosive wear on (a) AISI O1 at 30º, (b) AISI O1 at 90º, (c) AISI D2 at 30º, (d) AISI D2 at 90º.

C. Mass los and erosión rates

Fig. 5a-d present the mass loss vs. time graphs for the tested materials. In this particular case, it can be noted that AISI O1 had greater erosive damage at all impact angles, while AISI D2 exhibited the highest erosion resistance. It can be noticed that the mass loss of AISI D2 steel was greater than that of AISI O1 steel up to 6 min at 30º and 90º (Fig. 5a and 5d). After this time, its behavior changed, with AISI O1 steel exhibiting greater mass loss at 8 and 10 min. This could be related to the wear mechanisms observed in AISI O1 steel at these two impact angles, resulting in greater material removal. At 45º and 60º, the performance of both steels was more consistent, with AISI O1 steel showing greater mass loss than AISI D2 (Fig. 5b and 5c).



(a)

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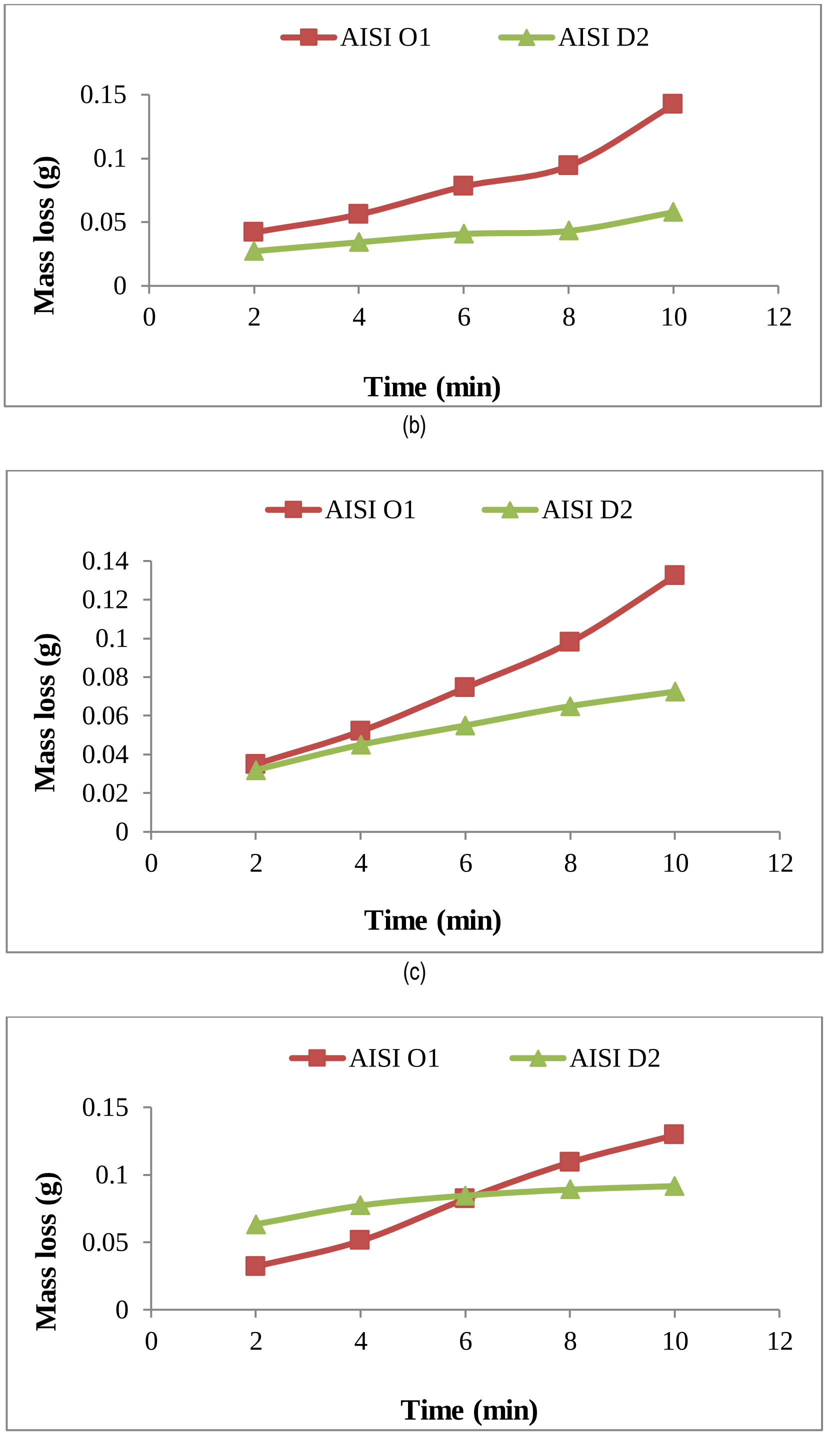

(b)

(c)

(d)

Fig. 5. Mass loss vs time graphs, (a) 30°, (b) 45°, (c) 60°, (d) 90°.

