26th ABCM International Congress of Mechanical Engineering
November 22-26, 2021. Florianópolis, SC, Brazil

COB-2021-1936
USE OF STATISTICAL TOOLS IN THE EVALUATION OF MICRO ABRASIVE WEAR IN THERMALLY TREATED AISI M2 STEEL

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Abstract. *The pursuit of continuous improvement of product design and processes in the different fields of engineering and technology has brought about significant changes in the manufacturing industry, driven by the improvement in the mechanical and tribological performance of new materials. For example, cutting tools need to withstand increasing loads and be equally resistant to wear. However, materials naturally available to man need structural adaptation so that these properties can interact. Applying thermal treatments to engineering materials has contributed to better tool lifespan by achieving greater mechanical resistance to wear. In particular, as machining is concerned, the AISI M2 fast steel is widely used as a cutting tool, also to forming prossesses and tool shop in general. In order for the AISI M2 to sustain high mechanical resistance at high temperatures, a series of thermal treatments are quite necessary. This work proposes to assess, using statistical methods, the effect of thermal treatments and structural changes on surface hardness and wear resistance of AISI M2 fast steel. In this study, a group of annealed, tempered and drawtempered commercially available test specimens were used.*

Keywords: *heat treatment; AISI M2 fast steel; wear; hardness*

1. INTRODUCTION

The machining operation requires tools not only with adequate properties to guarantee top notch quality products, but also to deliver excellent mechanical resistance, even under high temperatures (Noda *et al*., 2019). According to Cozza *et al*. (2005), some characteristics of the AISI M2 make it a much desirable candidate, particularly for milling, as it presents elevated hardness at high temperatures, high wear resistance and high tenacity compared to other commercially available fast steels. These characteristics have benefited this material to be used in a myriad of applications, notably in the production of bits, borers, mills, cores, slitting knives and thread mill rollers (Hacisalihoglu *et al*., 2017).

In the annealed state, the AISI M2 fast steel has low carbon content and is made up of fine carbides dispersed in a ferritic matrix that is comprised of a volumetric ratio of approximately 25-30% of the total steel volume. Notwithstanding, to dissolve them so as to tune the austenite for tempering, a minimum of 1180°C is necessary (Kayali *et al*., 2012). According to Park (2004), after a vigorous tempering, the final steel microstructure is generally made up of approximately 80% martensite, 20% of primary carbide and retained austenite, which will be later transformed into subsequent drawtempering.

According to Hua *et al*. (2006) and Abad *et al*. (2010), thermomechanical treatments are operations carried out under temperature, atmosphere, time and speed-controlled conditions, with the aim of improving the structural characteristics of steels and special alloys. Moor *et al*. (2008) defines heat treatment as: “bringing the steel at an intercritical temperature or complete austenitization, with a fast cooling to an intermediate temperature between the beginning and end of the martensite formation, followed by a partitioning step at the same tempering temperature (one step-process) or at higher temperature (two-step-process)”. During the partitioning stage, a fraction of the carbon trapped in the martensitic structure migrates to the austenite in sufficient amounts so that it leaves it stable, even after later cooling to room temperature.

Considering the vastly extended possibilities of heat treatments available to date to render phase transformation from austenite in transformed steels, the tempering and drawtempering are the most prominent to fulfill our study requirements. In fast steel, besides chemical composition, specially in terms of carbon content, the temperatures and the tempering or

drawtempering durations are of a major influence on hardness (Schlatter, 2012). The purpose of this work is to use statistical tools in order to assess the effect of the thermal treatment on a AISI M2 fast steel and measure its resistance to abrasive wear caused by the increase in surface hardness. In this study, a group of annealed, tempered and drawtempered commercially available test specimens were used.

