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# PENDULAR SCRATCH TESTS AS A TOOL TO EVALUATE ABRASION RESISTANCE OF WELDED COATINGS

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**Abstract.** Mechanical components, especially moving parts, suffer from wear as a result of the high contact pressures and temperatures. To reduce such damage, it is common practice the use of coatings, since the high contact pressures and temperatures and consequently wear mostly occur at the surface. Inconel 625 is widely used in the petroleum industry in the form of thick coatings. It consists of a nickel and chrome superalloy, highly resistant to corrosion, besides presenting high mechanical resistance at high temperatures. However, the use of Inconel 625 in the petrochemical industry also requires that it presents high abrasion resistance due to the possible presence of sand particles in moving contacts. This study used a single pass pendular to evaluate the scratch resistance of Inconel 625 deposits onto carbon steel substrates. In particular, it was evaluated the effect of the variation of the shielding gas composition during deposition of Inconel 625 by gas metal arc welding (GMAW).

**Keywords:** scratch tests, Uppsala's pendulum, abrasive wear, Inconel 625.

## 1. INTRODUCTION

Abrasive wear is one of the most recurrent damages suffered by industrial equipment. The relative movements between the components cause friction in the parts in contact generating wear by abrasion. According to Eyre (Eyre 1976), abrasive wear causes around 50% of failures by wear in the global industry. Even in the present century, developed countries still have large economical losses as consequence of the different forms of wear (Jost 2005). The costs associated with friction and wear and their associated tribological phenomena can account for a large proportion of the Gross Domestic Product (GDP) of most industrial countries (Jost 1966).

Abrasive wear results from the action of hard abrasive particles, where material is removed or displaced from the surface being abraded. Those particles can be free abrasives, abrasives embedded in the opposing surface or hard protuberances in the opposing surface (Hutchings 1992). Those particles can either roll between the surfaces, generating indentations and accumulated damage, or slide between the surfaces, generating grooves. Abrasive wear that occurs in practice is a very complex process that generally involves a combination of all those different particle dynamics.

However, abrasion can be regarded as a combination of substantially simpler events, such as individual scratches and individual indentations (da Silva, Costa et al. 2011). The advantage of using single events to simulate abrasive wear is that they allow a more fundamental understanding of the phenomena involved during abrasive wear. In this respect, sclerometric techniques involve the simulation of a single scratch and normally provide information regarding scratching energy, friction forces during scratching, micromechanisms involved during scratching, etc.

One very simple variant of the sclerometric techniques uses a pendular tester. The first pendular sclerometric rig was developed by Vingsbo and Hogmark, at the University of Uppsala, thus becoming known as the Uppsala's pendulum (Vingsbo and Hogmark 1984). The rig was generated from the structure of a Charpy impact test machine. An indenter of known geometry, made of WC-Co cermet, was placed at the tip of its hammer, thus forming the pendulum. The pendulum, when released from a certain height, hits the flat surface of the specimen, thus forming a groove. With the height difference of the pendulum it is possible to determine the energy spent during scratching (Figure 1). A scheme of

an Uppsala pendulum is shown in Figure 2. From this energy ( $E$ ) and the weight loss to produce each groove ( $W$ ), a specific grooving energy ( $e(W)$ ) can be derived as:

$$e(W) = kW^{q-1} \quad \text{Eq. 1}$$

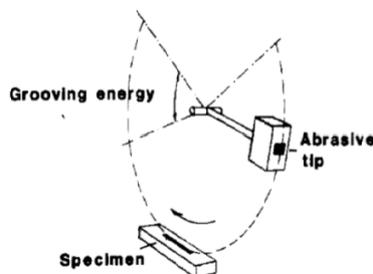


Figure 1. Schematic representation of the pendulum grooving technique (Vingsbo and Hogmark 1984).

