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The abrasion resistance estimation of the C120 steel by a multi-pass dual-indenter scratch test

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KEYWORDS

Abrasion resistant steels
Scratch test
Worn surface
Work hardening
Wear

ABSTRACT

In this work, a new scratch test method - multi-pass dual-indenter scratch test - is used to estimate the abrasion resistance of C120 steel. This steel is used in the moulds manufacture for injection of plastic materials filled with glass fibres that are very abrasive. Rp3 tools steel, with different work hardening capacity, was used for comparison. The methodology of multi-pass dual-indenter scratch test approaches the real state of abrasion by performing the scratch tests using a high indenter, that generates a stable large pre-scratch with work hardening and a small indenter to assess the wear performance, excluding the geometric effect of the contact. This method is testing the damage formation during the effective scratching process and its interaction with the damage in the deformed surface layer caused by the prior local scratching deformations. In this way, the abrasion resistance of the two hardened steels with different hardness, 59 HRC (C120) and 62 HRC (Rp3) was estimated.

1.0 INTRODUCTION

Abrasion is a wear mechanism frequently appeared and observed in various industrial applications such as automobiles, transportation, mining, minerals processing, agricultural industry, and composite materials with glass fibre processing industry. The type of industrial problem depends on the configuration of abrasive wear: with two bodies, or with three bodies closed or open. In addition to the various operating conditions, such as normal load and sliding

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speed, the abrasive wear is strongly related to the angular shape of the abrasive particle (Mezlini et al., 2006).

Several studies have investigated the influence of angle, and particles abrasion. So, (Stachowiak, 2000) showed that there was a good correlation between particles abrasion and abrasive wear speed.

Some authors (Vencl et al., 2013) have shown that a hard material is considered as a useful and economical way to improve the performance of components subjected to severe abrasive wear conditions, with a wide range of fill materials. It was investigated and compared the abrasion resistance of three different hard coatings (two on base of iron and one WC base), which were intended to be used to repair the impact plates of the ventilation system of the mill. Abrasive wear tests have been carried out using a scratch tester, in dry conditions. Three normal loads of 10, 50 and 100 N were used, and a constant sliding speed of 4 mm/s. Scratching was chosen as a relatively light and fast testing method. The wear mechanism analysis showed a significant influence of the hard coating structure, which, together with the hardness, determined the abrasion resistance of the coating.

Abrasion resistance is a very complex response of a material in a tribo-system involving many variables (Mutton and Watson, 1978). In addition to the testing conditions, the abrasion resistance can be correlated with different mechanical properties of the metallic structure, and ultimately with the microstructural development during the process. At a first approximation, the hardness is used predominantly as an indicator for enhancing the abrasion resistance of steels, as a result of the general hypothesis that there is a monotonous relationship between abrasion resistance and material hardness. Evolution of the microstructure of a material at and beneath the worn surface differs from the initial microstructure due to the plastic deformation and local work hardening. During the equilibrium state of the real abrasion process, the work hardening of the layer under the surface subjected to abrasive wear (Xu, 2016). This evolution of the local mechanical properties and changes in deterioration mechanisms in the area exposed to abrasive attack is seen as one of the main obstacles to build a general and quantitative model for abrasion speed depending on the mechanical properties of the exposed material.

Other authors (Mezlini et al., 2006) reported about the abrasive wear of aluminum alloys 5xxx, which is a major problem in industrial applications. First, the influence of hardening on the abrasion resistance is investigated. An aluminum alloy work hardened and annealed is subjected to the repeated scratch test using a spherical/ planar configuration. It is shown that in the early stage of repetitive sliding, the work hardening increases the resistance at abrasion wear. In the second part, the influence of the indenture geometry on the abrasive wear is investigated. Repeated scratch tests with conical indenter were performed on the same aluminum alloys. The scratch test using a conical indenter has shown that work hardening treatment (H24) on the aluminium alloy 5xxx does not improve the wear resistance. Moreover, the conical indenter induces a greater wear than the spherical indenter in the repetitive sliding with small number of cycles (10 cycles). A correct interpretation of these phenomena is then proposed.

