INFLUENCE OF CALCIUM TREATMENT ON CHIP FORMATION OF AUSTENITIC STAINLESS STEEL SAE303

INFLUÊNCIA DO TRATAMENTO COM CÁLCIO NA FORMAÇÃO DE CAVACO DO AÇO INOXIDÁVEL AUSTENÍTICO SAE303

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ABSTRACT: The objective of this work was to study the influence of calcium treatment in the formation of chips in austenitic stainless steel SAE303. The quick-stop tests showed different behaviours in the shear plane, both primary and secondary, between the calcium treated and non-treated steel. By use of a scanning electron microscope, it was possible to identify the homogeneous presence of calcium, after the life test in the case of calcium-treated steel, on the rake face of the tool. Thus, it was possible to verify the benefits that calcium treatment brings to machinability.

Key words: calcium, chip formation, austenitic stainless steels.

Resumo: *O objetivo deste trabalho foi estudar a influência do tratamento com cálcio na formação do cavaco de aços inoxidáveis austeníticos SAE303. Os testes de "quick-stop" mostraram diferentes comportamentos nos planos de cisalhamento primário e secundário entre o aço tratado com cálcio e o não tratado. Por meio do microscópio eletrônico de varredura foi possível identificar a presença homogênea do cálcio na superfície de saída da ferramenta após o teste de vida no aço tratado com cálcio. Deste modo foi possível identificar os benefícios que o tratamento com cálcio proporciona para a usinabilidade.*

Palavras chave: *cálcio, formação de cavaco, aços inoxidáveis austeníticos.*

1. INTRODUCTION

Austenitic Stainless steels are more difficult to machine than carbon or low alloy steel. This is due to characteristics such as: high deformability, high modulus of rupture, low thermal conductivity. As a result, there is a strong tendency to work-hardening, tendency to adhere to the tool and high coefficient of friction, high temperatures and strength of cut, bad superficial finishing and high wear rates (TESSLER and BARBOSA, 1993).

The chips adhere strongly to the cutting tool and often remain stuck to the piece and/or tool after the cut. When the chips flow upon the tool, they can scrape fragments off of it (TRENT and WRIGHT, 2000).

The additions of free cutting elements (sulfur, selenium, tellurium, lead, bismuth and certain oxides) have been considered as alternatives to improve the milling. Such elements create conditions that perform on lubrication, embrittlement of the chips and tension concentration. In some cases, the pure and simple addition of these elements proved to be prejudicial to the resistance of corrosion, ductility, tenacity and weldability (GENNARI and MACHADO, 1999).

Sulfur is typically the element more often used to improve milling performance. It is present in steels in the form of sulphide, generally manganese sulphide containing chromium and iron. According to DAVIS (1999), larger and more globular sulphides bring more benefits to the milling.

On the other hand, KIESSLING (1978) and OTOTANI (1986) cite the brittling ability of sulphur. According to KIESSLING (1978), the tension concentration effect depends on its form, as well as on is size. Prolonged inclusions have a higher value on the ratio between the maximum and medium tensions than circular inclusions, which is advantageous as long as they do not become too thin. Very small inclusions or inclusions that do not deform along the secondary shear plane, are not good tension concentrators. However, the hardness improvement is advantageous.

OTOTANI (1986) relates that prolonged shaped inclusions lead to a longer tool life than the globular ones, in steels with low oxygen treated with Al and CaSi.

Another important characteristic of the manganese sulphides is the capacity to deform plastically in a wide range of temperatures. The possibility of this kind of inclusion, to adhere to the rake face of the tool and deform plastically forming a thin barrier against diffusion, was verified only under low and medium speeds of cut. With high cutting speeds, the manganese sulphides layer disappears, this is due to the high temperature that is generated (KIESSLING, 1978).

In milling, the sulphides are elongated in the direction of the primary shear plane, and in the flow zone, the secondary shear plane, are even more elongated. The length of contact between the chips and the rake face of the tool is shorter with the presence of MnS, and as a result the chips become thinner, the cut strength is lessened and the power consumed is reduced (TRENT and WRIGHT, 2000).

While sulphur improves machinability, it also decreases corrosion resistance besides being segregated during forging, causing anisotropy and affecting the uniformity of the microstructure (JUVONEN, 2004).