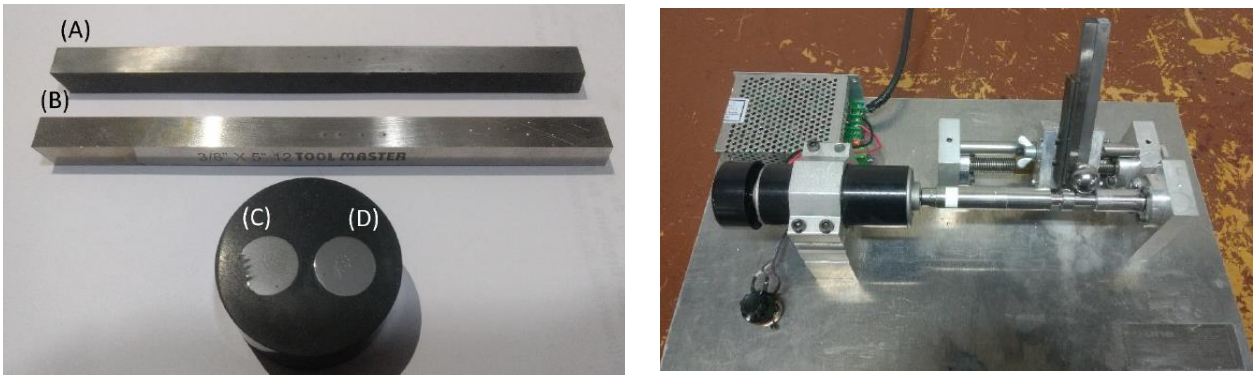
2. METHODOLOGY

An AISI M2 fast steel was used, having a similar composition to that described in Souza (2001): (0.89 %C), (4.20 %Cr), (4.90 %Mo). (6.20 %W) and (1.80 %V). As table 1 illustrates, test specimens were divided into four groups.

Table 1 - Materials and configuration

Grup	Dimensions	Heat Treatment	Details
A	9.5 x 9.5 x 120 mm	Annealing	Material heated at a rate of 22 °C/min and kept at the above recrystallization temperature of 900 °C for 3 h, then cooled;
B		–	As received;
C	Φ 5.5 x 15 mm	Tempering	Material heated at a rate of 22 °C/min and maintained at a preheating temperature of 500 °C for 30 min. Rehated at a rate of 22 °C/min up to 860 °C, maintained for 15 min, again reheated to the austenitization temperature of 1180 °C, maintained for another 5 min, from which it cooled down to 500 °C and removed to be air cooled at room temperature;
D		Tempering and drawtempering	Material heated at a rate of 22 °C/min and maintained at a preheating temperature of 500 °C for 30 min. Reheated at a temperature of 860°C, maintained for 15 minutes and again heated to an austenitization temperature of 1180°C for 5 min, from which it cooled.

After the heat treatment completion, samples from group A, having an external diameter of 305 mm, an internal diameter of 76 mm and a width of 25 mm were submitted to a precision flat rectifier, where a vitrified silicon carbide binder type 39C60KVK was used. Thermal treatments using a muffle oven have been carried out on the cylindrical test coupons, groups C and D, that were latter hot-mounted as pictured in figure 1(a). Figure 1(b) illustrates the equipment developed exclusively for the abrasive test.



(a) (b)

Figure 1 - (a) Test specimens; (b) assembly and coupling

In all the stages, five specimens were prepared per group. Loads of 0,5 kgf and 125 kgf, respectively for the micro and macro-Vickers hardness tests, were applied and maintained for 20 and 30 seconds. Microabrasion tests (calotest) at a constant speed of 1500 rpm, monitored by digital tachometer, completed the investigation, which was performed with an alumina-base abrasive medium for the duration of three minutes - figure 1(b). The caps had their diameters certified by a digital optical microscope, magnified at 200x.

3. RESULTS AND DISCUSSIONS

Table 2 represents the results of Vickers tests after tempering, indicating that the carbides are soluble in austenite, as expected for the AISI M2 steel and also found in commercial samples.