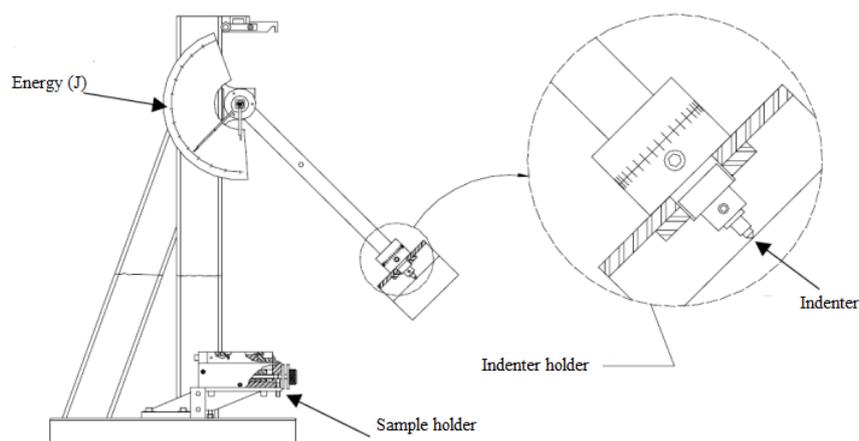


Figure 2. Schematic representation of a pendular sclerometer and its main components (Franco 1989).

Since then, the Uppsala's pendulum has been used to investigate abrasive resistance of various materials, being particularly suited to investigate abrasion under dynamic loading (Liang, Li et al. 1996). New advances in the technique include force measurements during scratching, the definition of other parameters, such as: *i*) dynamic hardness, given by the ratio between the integral of the normal force during the whole scratching event and the groove volume, and *ii*) scratching friction coefficient (Liang, Li et al. 1996).

It has been used to investigate abrasion resistance of different materials, such as Al-Si alloys (Franco 1989), polymers (Briscoe, Delfino et al. 1999), ductile cast iron (Vélez, Tanaka et al. 2001), brittle composites (Lamy and Burtin 1992), as well as to evaluate the efficiency of cutting fluids during machining (Sales, Machado et al. 2007).

In this work, an Uppsala's pendulum is used to investigate the abrasion resistance of Inconel 625. Inconel is the commercial denomination of a Ni-Cr superalloy. It is typically used in applications where high temperatures combined with a corrosive environment are present due to a thick, stable passivation oxide layer formed under heating. Inconel 625 has a nominal chemical composition of 58 %wt. Ni (min.), 20 to 23 %wt. Cr, 8 to 10 %wt. Mo, 3.15 to 4.15 %wt. Nb and 5 %wt. Fe (max.), is one of the most common nickel-based superalloys.

Due to the high costs of nickel-based alloys, they are normally deposited onto a much cheaper substrate using different deposition techniques. Its relatively good weldability when compared with many other nickel alloys encourages the use of welding deposition techniques. Among the different welding techniques, gas metal arc welding (GMAW) is not the most recommended technique, since it leads to high dilution of the substrate into the welded coating

(Badisch and Kirchgaßner 2008). However, the use of GMAW has the advantage of very high deposition rates (Scotti and Ponomarev 2008), reducing deposition costs substantially.

In another work, the use of CO<sub>2</sub> in the shielding gas was investigated as a means to improve the deposit wettability onto the substrate and arc stability, despite its potential negative effect on corrosion resistance of the deposits (Tavares, Souza et al. 2017). The results showed improved bead geometry and lack of defects between passes, but a small hardness reduction when the amount of CO<sub>2</sub> in the shielding gas increased. Microabrasion tests using a slurry of small silica particles did not show any statistically significant difference between the wear coefficients for the deposits with CO<sub>2</sub> when compared with deposition using pure Argon as the shielding gas.

However, since abrasion is a very complex process, and commonly abrasion tests lead to substantially high variability between tests, it is possible that microabrasion tests were not suited to detect small differences between their abrasion resistance. In the present work, single-pass pendular scratch tests are used to further understand the effect of CO<sub>2</sub> addition on the abrasion resistance of Inconel 625 GMAW deposits onto carbon steel substrates. This required the development of a new test rig based on the principle of the Uppsala's pendulum.