Considering, therefore, the machinability improvement with no prejudice to other properties of the material, techniques have been applied, such as metallic and non-metallic inclusions modifications, grain size and morphology control (HOLAPPA and HELLE, 1995).

An alternative to this is the application of calcium treatment, which has powerful deoxidizing and desulphurizing qualities. It can be used in steel with low levels of oxygen and sulphur, decreasing the number of inclusions and modifying them morphologically and chemically (WILSON and McLEAN, 1980; FONSECA et al., 2008).

Some processes of deoxidation during the making of steel apply elements like silicon and aluminum that combined with oxygen produce silicate and aluminate inclusions, respectively.

Calcium is generally added in the form of a wire of Ca-Si or Ca-Fe(Ni) during the refining of liquid steel, transforming the inclusions of alumina in calcium aluminates. Whilst the alumina inclusions are hard and abrasive, with a fusion point at 2045ºC, eutectic compounds of the system (CaO, MnO, MgO)-SiO_2-Al_2O_3, have a quite lower fusion point (1340-1500ºC).

The formation of such compounds generates globular inclusions, due to the superficial tension, generally involved by a layer of calcium and manganese sulphides. The calcium aluminates removed from the liquid steel prevent the formation of elongated MnS inclusions during the solidification (LARSSON and RUPPI, 2001; HOLAPPA and HELLE, 1995).

Another technique for adding calcium in the deep injection, in which calcium, also as CaSi or CaC and in fine powder form, is injected in the bath inside the pan by means of an immersed lance using argon as carrier gas. The calcium vaporizes and creates bubbles that combine with the sulphur and oxygen in the liquid steel. In this case, the products of the reaction are carried and form the slag.

BLAIS et al. (1997) demonstrated that the ratio between Ca/S of 0.7 produces a form factor of 0.73 for the inclusions of MnS; and that the MnS inclusions containing Ca have a strong tendency to solidify around the aluminate inclusions, as in Figure 1.

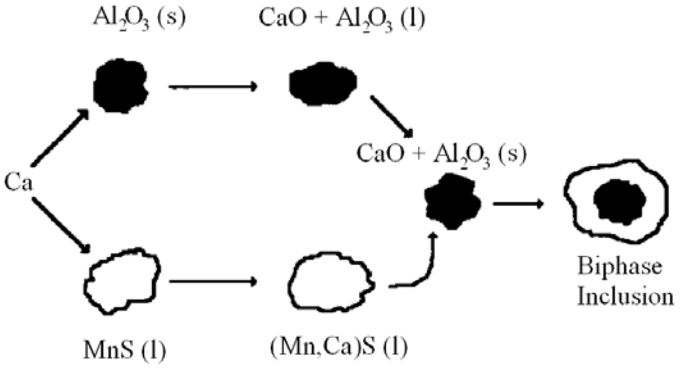

Figure 1. Empiric model for solidification of MnS inclusions by calcium addition (BLAIS et al., 1997).

The non-metallic inclusions can have their form and composition altered by the level of oxygen in the steel (SUZUKI et al., 2001; HARJU et al., 1999b).

According to KIESSLING (1978), inclusions that form a protective layer on the tool, that is, manganese sulphides and calcium aluminates are beneficial to the machinability.

However, it must be noted that these calcium aluminates, covered by a layer of sulphides as opposed to the manganese sulphides, do not deform during hot rolling. During milling, its deformation is also poor, but they form a protective layer on the tool, that is, the good deformability of the inclusions is not a pre-requisite for their ability of forming a protective layer during milling (VAINOLA et al., 1995).

TIEU et al. (1998) concluded that the layer composed by CaO, SiO_2, Al_2O_3 and MnS adhered to the tool is between 0.1 to 0.5 mm from the flank and the best temperature for cutting the layer is between 950 and 1050°C. That allows the temperature between the chip and the layer to be kept around 900°C. In that range of temperature, the aluminate inclusions are soft and viscous, easing their extrusion on the surface of the tool. However, the ideal temperature for the manganese sulphide is 700°C (MILLS et al., 1997).