Inspired by the understanding of the real abrasion process and derived from the conventional scratch test, (Xu et al., 2015a) has extensively presented a design concept of the scratching methodology that uses not only a single indenter but combines a large indenter and a small indenter. In this scratching methodology, the large indenter is designed to produce a surface local layer pre-deformed with equivalent work hardening as that of the surface layer during an abrasion test. The small indenter sliding on the pre-scratched surface is used to mimic the behaviour of single particles in an abrasion process in real equilibrium state, involving a surface state work hardening. This testing method proves not only the deterioration during the real scratching process (abrasion), but also proves its interaction with the deterioration in the deformed surface layer. The deformation is due to the local anterior deformations by scratching.

Scratch tests were performed (Xu et al., 2015b) on a high strength low alloyed (HSLA) steel to investigate the scratch resistance correlations, representing somewhat the abrasion resistance, with microstructural characteristics and different hardness. HSLA steel has been subjected to some thermal treatment cycles selected to produce different microstructural combinations, thereby obtaining different abrasion resistances. The results of the scratch tests suggested that only a high hardness cannot guarantee a high scratching (abrasion) resistance, but also microstructural characteristics play an essential role in determining the abrasion resistance. More specifically, it has been shown that a dual-phase microstructure (ferrite plus martensite) with a relatively low hardness has a better abrasion resistance than a fully martensitic microstructure with a greater hardness.

Furthermore, observations of the scratch scars revealed different characteristics of the scar surface and of the particles: the dual-phase microstructure led to a smooth surface of the scar and with flat wear particles, while a fully martensitic microstructure led to a relatively coarse surface of the scar, with sharpened wear particles. This is very damaging to abrasion resistance due to its secondary damage at the surface. Furthermore, the results suggested that the scratch test can well mimic the nature of the abrasive wear and, therefore, provide rapid, reproducible and quantitative information on the abrasion resistance of the various microstructures.

Xu et al., 2014 used the approach of the multi-pass dual-indenter scratch test to investigate the behaviour of the abrasive wear at sliding of a contact point and to establish a relationship between the thickness and characteristics of the hardened layer by formed work and the resulting failure mechanism. Of particular interest is the comparison of the area resulted from the multi-pass dual-indenter scratch test with that of the (ASTM G65) abrasive wear test and the exploration of the notion that the multi-pass dual-indenter test can offer a view of abrasion resistance for working conditions beyond the G65 standard conditions (load and particle size).

In this paper, for the abrasion resistance estimation of the C120 mould steel, multi-pass dual-indenter scratch test, adapted to an own-concept tester, was used. The difference from the original configuration (Xu, 2016) was that the radius of the large indenter used by the authors was 2.5 mm and the small indenter of 1 mm. The main objective of the paper is to determine whether the failure mechanism changes between the two scratching steps of the test.

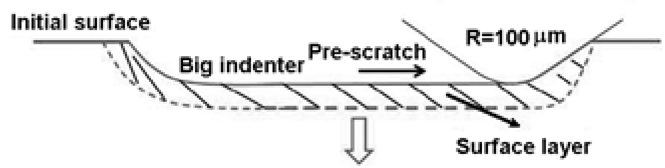
2.0 EXPERIMENTAL PROCEDURE

To understand the context, Figure 1 presents the original configuration of the multi-pass dual-indenter scratch test (Xu, 2016).

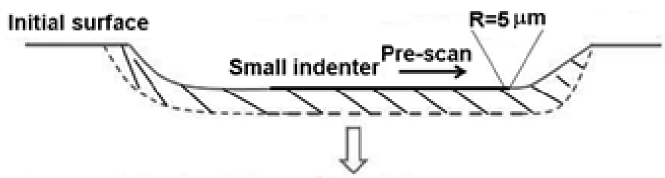
The original test has 3 stages:

1) Creation of a pre-deformed surface local layer, similar to the layer presented during the abrasion testing, realized by pre-scratching with a large indenter (R = 100 μm);
2) Pre-scanning with small indenter (R = 5 μm), without load, of the central region profile of the wear scar generated by the large indenter, made by pre-scratching with the large indenter;
3) Scratching with the small indenter (R = 5 μm), highlighting the local deterioration of the deformed surface layer and recording the evolution of damage by scratch.