Table 2 - Hardness and microhardness results

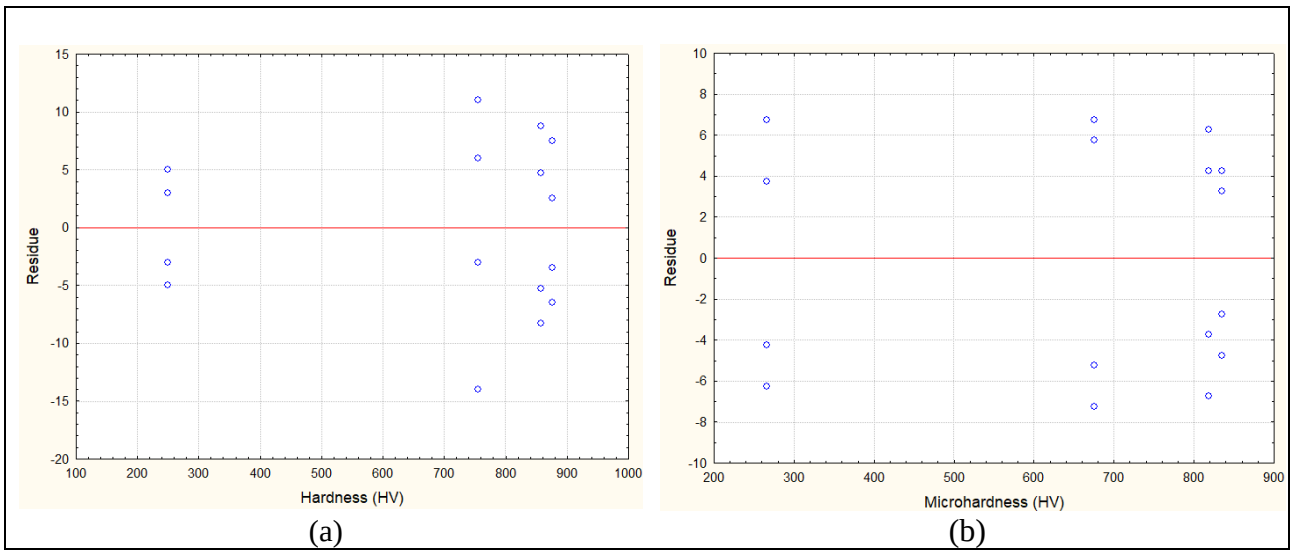
Group	Hardness (HV/125)	Microhardness (HV/0,5)
A	249 ± 8.2	268 ± 3.5
B	756 ± 11.1	676 ± 8.3
C	858 ± 11.6	820 ± 9.6
D	874 ± 8.6	834 ± 8.8

Table 3 is a summary for the hardness and microhardness ANOVA results. The hypothesis test reveals high values of 'F' combined with zero 'p' values, indicating a statistically significant difference between the analyzed heat treatments.

Table 3 - ANOVA for hardness and microhardness tests

Parameter	Effect	Degree of freedom	Average Square	F	p
Hardness	Difference between groups	3	346779	5610.2	0
	Standard deviation	12	62	-	-
Microhardness	Difference between groups	3	280673	7468.0	0
	Standard deviation	12	38	-	-

To validate ANOVA, standardized residuals and error estimates were analyzed. The charts represented in figure 2 illustrate the hardness and microhardness tests results, where residuals distribution around zero is observed, characterizing the selected variables as being equal and independent.



(a) (b)

Figure 2 – Standardized residuais for (a) hardnesss and (b) microhardness

Figure 3 represents the comparison between the average hardnesses, as described in table 2. It is observed a slight increase for the tempered sample (C), in contrast with the tempered and drawtempered samples (D), indicating a secondary gain in hardness for the former, due to the precipitation of carbides.