The stability of the layer of sulphides is related to various physical and chemical parameters. The temperature and the pressure on the secondary shear plane are, without doubt, the most important parameters in the plasticity of the layer of sulphides. The MnS enriched with Ca have higher fusion points and are more viscous than the pure MnS, and consequently, they can stabilize in the tool/chip contact zone under high speeds, reducing the friction on the surface during the cut and preventing the deposit of milled material (BITTÈS et al., 1995).

Complex inclusions of CaO have a strong tendency to adhere on the flank and rake face of the tools (Figure 2), which has a protective effect and prolongs the life of the tool (FANG and ZHANG, 1996).

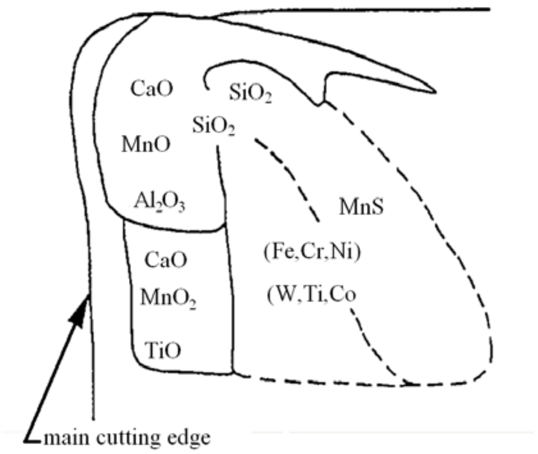

Figure 2. Distribution of the chemical compounds on the rake face of the tool (FANG and ZHANG, 1996).

During milling with higher cut speeds (v_c) the materials with inclusions of lower fusion points, the temperature on the point of the tool is high. The inclusions melt and a layer of oxide is not formed. In the flank the temperature is lower, the inclusions become soft and there is the formation of a layer of oxides that prevents abrasion.

However, when inclusions with high melting points are present they become soft on the point of the tool and there is the formation of an adherent layer of oxides that generates a small craterization by abrasion. In the flank of the tool the inclusions are not so soft and act as abrasives (OTOTANI, 1986).

LARSSON and RUPPI (2001) concluded that the reduction of wear in the milling of steels treated with calcium is due to the presence of soft inclusions, being of minor importance the formation of protective layer. In this case, the craterization wear is lower.

The homogeneity of the formed layer on a cutting tool depends on the amount and size of the inclusions (HARJU et al., 1999a).

The objective of this work is to evaluate the variation in the milling of an austenitic stainless steel SAE 303, related to the inclusion of calcium. This analysis will be achieved by tests of chips formation, using the quick-stop method, and of tool wear, using life tests.

The quick-stop tests consist of suddenly stopping the action of the cut. In that way it is possible to retain important details of the shear zones, primary, secondary and tertiary, and of the dynamic of the deformation in the formation of the chips (TRENT AND WRIGHT, 2000).

The machinability tests of these steels were limited to the external longitudinal turning with coated carbide as a cutting tool.

2. MATERIALS AND METHODS

The materials used were two resulphurized austenitic steels SAE303, all the ingots were hot rolled into bars of 50 mm diameter. Table 1 shows their chemical composition of the steels, area fraction, average size and average shape factor (the ratio of length to width) of the sulfide inclusion. The amount of sulfide inclusions in steel with Ca is less, due to lower amount of sulfur and manganese. The average size and shape factor of the inclusions in steel with Ca are also smaller than in steel without Ca treatment.

Table 1. Chemical composition (wt.%), area fraction, average size and average shape factor of the inclusions of the austenitic steels tested.

Material	C	Si	Mn	P	S	Cr	Mo	Ni	Ca	Area fraction (%)	Average size (μm^2)	Average shape factor
With Ca	0,059	0,36	1,54	0,031	0,27	17,3	0,46	9,65	0,0018	1,48	5,87	2,88
Without Ca	0,034	0,39	1,69	0,032	0,31	17,2	0,40	8,51	0,0008	2,02	8,17	3,66

Figure 3 show micrographs of the resulphurized austenitic steels used. The inclusions in dark grey are mostly manganese sulphurs due to the resulphurization treatment.

