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MODIFICATION OF SURFACE PROPERTIES OF AISI M2 STEEL BY PLASMA NITRIDING PROCESS APPLIED TO CUTTING TOOL OF TYPE END MILL

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Abstract. *Material engineering seeks economically viable improvements and technologies to improve material efficiency, one of the alternatives is plasma nitriding commonly used in metal components subject to wear in order to increase their useful life. In this way the objective of this paper was to use plasma nitriding to increase the surface hardness of a cutting tool (end mill) made of AISI M2 steel, resulting in increased tool life and resistance to wear and fatigue. Thus, the samples of AISI M2 steel and the tools were subjected to the plasma nitriding process, using different temperature values (400°C, 450°C and 500°C) in atmospheres with 20% nitrogen and 80% hydrogen for a time set of four hours. The microhardness test verified that the hardness of the AISI M2 steel is 745 HV and the hardnesses obtained after the thermochemical treatment at the temperatures of 400, 450 and 500°C were 1470, 1418 and 1130 HV, respectively. Microscopy revealed that the largest diffusion zone occurred in the process at 500°C. When applied in a universal milling machine, the tool nitrided at 400°C showed the lowest mass loss and wear at the cutting edges. Therefore, the best treatment for application in end mills made of AISI M2 steel is at 400°C.*

Keywords: *AISI M2. Cutting Tool. End Mill. Plasma Nitriding. Thermochemical Treatments.*

1. INTRODUCTION

Among the various manufacturing processes, various tools are used for drilling, cutting, turning and milling. These tools require particular properties in order to meet the demands during the process, such as mechanical wear resistance, corrosion and hardness (Araújo, 2015).

Currently the materials most applied in cutting tool are high speed steels and hard metal. They are called high speed steels because of their ability to withstand high working temperatures, allowing the use of high speeds in machining operations (Gobbi, 2009). Hard metal is a product of powder metallurgy, its constituents are generally mixed in the form of powders and submitted to compression, sintering and grinding, resulting in a consolidated and dense product with the mechanical characteristics suitable for use in cutting tools (Bork, 1995).

The AISI M2 high speed steel is a common material used in cutting tools such as drills, mills, saws (Darmawan et al., 2009), as well as being used for cutting blades and tool bits. They are high carbon steels with good results when at low speeds and when good precision is required.

Hoyle (1988) states that questioning what type of universal high speed steel, the AISI M2 nomenclature as the main favorite is almost unanimous, confirming that the use of this steel is enough to perform normal routine work. The use of more sophisticated tools implies higher costs and often waste.

Hard metal tools require stiffer machines to avoid the vibration caused in the process by possible machine tool gaps, which would cause shocks between tool and part, which could break the tool more easily than the high speed steel, since this material is more tenacious than the hard metal (Mussoi, 2015). Operations with high feedrate machining and great depth of cut for roughing or cutting interruptions, generate high tool stresses, requiring the use of higher tenacity materials.

For a higher efficiency of the cutting tools, a tenacious core and a wear resistant surface are desired, in this way the tools can be submitted to the thermochemical treatment, whose objective is to obtain the increase of superficial hardness from the modification of the chemical composition in the surface of the steel.

Chiaverini (1986) presents several alternatives of thermochemical treatments that alter the surface properties of steels, among them the nitriding consisting of the surface diffusion of nitrogen, widely used to improve the wear resistance of steels and other alloys.

Pye (2003) defines nitriding as a ferritic thermo chemical method of diffusing nascent nitrogen into the surface of steels and cast irons. This diffusion process is based on the solubility of nitrogen in iron. Most of the process parameters for gas nitriding can be controlled with relatively simple instrumentation and methods, for instance, time, gas flow and temperature.

The nitrided layer is formed by a zone of compounds and a zone of diffusion, being the zone of compounds located at the top of the layer, formed mainly by nitrides and carbonitrides. This region is called a white layer. The diffusion zone begins after the zone of compounds, being formed due to diffusion of the nitrogen to the interior of the part (Gobbi, 2009).