All sliding layouts realized with the small indenter were at the centre of the pre-scratching tracks made by the large indenter. The schematic configuration of this multi-pass scratch test with two indenters is presented in detail in Figure 1, taken from the original work of (Xu, 2016). Depth measurement consists of two steps: first, pre-scanning of the surface profile with the small indenter at a very low load of 0.03 N, and second, scratching of the same trace with the small indenter using a load of 0.3 N. The penetration depth is derived from the difference between the two stages.



(a)



(b)

(c)

Figure 1: Configuration of multi-pass dual-indenter scratch test. Adapted after Xu, 2016.

In the present research, the scratch resistance was analysed with a wear and fatigue tester, of own conception, shown in Figure 2(a). Figure 2(b) shows the inclination with the angle $\alpha = 15^{o}$ of the diamond tip. The creation of the pre-deformed surface local layer was made by scratching with a 2.5 mm diameter tip, and the second scratch was made with the small indenter having a diameter of 1 mm. The applied loads were in the 2.5 N - 125 N range.

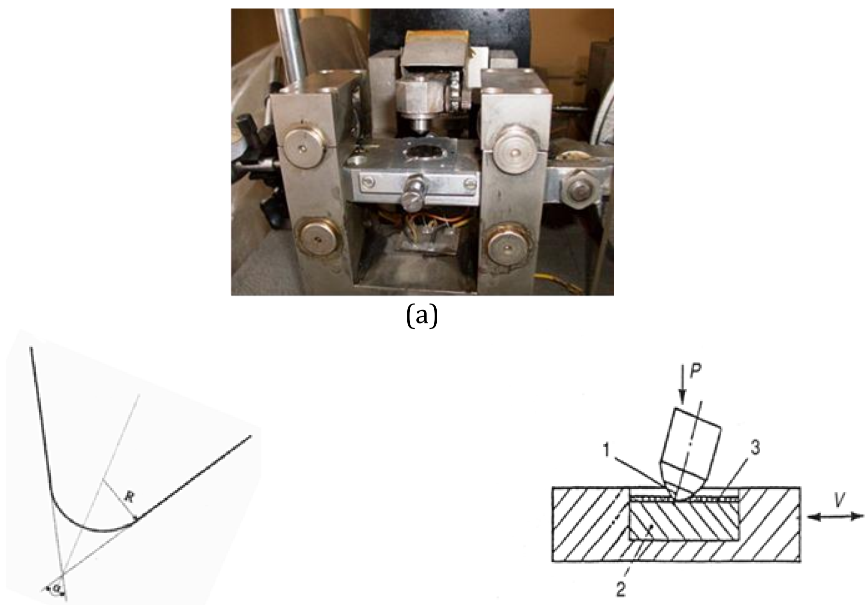
The use of a friction couple that implies natural diamond against the material that will be investigated allows a considerable simplification of the test device. The movement is in this case a pure sliding motion, common in many tribometers with continuous or alternative motion, and the tested sample is a circular plate (disk) of 11 mm diameter and 2.5 mm thick.

The samples were hardened, rectified and polished mirror, according to the standard procedures. Figure 2(c) shows a scheme of the scratch tester. The disk (2), made from investigated material, has a unidirectional movement (for scratch tests), or an oscillatory movement (for fatigue tests), respectively. The disk is loaded, in first instace, by an indenter with diamond spherical segment, with a radius R of 2.5 mm (1), and then by an indenter with diamond spherical segment with a radius of 1 mm. Diamond indenter can also be easily adapted to any wear testing device, with continuous or oscillating motion. The plate may be coated – or not, during the test, with a lubricant thin layer (3).

For the calibration of the method, at the beginning, double scratch tests with the two indenters were made, at one pass, and then with 10 passes. Prior to testing, the sample surface microhardness was measured, and then the microhardness of the surface of each scratch made with the large indenter, respectively, with the small indenter, in order to assess the evolution of the scratch scar surface hardness following the dual indentation test.