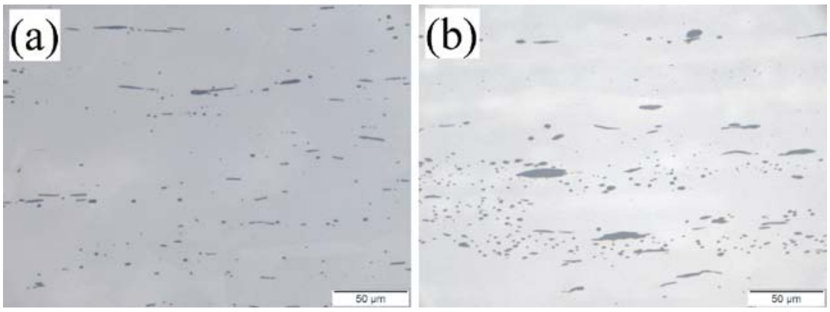

Figure 3. Resulphurized austenitic steel treated with calcium (a), without the calcium treatment (b). Bar scale 50µm.

It can be seen that the calcium treated steel has a greater number of inclusions to 5µm2 and more inclusions with small shape factor (Figure 4a and 4b). The smaller shape factor can be attributed to the addition of calcium, which results particles more difficult to deform during hot rolling (VAINOLA et al., 1995).

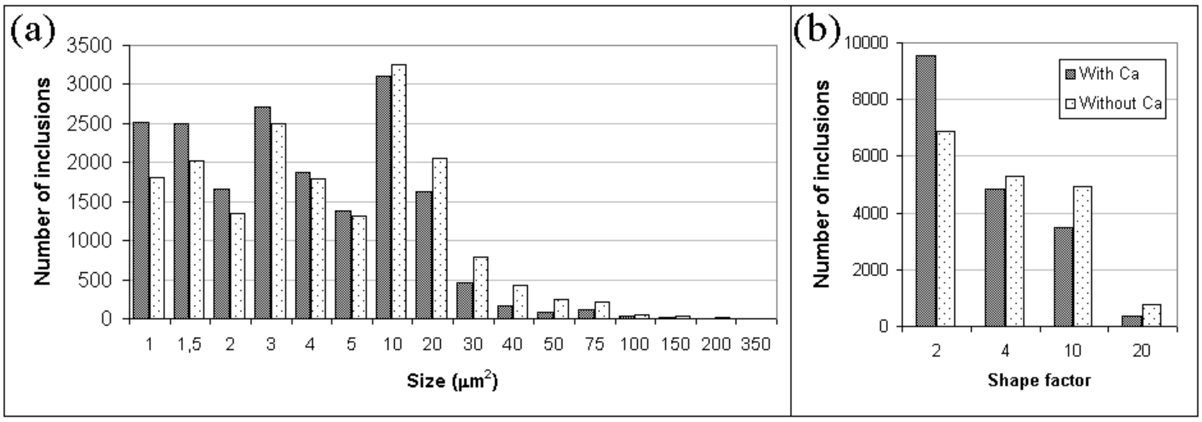

Figure 4. Number of particles in function of the size (a) and shape factor (b) in steels tested.

The tool-machine used was a turning centre Romi CNC E280. It has 11 kW power, plate maximum speed 4.000 rpm and 30 m/min maximum advance speed. The cutting tool used was a support SDJCL 2020K 11, with insert DCMX 11 T3 04-WF, by Sandvik. This tool has Wiper technology with 55º point angle, 7º clearance angle, 0.4 mm nose radius. The material of the tool was CERMET GC 1525 with coated of TiN by means of PVD. For the quick-stop test, the speed of cut (v_c) used was 40m/min, feed per turn (f) of 0.05 mm/rot and depth of cut (a_p) of 2 mm. In the life test of the tool, the tool started milling in a length of 160 mm with v_c=300 m/min, f=0.05 mm/rot, a_p=0.5 mm and refrigeration (synthetic fluid BioG1210) directed to tool.

Scan electron microscopy and optic microscopy were used in the evaluation of the microstructures. For the attack of the micrographics, an electrolytic attack with oxalic acid was performed for one minute. The measurements of Vickers micro-hardness were taken in a micro-hardness tester Zwick 3212, with loads of 25 and 200 grams, for 10 seconds.