## 2. METHODOLOGY

### 2.1. Development of the apparatus

A test rig was developed to evaluate abrasion resistance via single pass scratching tests, since abrasion can be regarded as the interaction of multiple events involving the contact between a hard abrasive and the surface (da Silva, Costa et al. 2011). It is based on the principle of the Uppsala's pendulum.

The pendular sclerometer, or Uppsala's pendulum (Figure 3) was fabricated from the structure of a Charpy impact tester (Souza 1982). It involved the substitution of the original hammer by a high speed indenter of known geometry (Figure 3.b). Masses of different values can be added to vary the pendulum energy. The masses that can be added, the length of the arm and the initial height from where the indenter is launched were calculated in order to result in pendulum energies in the range between 4.5 and 11.5 J, which covers the energies of most test rigs available in the literature (Franco 1989) (Liang, Li et al. 1996) (Briscoe, Delfino et al. 1999). The new accessories that were developed to convert the Charpy tester into a pendular sclerometer are interchangeable, so that it can be easily setup as either a Charpy tester or an Uppsala's pendulum.

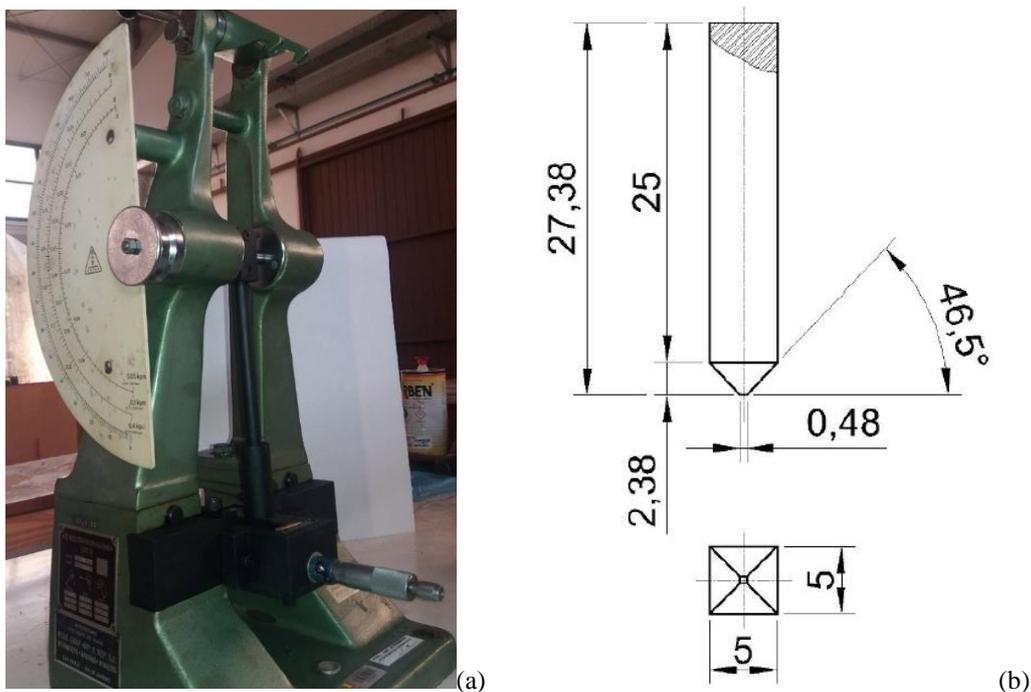


Figure 3. Developed Uppsala's pendulum test rig (a); indenter geometry (b).

The scratch penetration depth is controlled via the displacement of specially designed specimen holder (Figure 4) with a vertical displacement resolution of 0.25  $\mu\text{m}$ . The specimens are referenced with the aid of an open circuit rig, which is closed and then fires a sound and visual signal when the indenter tip comes into contact with the specimen surface (Figure 4.b).