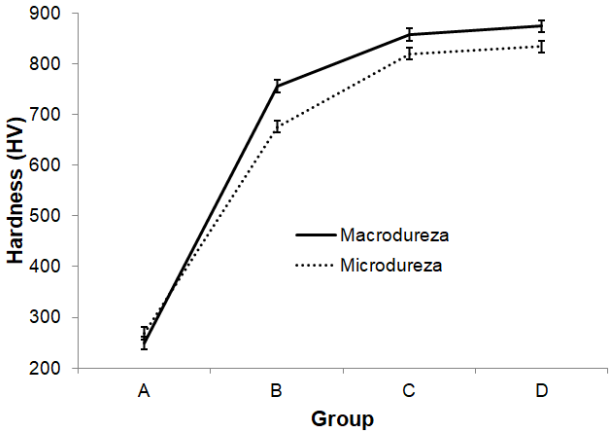


Figure 3 - Effect of the thermal treatment on hardness and microhardness

Table 4 represents the percentage and statistical difference among the distinct groups. It is noticed that, in relation to hardness and microhardness, there is no statistically significant difference between the samples from groups C and D.

Table 4 - Percentage and statistical difference for hardness and microhardness

	Group comparison	Difference (%)	p-value
Hardness	A → B	+ 203.61	**p<0.05**
	A → C	+ 244.58	**p<0.05**
	A → D	+ 251.01	**p<0.05**
	B → C	+ 13.49	**p<0.05**
	B → D	+ 14.61	**p<0.05**
	C → D	+ 1.86	p>0.05
Microhardness	A → B	+ 152.23	**p<0.05**
	A → C	+ 205.97	**p<0.05**
	A → D	+ 211.19	**p<0.05**
	B → C	+ 21.30	**p<0.05**
	B → D	+ 23.37	**p<0.05**
	C → D	+ 1.71	p>0.05

Table 5 represents the cap diameter and the amount taken out in the calotest process, from which it is found that the thermally treated groups depicted an increase in the abrasive wear resistance. It is also noticed that the average loss volume is inversely proportional to wear.

Table 5 — Results of the cap diameter and the volume from the withdrawn material

Group	Cap diameter (mm)	Withdrawn from cap (mm^3)
A	1.3014 ± 0.0763	$11.273 \times 10^{-3} \pm 2.762 \times 10^{-3}$
B	1.0981 ± 0.0289	$5.636 \times 10^{-3} \pm 5.636 \times 10^{-4}$
C	1.0514 ± 0.0763	$2.652 \times 10^{-3} \pm 4.383 \times 10^{-4}$
D	1.0333 ± 0.0812	$2.582 \times 10^{-3} \pm 3.848 \times 10^{-3}$