3. RESULTS AND DISCUSSION

Figures 5 present the micrographs of the quick-stop tests on the material with and without the addition of Ca, respectively.

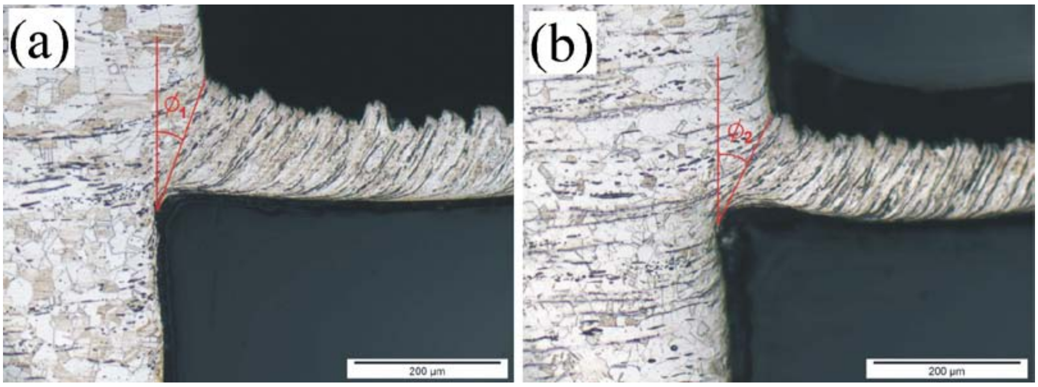

Figure 5. Micrographs of the quick-stop test on the material with the addition of Ca (a) and without the addition of Ca (b). Bar scale 200µm.

It is observed that in the material with the addition of Ca, the width of the chip is larger in relation to the material without Ca (Φ1<Φ2). Consequently, the exit speed of chips on the material without the addition of Ca is higher.

Due to the larger primary shear angle (Φ2), the material with no addition of Ca follows the shape of rake face of the cutting tool. In this case, the secondary shear plane presents larger sliding zone.

Thus, it can be said that pressure per area unit in the point of the tool without Ca is lower than on the material with Ca.

Figure 6 presents a micro-hardness measuring band in the primary shear plane region on the material. Significantly higher values are observed when compared to the measurements on the steel with Ca inclusions. It is evident that the calcium aluminate inclusions are softer, easing their extrusion.

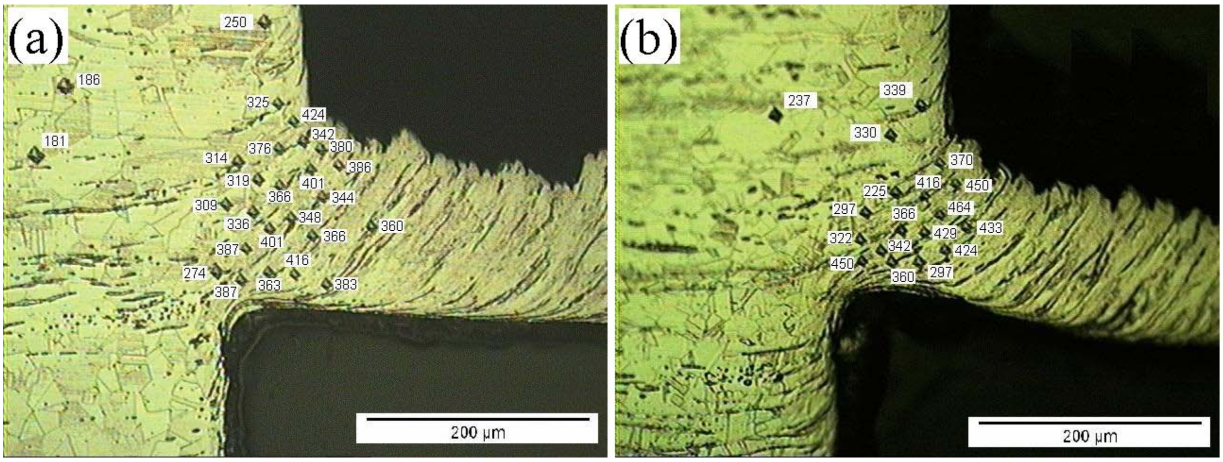

Figure 6. Micro-hardness around the primary shear plane on the material with the addition of Ca (a) and without the addition of Ca (b) (load 25 g, 10s).