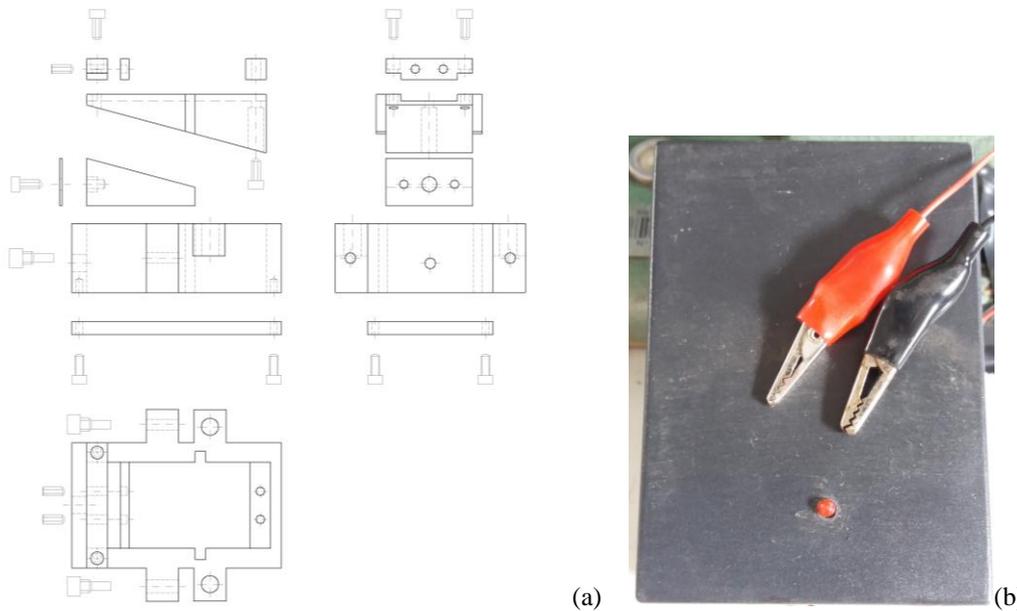


Figure 4. Control of scratch penetration depth: (a) scheme of the specimen holder; (b) open circuit rig.

## 2.2. Specimens

For the preparation of the specimens, Inconel 625 wire was deposited onto AISI 1020 carbon steel substrates. The weaving technique was used to increase wettability, using a 6-degree of freedom robot. During deposition, different gas mixtures were used as shielding gas, consisting of: *i*) 100% Ar; *ii*) Ar+8%CO<sub>2</sub>; and *iii*) Ar+35%CO<sub>2</sub>. Further details can be found in (Tavares, Souza et al. 2017).

The deposited area was 150x140 mm<sup>2</sup> and the final coating consisted of two layers. After deposition, specimens were cut (Table 1) and their top surfaces were ground to obtain a flat surface. After grinding, the specimens were polished using sand papers down to mesh 1000 and then with alumina paste.

Table 1. Specimen description.

	Specimen I	Specimen II	Specimen III
Shielding Gas	100% Ar	8% CO <sub>2</sub> +Ar	25% CO <sub>2</sub> +Ar
Dimension	60 x 19 x 10 mm	60 x 16 x 10 mm	60 x 14 x 10 mm

Electrolytic etching was performed with a chromic acid solution under a voltage of 60V during 20 seconds, to identify the microstructures of the deposits using an optical microscope. The specimens were then sanded again with 1000 grit sandpaper and repolished.

## 2.3. Scratch tests

Before the tests, the pendulum was freed without any specimen to identify the energy spent as a result of friction, wear of the rig and other forms of mechanical energy heatsinks. The pendulum was dropped from an angle of 154°. A reduction of 14° in the amplitude of the arc generated by the pendulum was verified. From this pre-test a scale was set up in percentage where the 0 ° point of the scale equals 100% energy consumption and the 140 ° point indicating that there was no energy consumption.