A feature of the nitriding process is the generation of compressive residual stresses on the surface, which are beneficial for fatigue strength, as these residual stresses overlap the normal tensile stress on the cutting surface, reducing the effective stress applied during machining. These stresses can be explained by precipitation of nitrides in the material matrix, since the molar volume is larger than the matrix, which will provide a higher degree of crystalline distortion, thus increasing the residual compressive stress level (Kolozsváry et al., 2002).

The effectiveness of the ionic nitriding process, or plasma nitriding, is given by a range of advantages over conventional processes, among them we can highlight the low treatment temperature, uniformity of the layer and time of inferior treatment. In this paper the conventional plasma nitriding was used because it a process that is well accepted industrially and has several advantages over other nitriding processes (gas and bath salts), such as higher gas savings and shorter process life, due to the higher velocity of diffusion of nitrogen (Alves Jr, 2001).

In this way the application of the plasma nitriding process in AISI M2 steel cutting tool can present significant results in terms of corrosion and wear resistance that meet the aforementioned needs, corroborating to the increase of individual production of each tool.

2. MATERIAL AND METHODS

2.1 Samples

In this paper was analyzed end mills made of AISI M2 high speed steel, a cutting tool commonly used in industry and easy to acquire in the market. Its nominal composition is described in Tab. 1.

The eight samples of 10 mm in diameter and 8 mm in height, which would later be used for metallographic characterization were removed from the tools by cutting in a constantly cooled cutter. The samples were submitted to a metallographic preparation, they were grinded with 180, 220, 360, 400, 600 and 1200 mesh sandpapers and polished with felt disks using alumina abrasives with 3, 1 and 0.05 μm . After the samples were prepared, all were washed with water and alcohol, dried and stored.

Table 1. Chemical composition of AISI M2, (Naz et al., 2015).

C	V	Cr	W	Mo
0,85 %	2,00 %	4,00 %	6,00 %	5,00 %

The Figure 1 shows the samples nitrided and the design of end mill used in this paper. The edge effect can be seen in nitrided samples, where conventional plasma nitriding produces a non-uniform surface layer, the surface color varies from the center to the periphery of the samples. This phenomenon can be seen without microscope, triggered by competition between sputtering and deposition during the process, due to changes in the electric field in the corners and edges (Sousa, 2007).

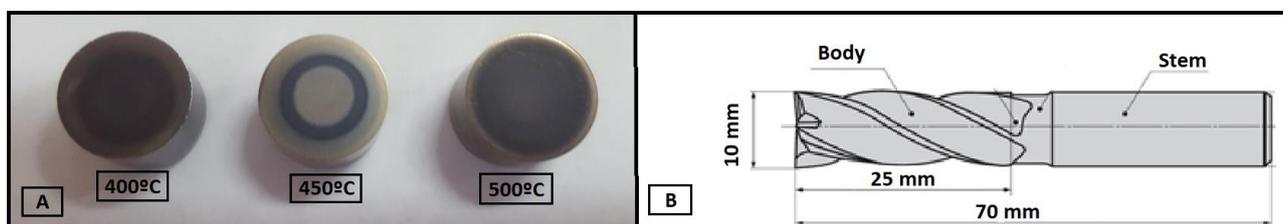


Figure 1. Samples after the nitriding process (A) and the design of end mill (B), (Author, 2019).

2.2 Nitriding parameters

At first, a sputtering cleaning (pre-sputtering) was carried out, that is, by bombardment of energetic ions and fast particles, necessary to remove oxides and prepare the substrate to receive the coating, a practice known as surface modification or texturing. In his master thesis Albano (2014) found that sputtering prior to plasma treatment contributes

to this surface modification, improving the adhesiveness of the deposited film. The parameters used are described in Tab. 2.

Table 2. Sputtering cleaning parameters, (Author, 2019).

Time (minutes)	Temperature (°C)	Pressure (mbar)	Gases	Flow rate (sccm)
30	300	2.5	100% H ₂	20

When complex geometries were subject to the nitriding process, these are subject to the edge effect that induces a temperature gradient in the part, this phenomenon was reported by (Olzon-Dionysio et al., 2010) that verified the existence of greater hardness in the edges and corners of the piece. Thus, the cutting tools were nitrided without cathodic cage in order to obtain greater hardness in the cutting edges. In his doctoral dissertation Sousa (2007) found that the nitrite mixture of 20% N₂ - 80% H₂ allows to obtain thicker and harder layers.