Extending these analyses to a tool life test, a wear on the flank (VBmax) was noted, the volume taken being around 40% higher on the material without the addition of Ca in relation to the one with Ca (Figure 7).

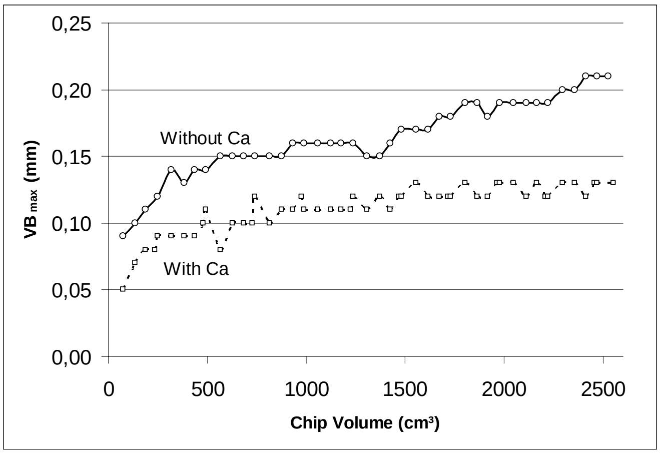

Figure 7. Tool life when turning.

In the material with Ca, the chip generated has a long helicoid shape, due to the higher strain hardening on the primary shear plane during the cut (Figure 8).

Figure 8. Chips obtained during life test with the steel with the addition of Ca. Bar scale 50µm.

The steel without the addition of Ca, however, presents a comma shaped ship. This is due to higher strain hardness as well as to the larger amount of sulphides that cause cracks during deformation in the cut (Figure 8).

In the micrography of figures 8 and 9, larger amounts of sulphides particles deformed in the primary and secondary shear plane for the material with the addition of Ca can be observed.

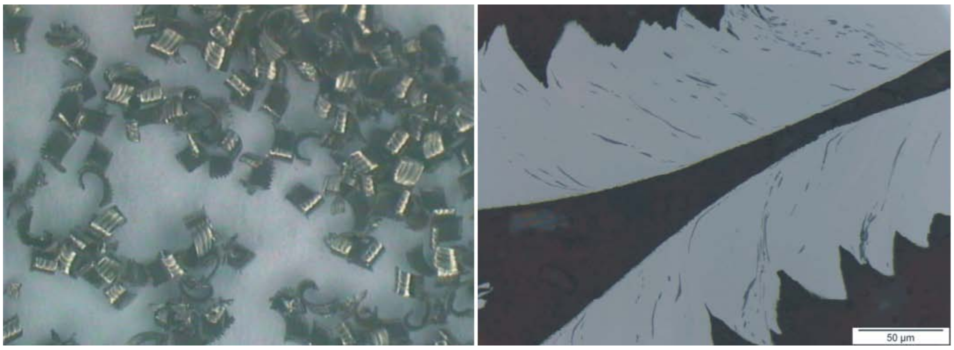

Figure 9. Chips obtained during life test with the steel without the addition of Ca. Bar scale 50µm.

The notch wear was observed after the life test in the steel with the addition of Ca. This wear is typical of the milling of materials that superficially work-harden afterwards. The flank wear with a smooth appearance also occurs, according to TRENT and WRIGHT (2000) (Figure 10).

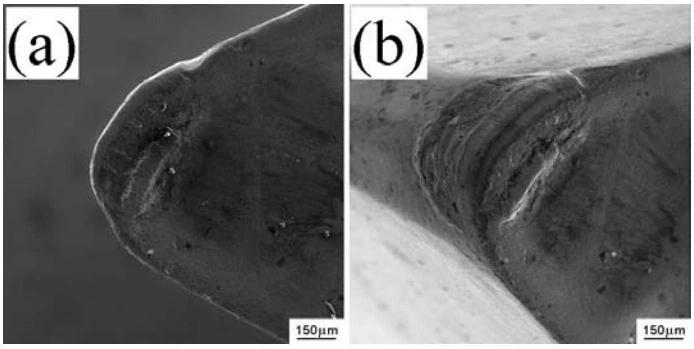

Figure 9. Analysis of the wear in the tool after testing the material with the addition of Ca. (a) face and (b) corner. Bar scale 150µm.