In this paper, samples of C120 mould steel and, for comparison, samples of Rp3 bearing steel were used. The hardness and roughness R_a of all polished surfaces of the samples used were measured. Samples with roughness R_a = 0.015 µm, R_a = 0.045 µm, R_a = 0.075 µm and R_a = 0.19 µm were used.

C120 steel samples had a hardness of 59 HRC and those of Rp3 a hardness of 62 HRC.



(a)

(b) (c)

Figure 2: Scratching tester with a diamond spherical segment. (a) General view; (b) Indenter tilt; (c) Functional scheme: 1 – natural diamond spherical segment; 2 – sample of tested material; 3 – lubricant (bovine serum). The plate has an oscillatory movement.

3.0 RESULTS AND DISCUSSION

After the performance of multi-pass dual-indenter scratch tests, the samples were inspected by scanning electron microscopy (SEM), as well as by optical microscopy, microphotographs of their scratches being made.

The most relevant SEM microphotographs are shown in Figure 3 for C120 steel (59 HRC) with a roughness of R_a = 0.015 µm.

It can be seen that the scar produced at 2.5 N has a width of about 37 µm, at 5.0 N is 25.7 µm, 74.1 µm at 10.0 N, 111.1 µm at 20.0 N, 163 µm at 40.0 N, 185.2 µm at 80 N, reaching 214.8 µm at 125 N.

It is clearly seen that the surface material is pushed to the sides of the scratch, as well as the formation of wear debris expelled to the edge of the scar. The scar presents a typical aspect of ploughing wear.

At loads of 2.5, 5.0, 10.0, 20.0 and even 40.0 N, particles that remained adhered inside the scratch were observed, while at 80.0 N and 125.0 N, are expelled from the scratching scar. Taking into account the shape of the scars bottom at loads between 2.5 N and 5.0 N, the removed material seems to have been torn out from the substrate.

Figure 4 shows the scratching scars on the surfaces of Rp3 steel samples (62 HRC) with roughness R_a = 0.015 μm at loads of 10.0 N, 20.0 N, 40.0 N, 80.0 N and 125.0 N.

In the case of Rp3 steel (62 HRC), it can be seen that the scratching scar produced by the large indenter at 2.5 N has a width of about 51.9 μm, at 5.0 N is 46.7 μm, 88.9 μm at 10 N, 133.2 μm at 20 N, 200.7 μm at 40 N, 251.8 μm at 80 N, reaching 281.5 μm at 125 N.

These values are higher than for C120 steel (59 HRC). At first sight, this may seem surprising, given that the hardness of the Rp3 steel is higher. However, the explanation should take into account that the scars depths have been found to be much smaller (Figure 5), and the amount of material removed by scratching is incomparably lower than for C120 steel.

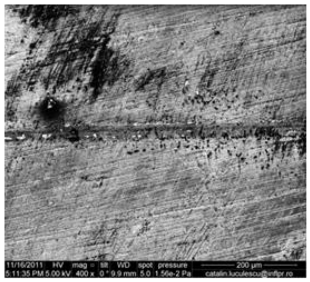
By comparing the images in Figure 3 with the images in Figure 4, it can be seen that the sides of the scratching scars on the Rp3 samples surfaces are more net than those on C120, the material expelled on the sides of the scars is much less, the amount of wear particles is much smaller, and the particles remaining adherent in scratching scars are small and sporadic. From the images in Figure 3 and Figure 4 it can be seen that at a certain value, the surface layer is removed during the scratch test. When the layer is removed, along the main scratch, destruction of the underlayer was noticed when the applied force is higher. The depths of the scratches obtained are different depending on the force values.

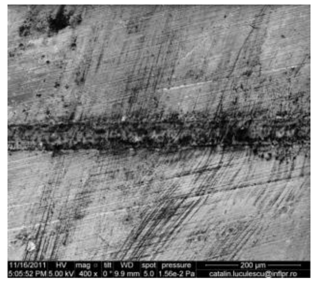
In this paper, for the pre-scratch state at 5 N, it was observed a small amount of delamination on the side of the scratch, as shown in Figure 3 and Figure 4. When the load is increased to 15 N, a severe delamination occurs due to the fragile nature and low capacity of work hardening of the martensite. The failure mechanism has changed into micro-cracks and cutting mechanism. Consequently, the (additional) depth of the scratch increases significantly.