For the tests, the specimens were carefully mounted in the specimen holder and then referenced as described in Figure 4.b. The pendulum mass was constant (19.6 N). The scratch penetration depth in all the tests was 50  $\mu\text{m}$ .

After the scratching tests, the grooves produced were observed using scanning electron microscopy (SEM) to identify the scratch mechanisms.

### 3. RESULTS AND DISCUSSIONS

Figure 5 presents the microstructures of the Inconel 625 deposits. They show dendritic structure, which is typical of welded deposits (Hou, He et al. 2007). They also present non-equilibrium, interdendritic precipitates (Chang, Lai et al. 1994), which become coarser as the amount of  $\text{CO}_2$  used in the shielding gas increases.

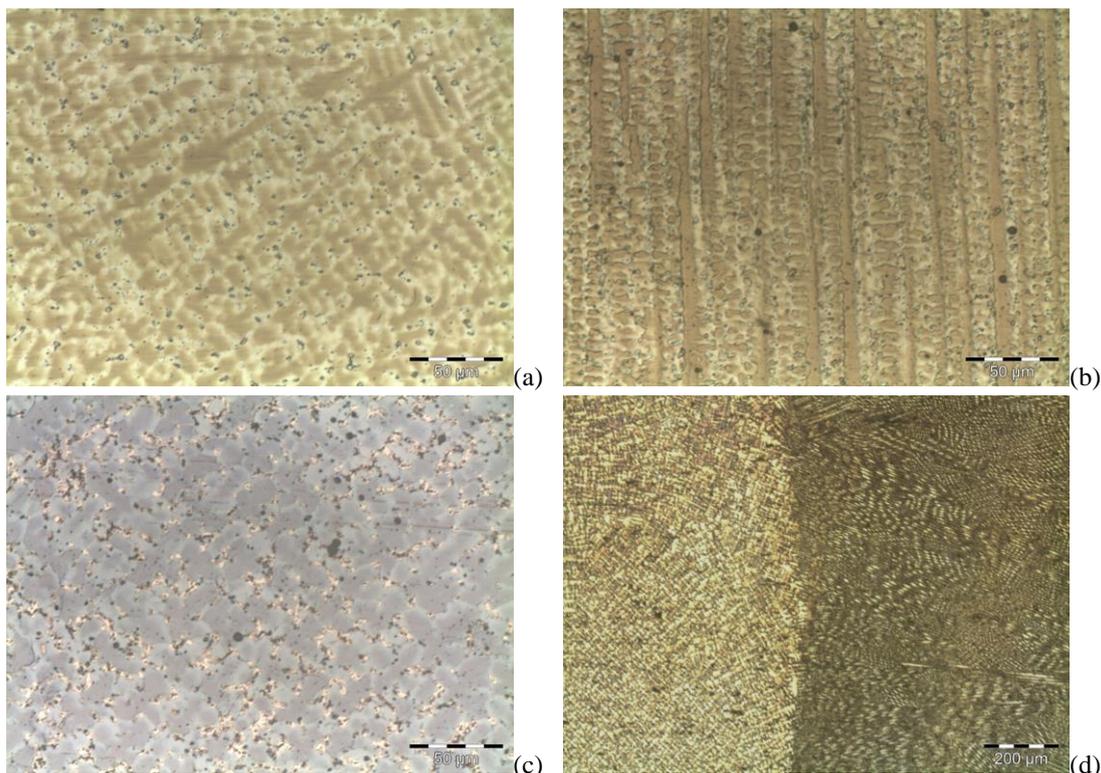


Figure 5. Microestrutture of the deposits: (a) 100% Ar; (b) 8%  $\text{CO}_2+\text{Ar}$ ; (c) 25%  $\text{CO}_2+\text{Ar}$ , (d) 25%  $\text{CO}_2+\text{Ar}$ , interface between the two welded layers, 25%  $\text{CO}_2+\text{Ar}$ .

Eight scratches were produced in each specimen (Figure 6). From those, three scratches for each specimen that presented the most similar penetration depths were selected for the analysis.