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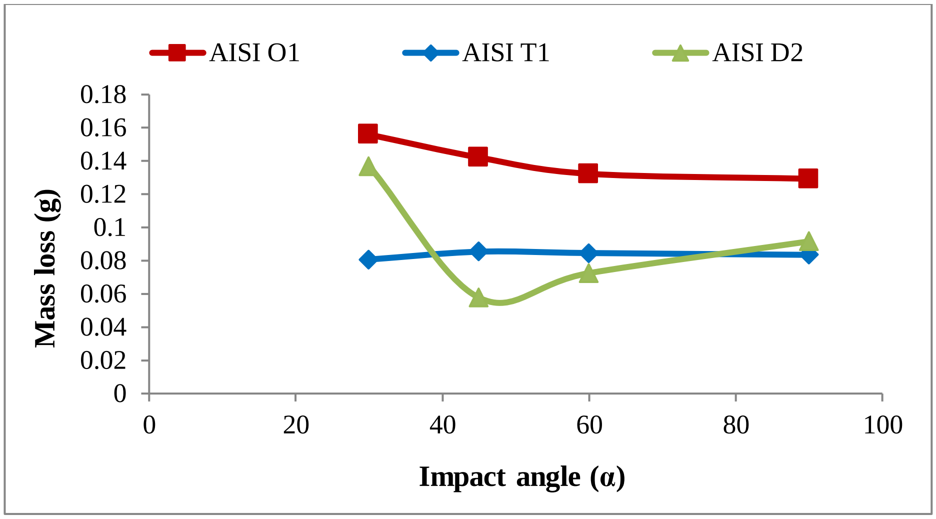
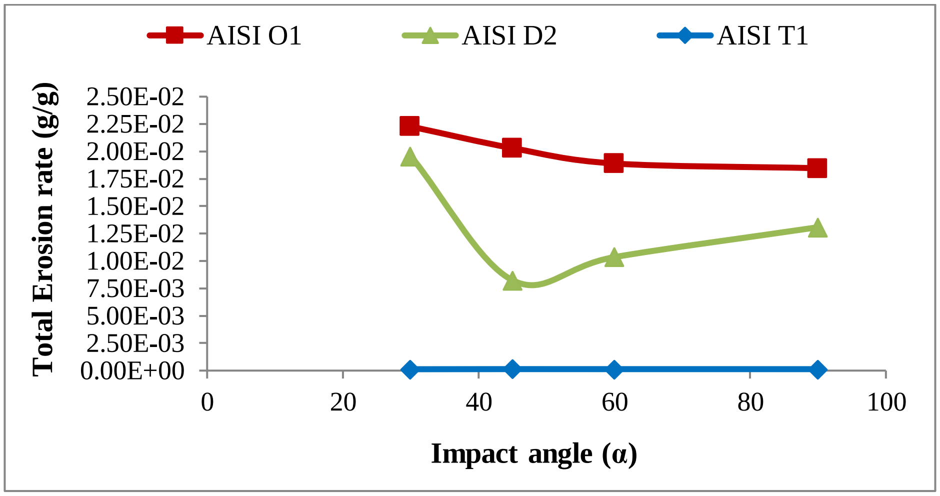
Fig. 6a-b shows graphs of mass loss and total erosion rates versus impact angle, respectively. In this particular case, a comparison was made with the results of the two steels tested in this research work and the AISI T1 steel, which is also a cold work tool steel and was previously tested under the same conditions [21]. All the steels exhibited higher erosion rates at lower impact angles ($\alpha \leq 45°$), which was reduced in most cases when the impact angle was increased to 60° and 90°. Based on the graphs, it can be concluded that these materials showed a ductile behavior in accordance to erosion literature [22]. From the graphs (Fig. 6b), it can be concluded that AISI O1 steel had the lowest erosion resistance, followed by AISI D2, whereas AISI T1 steel showed maximum erosion resistance.



(a)



(b)

Fig. 6. (a) Mass loss and (b) Total erosion rates vs impact angles.

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D. Discussion of results

In relation to the wear mechanisms observed in the tested materials, AISI O1 and AISI D2 steels, there was a notable difference. In AISI O1 steel, a large number of craters were visible on its surface, particularly at 30°, which were not filled with wear debris. This resulted in a greater mass loss and, consequently, a higher erosion rate at this impact angle. In this case, the abrasive silicon carbide particles, upon impact, significantly removed material, leading to a volumetric loss. In contrast, at 90°, although holes and craters were present, they were clearly filled with wear debris, resulting in a lower mass loss at this incidence angle. While craters and holes were seen on the test surfaces of AISI O1 steel, the wear mechanisms in AISI D2 steel were constant micro-cutting, scratching, grooves, and micro-ploughing actions. This could have been caused by the lower hardness of this material, which allowed the abrasive particles, upon impact, to quickly withdraw and slide over the surfaces of this material, acting as a cutting tool and constantly displacing the material and plastically deforming it. This led to a marked difference in the wear damage observed in each test material.

IV. Conclusions

The results presented in this research lead to the following conclusions,

1. In relation to the behaviour of tested steels, it is possible to conclude that AISI O1 presented higher erosion rates compared to those obtained in AISI D2 and AISI T1 (previously tested), at all incidence angles.
2. Typical wear mechanisms of solid particle erosion were identified on each tested material; AISI O1 exhibited large craters in random positions at 30º and filled craters with wear debris and irregular indentations at 90º. On the other hand, micro-cutting, micro-ploughing, pits and wear debris were identified on AISI D2 at 30º and 90º. The craters observed on AISI O1 steel made a clear difference in the erosion rate results.

CRediT (*Contributor Roles Taxonomy*)

Author Contributions: Conceptualization: JR**LC**; Methodology: JR**LC**; Investigation: JA**FF**, V**VM**, AS**C**L; Writing-original draft preparation: SM**SY**, V**VM**, AA**MR**, A**AM**; Writing-review and editing: SM**SY**, V**VM**, AA**MR**; Supervision: JR**LC**, JA**FF**; Formal analysis: JR**LC**, V**VM**, A**AM**.

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Conflicts of Interest: The authors declare no conflicts of interest.

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