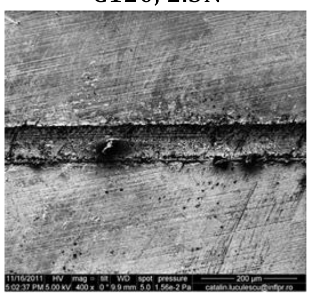
For C120 steel, scratching at low load produces some craters due to the ploughing as shown in Figure 3, while for pre-scratching at 15 N, perpendicular cracks propagate to the scratch track and the delamination appears showing micro-cracks and cutting mechanism. It is important to note that these cracks do not occur even after pre-scratching with the big indenter, but only after the second scratching with the small indenter made in the centre of the scratch using the large indenter. This indicates that the failure mechanisms revealed here are associated with the scratch resistance of the work hardened surface, which may differ from the scratch resistance of the original surface.

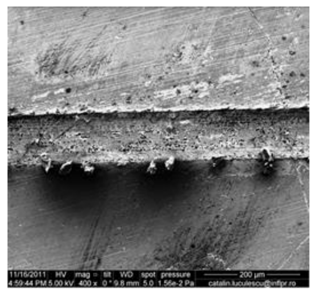
In essence, it was noticeable for both types of steel that at the increase of the large indenter load, the scratch depth due to the small indenter drops a bit first, and then starts to increase if the large indenter load increases. Decrease of the scratch depth reflects the effect of hardening by deforming the sub-surface layer due to pre-scratching, which corresponds to the surface hardening regime.

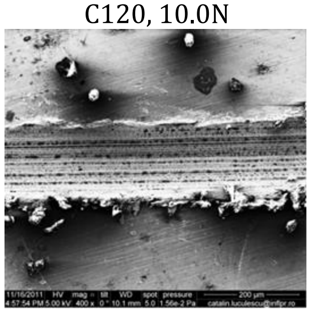
The image of scars made after the scratching with the small indenter (R = 1 mm) on the C120 and Rp3 samples are shown in Figure 6 and Figure 7, respectively. These represent the results of the multi-pass dual-indenter scratch test, under the adopted test conditions.

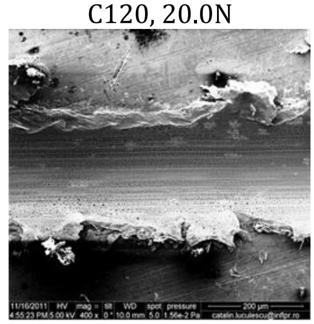

C120, 2.5N


C120, 5.0N


C120, 10.0N


C120, 20.0N


C120, 40.0N


C120, 80.0N

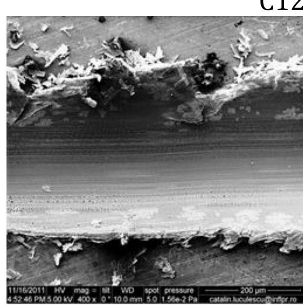

C120, 125.0N

Figure 3: SEM microphotographs of the scratching scars on the surfaces of C120 steel samples (59 HRC) made at 10.0 N, 20.0 N, 40.0 N, 80.0 N, and 125.0 N loads, with the indenter having a radius of 2.5 mm.