In the material without the treatment with Ca, the notch wear and smooth flank are also present; however, material adhered on the surface of the tool is also observed (Figure 11).

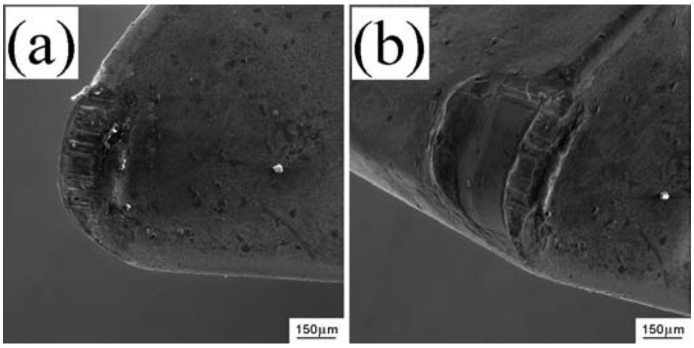

Figure 10. SEM of the inserts used on the tool life test of the material without Ca. (a) face and (b) corner. Bar scale 150µm.

The elemental mapping of the elements present on the rake face of the tool after the test with Ca treatment is present on Figure 12. On the point of the tool it is observed the presence of Ti close to the flank. It is evidence of coated exposure, that is, in this region the adherence zone of the secondary shear plane the normal tension is very high, preventing stable deposit of any element.

After this region, a deposit of a small amount of material is observed, due to the presence of Al, Cr, Mg, Mn and Si. An interesting fact is the presence of Ca homogeneously distributed after the adherence zone, in agreement with the literature (OTOTANI, 1986; FANG and ZHANG, 1996). Sulphur remains concentrated far from the flank, due to the high tensions and temperature generated next to it.

Figure 13 presents the elemental mapping of the elements present on the rake face of the tool after the tool life test with material without the treatment with Ca.

Beside the flank, a small amount of Ti is observed. Directly next to it, the presence of Al, Cr, Mg, Mn and Si evidences that the surface of the tool has a large amount of adhered material. In this region a punctual presence of Ca can also be observed, probably because of residual compounds.

Sulphur is present in the region where there is adhered material, due to the large amount of it on the resulphurized material and also after that region, where the tensions and temperatures are lower.

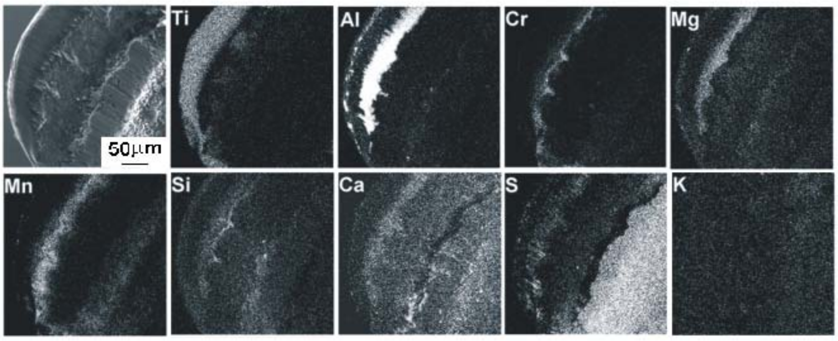

Figure 12. Elemental mapping of the elements present on the rake face of the tool in the milling of material with Ca.