For this paper three temperature parameters were studied, in which they were repeated twice in different samples, the results of both microhardness test and microscopy revealed approximate values, confirming the uniformity and standardization of the treatment. The nitriding parameters used for both samples and cutting tools are described in Tab.3.

Table 3. Plasma nitriding parameters, (Author, 2019).

Time (hours)	Temperature (°C)	Pressure (mbar)	Gases	Flow rate (sccm)
4	400	2.5	80% H ₂ - 20% N ₂	20
	450			
	500			

The visual aspect of plasma nitriding is shown in Figure 2, the arc opening phenomenon was not observed in most of the process. When the arc is opened, there is a potential drop in the edges and corners of the sample that can extinguish the plasma.

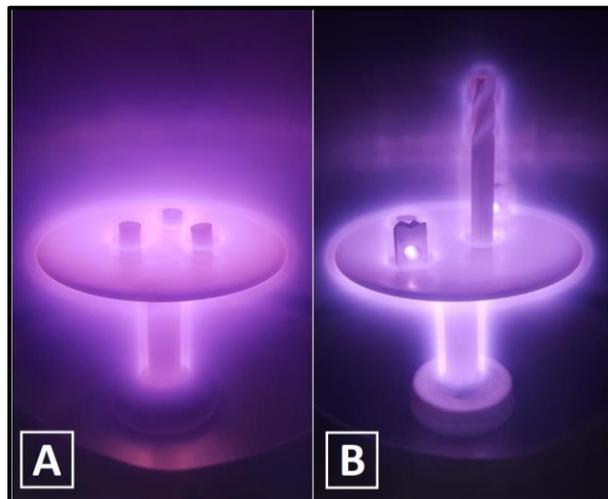


Figure 2. Sample (A) and tool (B) inside the reactor during nitriding, (Author, 2019).

2.3 Optical microscopy and microhardness test

The microscopy was used to measure and observe the microstructure of the nitride layer and the diffusion zone that was formed on the surface of the samples after the nitriding process.

Due to the thickness of the nitride layer is extremely thin, a load of 25 gram-force was used in the vickers microhardness test. For the cutting tools it was not possible to verify the hardness due to its cylindrical shape and not having a flat surface for the test to be performed.

2.4 Tool wear

The nitrided and non-nitrided cutting tools were used in a universal milling machine, later verified their wear. The wear resulting from the application of the tools was quantitatively analyzed for loss of tool mass after use, and qualitatively analyzed by the observation of wear due to limitations of the equipment, not allowing to measure the magnification of the lens and thus not being able to measure the magnitude of the wear on the cutting faces of the tool.

The data for calculating milling parameters was set from the cutting data recommendations of manufacturer, and is contained in the Tab.4.

Table 4. Cutting data recommendations for high speed steel, (Author, 2019).

Cutter diameter (mm)	Cutting speed (m/min)	Feed per tooth (mm/tooth)	Number of teeth
10	20-25	0.04-0.05	4

The spindle speed (n) and table feed (V_f) are calculated by Eq. (1) and (2) as a function of cutter diameter (D), cutting speed (V_c), feed per tooth (f_z) and number of teeth (z), (Diniz et al.,2010).

$$n = \frac{1000.V_c}{\pi.D} \quad (1)$$

$$V_f = f_z \cdot z \cdot n \quad (2)$$

The spindle speed and table feed calculated are 796 RPM and 159.2 mm/min respectively, but the closest values available in the milling machine are 810 RPM and 168 mm/min. The amount a tool engages a workpiece radially during peripheral milling is dependent upon the operation being performed, due to sever process conditions were applied the maximum recommended axial and radial depth of cut, of twice the diameter and 60% of the diameter respectively (Diniz et al., 2010). The milling parameters were adopted according to Table 5, these were applied to the SAE 1045 steel by heavy roughing, but within the specifications.

Table 5. Milling parameters, (Author, 2019).