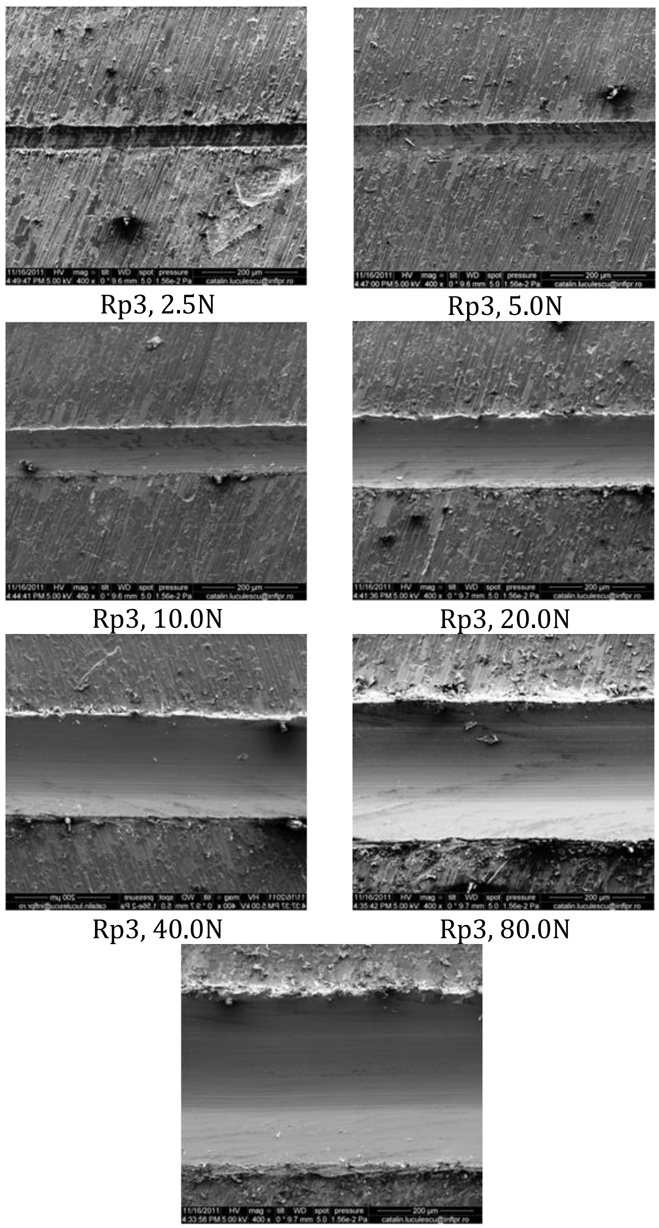
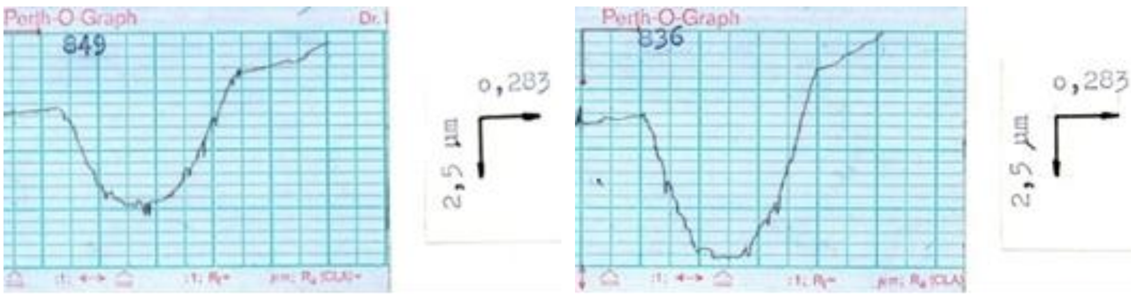


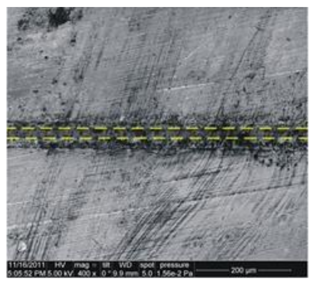
Figure 4: SEM microphotographs of the scratching scars on the surfaces of Rp3 steel samples (62 HRC) made at 10.0 N, 20.0 N, 40.0 N, 80.0 N, and 125.0 N loads, with the indenter having a radius of 2.5 mm.



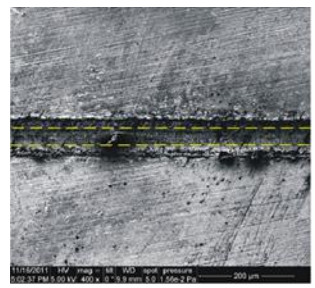
(a) (b)

Figure 5: Recordings of the cross-sectional profile of the scratching scar made by the large indenter on the (a) Rp3 and (b) C120 steels, at 5.0 N.