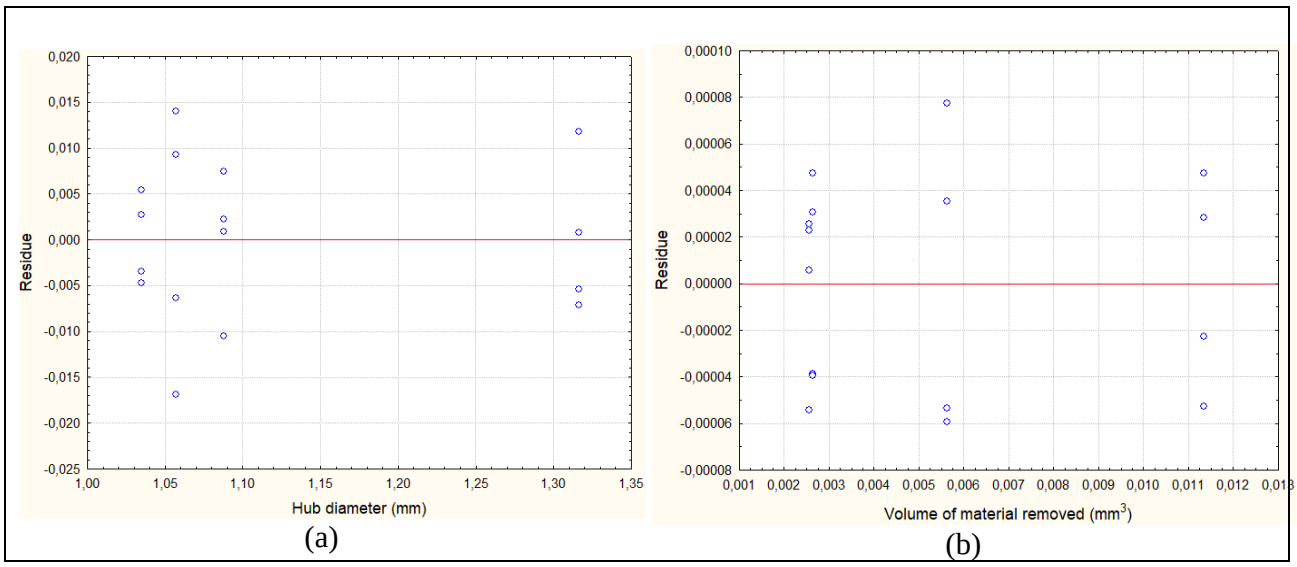
Table 6 represents the ANOVA for the results described in table 5. It can be seen that the standart deviation associated with the cap diameter and with the volume of withdrawn material were nearly zero. In other words, the data obtained are from a normally distributed population and they do not indicate systematic error, but statistical.

Table 6 - ANOVA the cap diameter and the volume from the withdrawn material

Parameter	Effect	Degree of freedom	Average Square	F	p
Cap diameter	Difference between groups	3	0,06773	759.4	0
	Standard deviation	12	0.00009	-	-
Volume of withdrawn material	Difference between groups	3	0.000068	26920.1	0
	Standard deviation	12	0.000002	-	-

Figure 4 shows the residues obtained for the cap diameter and the volume of withdraw material. The distribution around zero makes the proposed model valid, as it confirms that both the measured average values of the cap diameter and the volume of withdrawn material are statistically different - figure 5.

Table 7 represents the percentage and statistical differences in the cap diameter and the volume of withdrawn material obtained from calotest. For a confidence level of 95%, there is indeed a statistical difference between annealed samples of the group A and the other specimens.



(a) (b)

Figure 4 - Standardized residues of the (a) cap diameter and (b) volume of withdrawn material

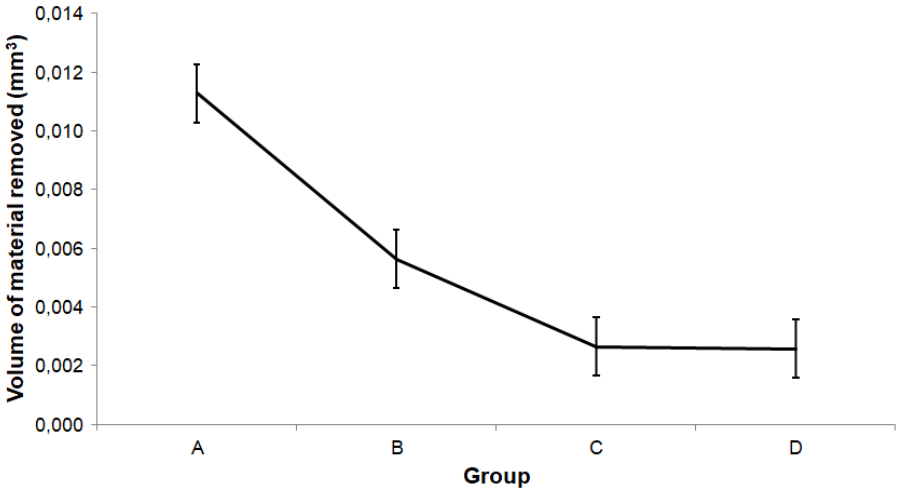


Figure 5 – Volume of withdrawn material as a function of termal treatment

Table 7 - Percentage and statistical difference for the diameter of the calota and the volume of material taken. Figure 6 shows the correlation between hardness and the volume of material removed from the evaluated samples. An inversely proportional relationship between material hardness and abrasive wear resistance can be observed. It is possible to infer that the increase in resistance to abrasive wear originates from an increase in the hardness of the material, that is, the harder the material, the more resistant to abrasive wear it becomes.