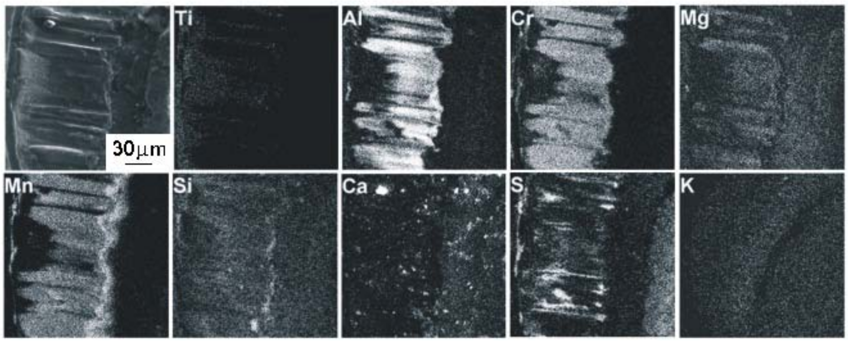

Figure 13. Elemental mapping of the elements present on the rake face of the tool in the milling of material without Ca.

The steel, with addition of Ca, presented even lower hardness towards the inside of the piece, in relation to the steel without its addition (Figure 14). For this reason it work-hardens more on the surface.

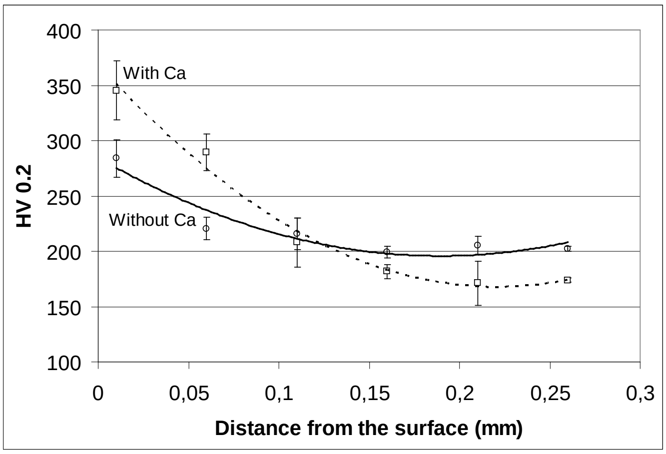

Figure 14. Micro-hardness Vickers (HV 0.2; 10s) transversal to the milled surface in the life test.

The steel treated with Ca presents higher chips settlement, and with that, the work-hardening of the newly milled surface is higher than that on the steel without the addition of Ca.

This work-hardening causes the chips to be thicker and present a shorter length of contact with the tool. This work-hardening is higher, combined with the treatment with Ca that diminishes the hardness of abrasive inclusions (oxides) and permits the contact of the material with the tool flank (tertiary plane) is smaller and, consequently, lessens the wear of it.

The Ca deposited on the surface of the tool diminishes the friction and serves as a barrier against diffusion between the chips flow and the surface of the tool, thus avoiding possible craterization wear.

The steel without Ca treatment presents lower settlement of chips and lower work-hardening of the surface. However, this combination, along with the hard inclusions (probably Al_2O_3), are the cause of higher wear of flank in relation to the steel treated with Ca. The adhered material on the surface of the tool can be removed by the flux of chips and generate craterization wear.

As related on the literature, the pure sulphides cannot stabilize in the areas of the tool that reach high temperature and that are prone to high tensions; they only accumulate on the region far from the flank, where the shear tension and the temperature are lower.

The long helicoid chips found in the life test of the material with Ca was the only disadvantage in relation to the comma shaped chips of the steel without Ca treatment. The breakage of chip is helped by the lesser thickness and higher exit speed in relation to the steel treated with Ca. Larger and more deformed sulphides present in the microstructure can facilitate the nucleation and enlargement of the cracks, causing discontinuity of chips.

4. CONCLUSION

From this work, the following conclusions can be taken in relation to the treatment with Ca on austenitic stainless steels:

The calcium makes the sulphide inclusions less deformable, which decrease the contact of the tool with the scrap chips.

The treatment with calcium allowed a longer life for the tool, probably due to the transformation of hard and abrasive oxides in milder inclusions.

Also noted was the homogeneous deposit of calcium on the surface of the tool, which protects from diffusion, decreases friction and the temperature on the interface, thus retarding the wear by craterization. In the non-treated steel, a strong adherence of the material on the surface of the tool was observed. .

In both materials the sulphur was deposited far from the flank, where the shear tension and temperature are lower, due to its low index of deformability and low melt temperature.

The disadvantage observed was the formation of long helicoid chips in the material treated with Ca and comma-shaped chips in the material not treated with Ca.

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