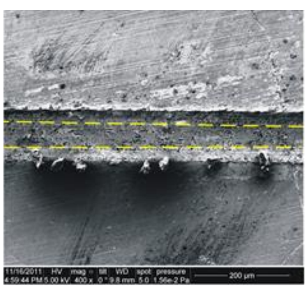
C120, 2.5N



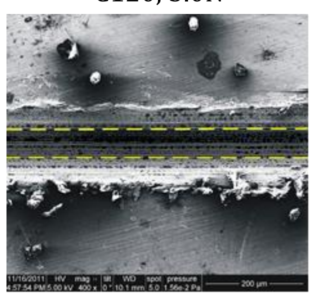
C120, 5.0N



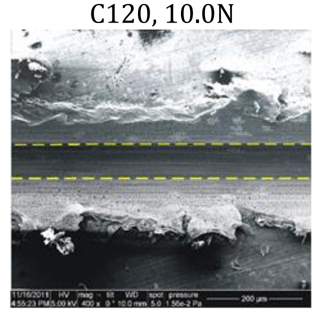
C120, 10.0N



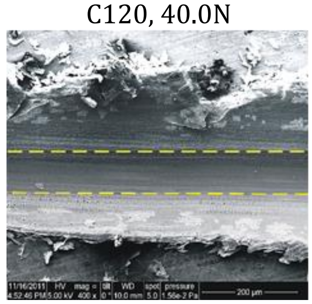
C120, 20.0N



C120, 40.0N



C120, 80.0N



C120, 125.0N

Figure 6: SEM microphotographs of the scratching scars on the surfaces of C120 steel samples (59 HRC) made at 10.0 N, 20.0 N, 40.0 N, 80.0 N, and 125.0 N loads, with the indenter having a radius of 1 mm (dual indentation), after 10 passes (multi-pass), i.e. multi-pass dual-indenter.