Material	Hardness (HV)	Spindle speed (RPM)	Table feed (mm/min)	Axial depth of cut (mm)	Radial depth of cut (mm)	Milling time (min)
SAE 1045	295	810	168	20	6	60

3. RESULTS AND DISCUSSION

3.1 Microhardness test

The vickers microhardness test results showed a significant increase in the surface hardness of the AISI M2 steel. It should be noted that the hardness of the samples measured was 745 HV before nitriding, after the nitriding the samples presented hardness values as shown in Tab. 6.

Table 6. Hardness of the samples after nitriding, (Author, 2019).

	Sample 1	Sample 2	Sample 3
Temperature (°C)	400	450	500
Hardness (HV)	1470	1418	1130
Increase of hardness (%)	97.3	90.3	51.7

The nitriding when performed for AISI M2 steel at 450°C, the sample presented an increase of 90.3% in relation to the hardness of the sample without treatment, having a layer thickness (diffusion zone) of approximately 44 μm . At the temperature of 500°C, the hardness increase was approximately 51.7%, with a diffusion zone thickness of approximately 80 μm .

When nitrided at 400°C, the sample has a hardness of 1418 HV, about 97.3% in relation to the sample without treatment and with a diffusion zone of 31 μm . Although the nitrided sample at 400°C has the lowest layer thickness among the others, it is the one with the highest surface hardness.

It can also be observed that when raising the temperature, the thickness of the layer also increases proportionally. According to Calister (2008), the increase of the diffusion zone length with the increase of the nitriding temperature is related to the higher diffusion rate of the nitrogen in the substrate of the material. Thus, at low temperatures the hardness increases, due to higher temperatures, the diffusivity of nitrogen is higher, resulting in a layer of nitrides that are poorer in nitrogen (Araújo, 2015). This represents a very large gain in terms of energy consumption, since in order to obtain a more resistant layer it is not necessary to use high temperatures.

The Figure 3 (A) details the hardness profile of the nitrided samples, along the layer, zone of diffusion and substrate, where the hardness returns to normal, 745 HV. This profile was not realized in the nitrided cutting tools, because, due to its geometry, a cross-section would be necessary and this would damage the tool and render it useless.

In order to confirm the accuracy of the literature on the uniformity of the nitride layer, measurements were made of hardness (from the edges to the center of the sample), which revealed few hardness variations towards the center of the sample, the results can be observed in the Fig. 3 (B).

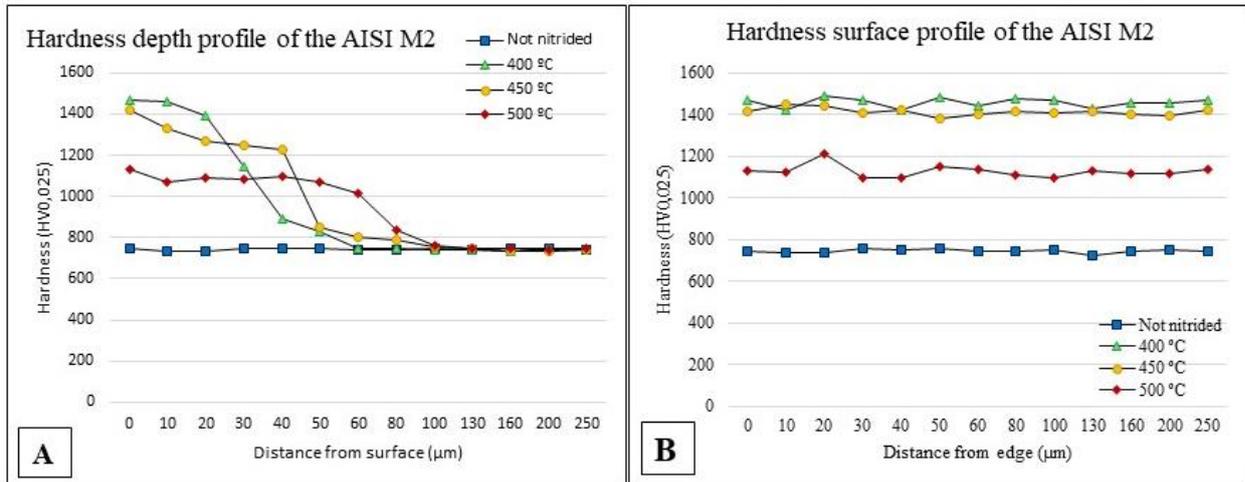


Figure 3. Hardness profiles, depth (A) and surface (B), (Author, 2019).