	Group comparison	Difference (%)	p-value
Cap diameter	A → B	+ 15.62	**p<0.05**
	A → C	+ 19.21	**p<0.05**
	A → D	+ 20.60	**p<0.05**
	B → C	+ 4.25	p>0.05
	B → D	+ 5.90	p>0.05
	C → D	+ 1.72	p>0.05
Withdrawn volume	A → B	+ 50.01	**p<0.05**
	A → C	+ 76.47	**p<0.05**
	A → D	+ 77.09	**p<0.05**
	B → C	+ 52.94	**p<0.05**
	B → D	+ 54.18	p>0.05
	C → D	+ 2.63	p>0.05

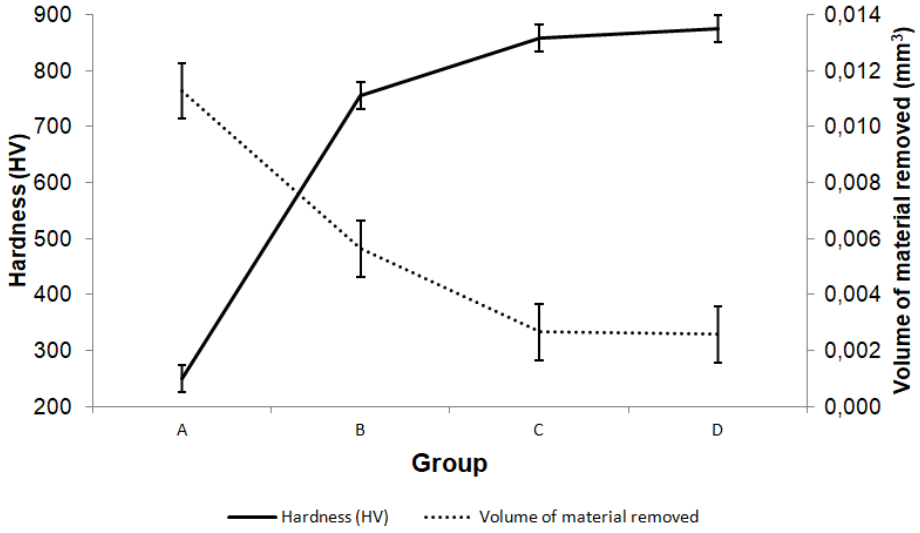


Figure 6 – Relationship between hardness and volume of withdrawn material in termally treated specimens

4. CONCLUSIONS

The tempering and drawtempering treatments are of a great importance, as they not only increase hardness and reduce abrasive wear in commercially available AISI M2 fast steel, but also contributes to a considerable improvement on the duration of its toolling. In addition, the drawtempering, if undertaken at temperatures of around 1800 °C, has also proven to be especially beneficial. Unlike conventional carbon steels, which suffer from a reduction in hardness when they pass through the drawtempering process, the presence of alloy elements and equivalent carbides makes not only the hardness of the fast steel increase, but also its tenacity.

The group D (tempered and drawtempered) has yielded a staggering 326% increase in hardness, as compared to group A (annealed state), mostly as a concequence of the retained martensite precipitation in the matrix.

5. ACKNOWLEDGEMENTS

The authors wish to express their gratitude with the following organizagions: CAPES, Araucária Foundation, the State Secretariat for Science Technology and Higher Education of Paraná. They are also very greateful with UNA, UFU, UTFPR/Londrina and UFEI.

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