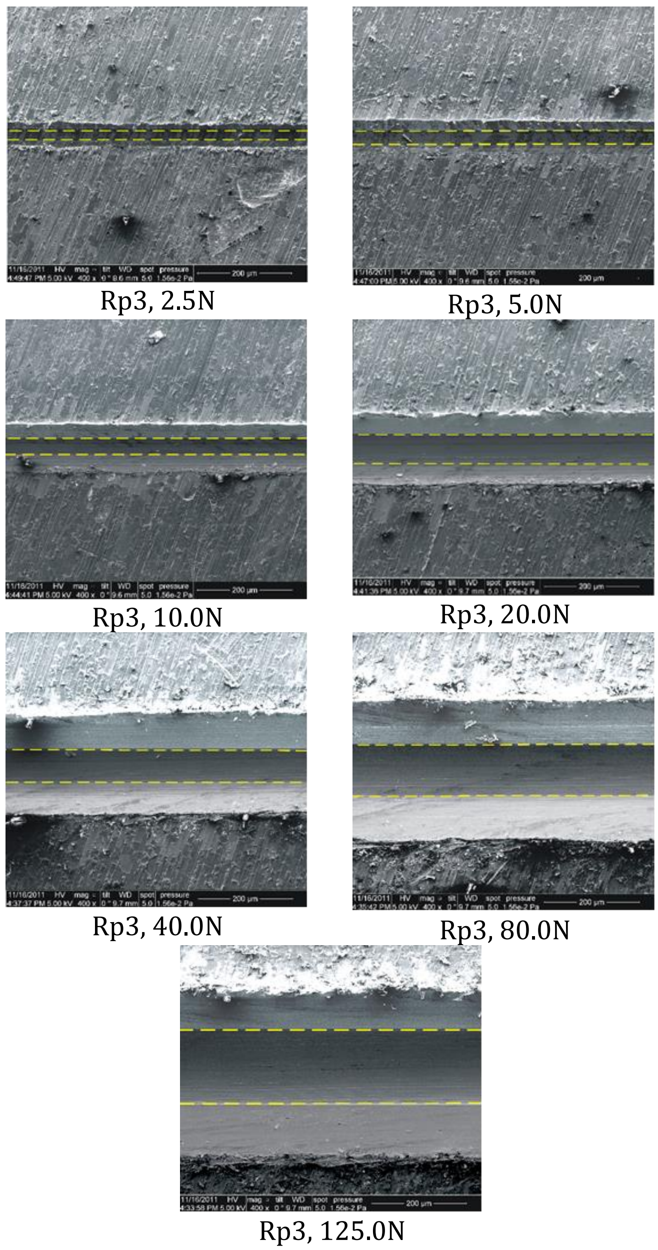


Figure 7: SEM microphotographs of the scratching scars on the surfaces of Rp3 steel samples (62 HRC) made at 10.0 N, 20.0 N, 40.0 N, 80.0 N, and 125.0 N loads, with the indenter having a radius of 1 mm (dual indentation), after 10 passes (multi-pass), i.e. multi-pass dual-indenter.

The Vickers micro-hardness 0.05 kgf of the samples was measured before the dual scratch test and of the scar bottom after each of the two scratching steps, with the two indenters, to see the effect of this multi-pass dual-indenter scratch test.

Table 1 shows the average microhardness measured on the surfaces of the C120 and Rp3 steel samples before the dual scratch tests, and Tables 2 and 3 show the average microhardness $HV_{0.05}$ measured on the surface of scratch scar (1 pass) and, respectively, the average microhardness $HV_{0.05}$ measured on the surface of the scratch scar multi-pass dual-indenter (5 passes).

Table 1: The average microhardness measured on the surface of the C120 and Rp3 steel samples before the dual scratch tests.

Sample	Microhardness $HV_{0.05}$ of the surface material	Microhardness $HV_{0.05}$ of the material under the surface
C120	349	349
Rp3	438	438

Table 2: The average microhardness $HV_{0.05}$ measured on the surface of the scratch scar (1 pass).

Sample	After passing with the large indenter (R = 2.5 mm)	After passing with the small indenter (R = 1.0 mm)
C120	370	395
Rp3	464	472

Table 3: The average microhardness $HV_{0.05}$ measured on the surface of the scratch scar multi-pass dual-indenter (5 passes).

Sample	After passing with the large indenter (R = 2.5 mm)	After passing with the small indenter (R = 1.0 mm)
C120	394	407
Rp3	470	478

4.0 CONCLUSION

In this paper, the authors have checked and applied a modified application of the multi-pass dual-indenter scratch test to reproduce the real abrasive wear process of two different types of steel, with different destinations (C120 for injection moulds and Rp3 for tools) and different work hardening capabilities, and to see if this test can be correlated with the ASTM G65 abrasion test, that uses dry sand and rubber wheel. Although modified against the original test (Xu, 2016; Xu et al., 2015a; Xu et al., 2015b), the test used reveals the two stages of the abrasion process and reveals the deterioration mechanisms appropriate to the studied materials, under different loading conditions. It has been observed that the abrasion and scratch resistance is controlled by the development of the sub-surface layer work hardened, i.e. of the surface hardening equilibrium and the thickening of the deformed sub-surface layer, which is ultimately determined by the capacity of work hardening.

Considering the correlation between the scratch depth and the thickness of the sub-surface layer, the latter one may be considered as a parameter to justify whether the material is applied in its hardening area or in its deterioration area. It can also provide orientative information to select the appropriate material for a particular application or to adjust the performances of application conditions, to allow the best performance of a given material. At a defined pre-load corresponding to the equivalent thickness of the sub-surface layer, the test reproduces well the ASTM G65 response. This seems to be a quick method to quantify the abrasion resistance of a material not only for lightweight loading conditions (as in ASTM G65) but also for working conditions beyond the standardized testing ones of G65, as in the present paper.

For edification on the use of the multi-pass dual-indenter method in the variant proposed in this paper, additional work is needed to elucidate the influence of all material and test parameters as well as those related to the microstructure of the tested materials. An approach will be attempted through energetic models of plastic deformation during the abrasion of the two steels.

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