3.2 Optical microscopy

Optical microscopy allowed to validate the thickness found by microhardness tests, as shown in Fig. 4.

According to the microscopy analysis for the sample nitrided at 400°C, Figure 4, the compound layer was measured with a value of 31 µm while the diffusion zone showed 34 µm. These results confirm the values obtained in the microhardness test. It is worth mentioning that the hardness decreases at distances of the edge (depth) greater than 31 µm, due to the diffusion zone.

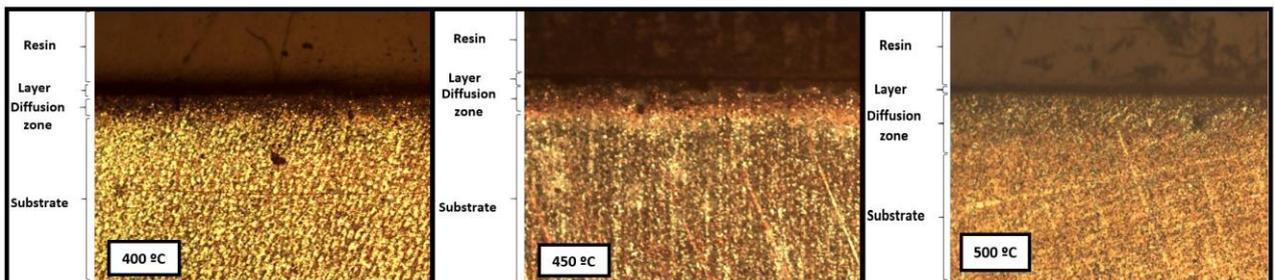


Figure 4. Optical microscopy of the nitrided sample, (Author, 2019).

The sample nitrided at 450°C presented the values of 21 µm and 42 µm for the compound layer and the diffusion zone respectively. When looking at Figure 3 (A) it is clear that the hardness drops dramatically when it reaches a depth of 40 µm. The sample at 500°C for the compound layer as seen also in Figure 4 shows a very thin layer of 13 µm and a diffusion zone of 82 µm.

3.3 Wear of cutting tools

The cutting tool is required chemically, mechanically and thermally during machining. The life of the tool is the time it actually works (deduced from passive times), and the end of life can be defined by loses its cutting capacity, affecting accuracy, quality and increased cutting force required.

Among the main types of wear that occur in a cutting tool, Araújo (2015) highlights flank wear and crater wear, given the frequency with which they occur, being inevitable and most responsible for the end of the service life of the tool. tool under normal working conditions. Flank wear is related to modifying the shape of the original cutting edge causing the

part to change size and may fall out of its tolerance range. The Figure 5 shows the cutter faces of the end mill without use and without nitriding.



Figure 5. Cutter faces of the end mill before use, (Author, 2019).

At Figure 6 (A, B, C and D) the tool profile image is shown after use, showing flank wear resulting from contact between the tool and the workpiece. The tool without nitriding (A), the flank wear was of great magnitude, great wear of the cutting edges and reduction of the diameter of the cutting face of the tool, the same occurred with the tool nitrided at 500°C (D), but to a lesser extent, but it can be observed that in this the cutting face diameter was reduced, reducing the size of the cutting edges.

The nitrided tools at 400°C and 450°C, (B) and (C) respectively, maintained the initial diameter and showed a change in the thickness of the cutting edges, but the end mill nitrided at 450°C showed higher wear than 400 ° C. In this way it can be observed that the tool with the least wear is the end mill nitrided at 400°C.