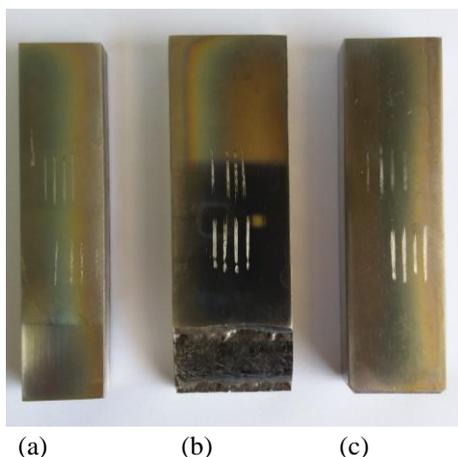


Figure 6. Scratches generated in specimens: (a) 25%  $\text{CO}_2+\text{Ar}$ ; (b) 100% Ar; (c) 8%  $\text{CO}_2+\text{Ar}$ .

Table 2 summarizes the results relative to the computation of the scratching energy for the different tests. The specimen that used a shielding gas of 100% Ar presented the highest scratch energy. As the amount of CO<sub>2</sub> in the shielding gas increased, the scratching resistance decreased.

Table 2. Scratching energy results.

Shielding Gas	25% CO <sub>2</sub> + Ar		8 % CO <sub>2</sub> + Ar		100% Ar	
Scratch	Angle	Scratching Energy (J)	Angle	Scratching Energy (J)	Angle	Scratching Energy (J)
Repetition 1	102.0°	3.35	95.0°	3.12	76.0°	2.50
Repetition 2	106.0°	3.48	98.0°	3.22	76.0°	2.50
Repetition 1	101.0°	3.32	96.0°	3.15	75.0°	2.46
Mean Scratching Energy	3.38		3.17		2.49	
Standard deviation	0.09		0.05		0.02	

The scratch morphologies, observed using SEM, are presented in Figure 7. The scratches produced in the specimen using pure Argon showed some discontinuity in the grooves produced in the beginning of the scratching test, as shown in Figure 7.a. This initial discontinuity reduced substantially as the amount of CO<sub>2</sub> increased (Figure 7.b and c). This tendency repeated in all eight scratches produced in each specimen. After this initial discontinuity, all grooves showed similar characteristics. All specimens presented ductile behavior, as exemplified in Figure 7.d for a scratch produced in a specimen with 25% CO<sub>2</sub>. Some ploughing could be observed at the edges of all the scratches produced (indicated by arrows), but to a very limited extent.