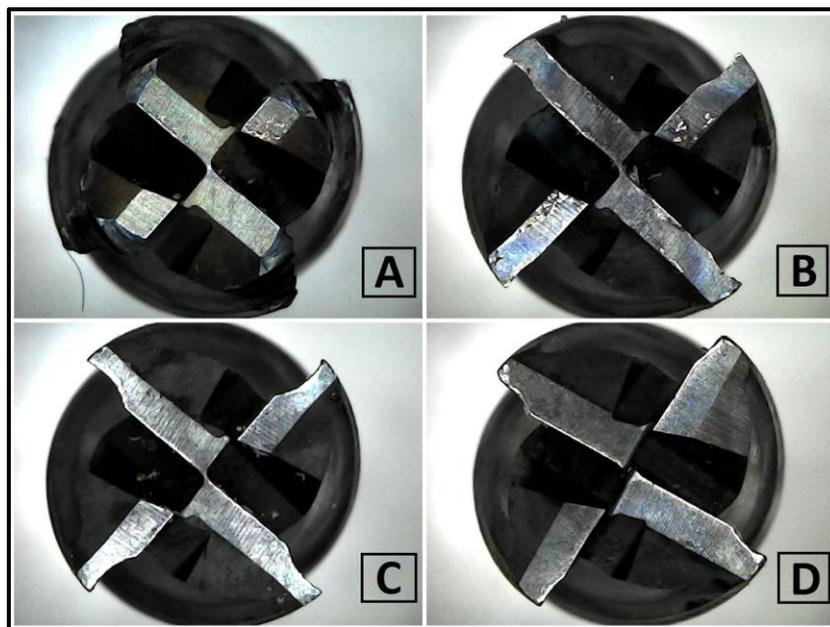


Figure 6. Cutter faces of the end mill after use, A (not nitrided), B (400°C), C (450°C) and D (500°C) (Author, 2019).

The wear resulting from the machining process results in the loss of mass of the tools that originally had 40 grams. This variation of mass allows to quantify the wear resistance of the tools. At Table 7 shows the mass after the machining process and the respective percentage of mass loss.

Table 7. Reduction of mass after machining, (Author, 2019).

Samples	Mass (gram)	Reduction of mass (%)
Without nitriding	36.14	13.95
400°C	39.18	6.71
450°C	38.83	7.55
500°C	37.41	10.93

The results obtained confirmed the previous qualitative analysis, showing a lower wear of the nitrided sample at 400°C, which lost 2.82 grams, followed by samples at 450°C and 500°C, which had a reduction of 3.17 and 4.59 grams, respectively. These results represent an increase in working time and a decrease in tool replacement. For industries that work with frequent use of these tools, this thermochemical treatment procedure represents an alternative to the economy over the production process.

4. CONCLUSIONS

The results obtained were similar to those of (Araújo, 2015), being the best plasma nitriding parameter for AISI M2 steel cutting tools, in terms of hardness and wear the temperature of 400°C. In terms of zone of diffusion, the best parameter is when using a temperature of 500 °C and the most suitable in terms of production occurred with the treatment at 400°C.

By the application of ionic nitriding in end mill made of AISI M2 high speed steel, it was possible to significantly increase the surface hardness for the three defined nitriding parameters, with the treatments being listed in order of increasing the hardness at 400°C, 450°C and 500°C respectively, being confirmed by microhardness tests.

The greatest influence on the ionic nitriding process is given by the temperature when applied to the definitions of this paper, because it influences the extent of the diffusion layer of nitrogen and the thickness of the nitride layer, as shown by the optical microscopy tests.

In her master thesis (Gonçalves, 2012) found a high compressive stress on the surface of the studied steels, being more intense the lower the temperature of the nitriding process. This factor probably contributes to the success of nitriding at 400°C.

When nitrided at 500°C, the process is not as advantageous due to the formation of a layer of nitrogen-poor nitrides, even though at this temperature the tempering of the steel is reached. This result is important because the process at lower temperatures represents a lower cost in energy production for similar gains in terms of hardness and resistance in tool life.

Therefore, the plasma nitriding process when applied to end mills made of AISI M2 steel becomes efficient when carried out at a temperature of 400°C and 450°C, as it reduces the effects of flank wear on the cutting edges of the tool. The hardness for these two temperatures is almost equivalent, however the wear was higher in the tool nitrided at 450°C.

5. ACKNOWLEDGEMENTS

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