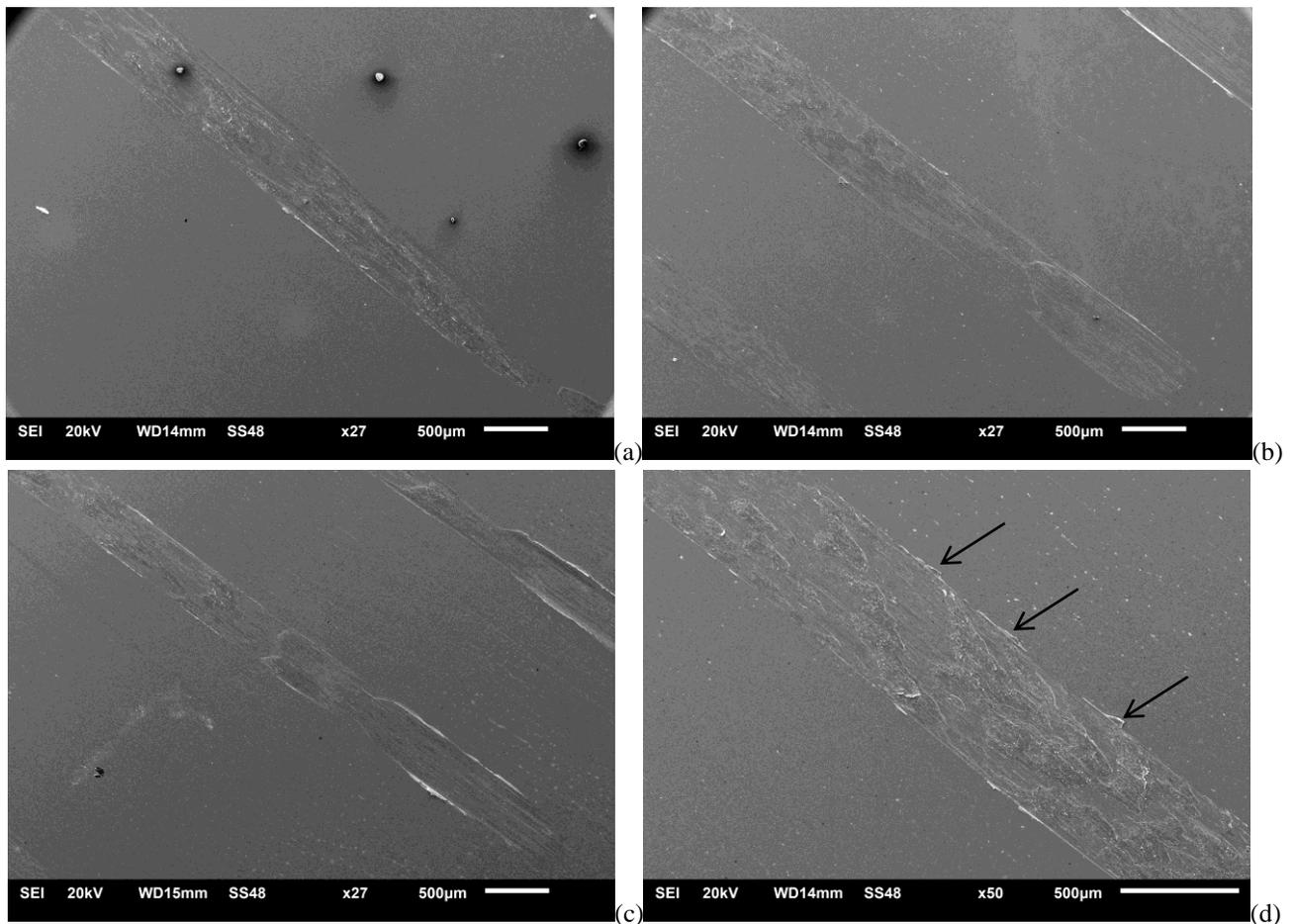


Figure 7. Morphologies of scratches: (a) 100% Ar; (b) (c) 8% CO<sub>2</sub>+Ar; (c) 25% CO<sub>2</sub>+Ar.

Therefore, it seems that although the complexity and great variability of the microabrasion tests did not allow to detect differences in abrasion resistance due to the addition of CO<sub>2</sub> in the shielding gas during GMAW deposition (Tavares, Souza et al. 2017), their scratching resistance was affected. The addition of CO<sub>2</sub> produced coarser precipitates, probably due to the increase of the dilution of the substrate into the coating. This is likely to occur because the addition of CO<sub>2</sub> increases the heat generated in the plasma column (SUBAN, 2001). This apparently reduced their resistance to scratching, resulting in lower scratching energies. The discontinuities that were observed in the beginning of the scratches when using CO<sub>2</sub> need to be further investigated. Future instrumentation of the test rig to measure scratch forces might help to understand in more detail the differences observed.

#### 4. CONCLUSIONS

A new test rig based on the principle of the Uppsala's pendulum was developed. Single pass scratches were produced in Inconel 625 deposits onto carbon steel substrates produced using GMAW with different shielding gases. The results showed that:

1. The test rig allowed to detect differences due to the addition of CO<sub>2</sub> in the shielding gas.
2. The increase in the amount of CO<sub>2</sub> in the shielding gas reduced scratching resistance, probably due to the presence of coarser precipitates.

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