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EFFECT OF COOLING RATE DURING QUENCHING ON THE TOUGHNESS OF HIGH SPEED STEELS[1]

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Abstract

High speed steels are usually employed in cutting tools and forming dies. Heat treatment is a primordial step during tools manufacturing process, being responsible for most of final properties, principally hardness and toughness. In this context, a especial interest relies on the effect of hardening variables on mechanical properties and tools performance. Therefore, the present paper aimed to study the effect of cooling rate during the quenching process of AISI M2 high speed steel, under typical industrial conditions. The experiments were carried out in an industrial vacuum furnace, with high pressure nitrogen quenching. Several cooling rates were obtained by modifications of nitrogen pressure and by the use of test specimens with different dimensions. Toughness results were mainly evaluated through static bend test. Low cooling rates were shown to decrease material toughness and large parts presented a decrease in mechanical properties from surface to core regions. Carbide precipitation on grain boundaries are pointed as the main explanation for all these effects.

Key words: AISI M2; High speed steels; Cooling rate; Toughness; Bending test.

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1 INTRODUCTION

High speed steel tools are used in several industrial applications, mainly for cutting tools and forming dies.[1,2] In such applications, the performance of a given tool depends on combination of several mechanical properties, mainly strength, toughness and wear resistance. And all these properties are deeply influenced by the final heat treatment applied.[2]

For instance, a cutting tool is normally hardened and tempered to 65 HRC and presents, in its microstructure, dispersion of large undisolved carbides. This microstructure is typically highly wear resistant, but also presents low toughness.[2-6] Although the material toughness is not easily observed in cutting tools or dies highly wear resistant, this property is essential in determining the tool life and performance. In several adhesive wear mechanisms, microchipping and microcracking deeply influence the wear of working area and both mechanisms are delayed if tool steel toughness is enhanced. This concept is applied either for cutting or forming tools[1-2,6]

By this reasoning, it is shown to be important the evaluation of toughness for high strength tool steels. Several studies have concerned the evaluation of high speed steel toughness (mainly for M2 grade), by using classical fracture toughness tests (ASTM E399-81e ASTM E399-74)[4-6] or modified impact tests (C-notched specimens).[3] However, the results always show appreciable scattering and experimental difficulties. An alternative test which has shown proper results regarding laboratory easiness and scattering[7-10] is the bend test, initially developed by Grobe and Roberts[11] and Hoyle et al.[12]

Using the bend test, the present work aimed to determine the effect of cooling rate on the toughness of M2 high speed steels. Firstly, it is evaluated the effect of cooling rate in vacuum furnaces on M2 toughness, due to possible effects of grain boundary embrittlement by carbide precipitations; such variations are performed using different cooling pressures. And, secondly, this paper also studies how the part size can affect the cooling rate and impact the mechanical properties obtained in different positions (core and surface) of bars with 2 different sections.

2 EXPERIMENTAL

M2 high speed steel was obtained from hot rolled and drawn coils. Different materials were used for the two studied experiences, i.e. the effects of quenching pressure and the effects of large parts in mechanical proprieties. These experiences can describe two parameters of cooling rate. Table 1 summarizes the chemical composition for the evaluated high speed steels. Due to different production lots, sizes and chemical compositions, the results can only be compared within a given experience. For all, the chemical composition meets the standard for grade 1.3343 (standard DIN 17350).

For all experiments, hardness was measured using a digital the Rockwell C tester, with 0.1 HRC precision. Toughness test were carried out using the 4 point bend test, which is detailed in references 7 to 12. All specimens, with different sizes, were ground after end heat treatment with sand paper down to #600 mesh, using a lathe and also manually in the longitudinal direction; the purpose of such preparation is to remove any notching surface defects, which influences the final strength (and toughness) measurement due to the low fracture toughness of hardened tool steels. Through the bend test, maximum strength, plastic deflexion and fracture energy (the area bellow force x deflexion curve) were determined. These data were then used as indicators of material toughness, also according to references 7 to 12.

Table 1. Chemical composition and size of M2 (DIN 1.3343) high speed steel bars, from which were prepared specimens for each heat treating experience; the details for these three experiences is given bellow

Experience Number (effect of)	Size	C	Si	Mn	Cr	Mo	W	V	P	S
1- Cooling Pressure	∅ 6.5 mm	0.92	0.43	0.34	3.88	4.75	6.06	1.81	0.025	0.001
2- Bar size	∅ 6.15 mm	0,92	0,38	0,26	3,91	4,79	6,10	1,76	0,03	0,001

The details of each experiment are shown in separated items, as follows:

2.1 First Experiment – Effect of Quenching Pressure

As briefed along the introduction, the objective of both experiments was to evaluate the effect of cooling rate on the toughness of M2 high speed steel, by two different approaches. First, the cooing pressure effect was evaluated in an industrial vacuum furnace, with the gas flow (agitation) fixed at a high level (not maximum, but the usually employed for tools). The distinct conditions were characterized by changing the cooling pressure: 2 bar, 6 bar or 9 bar. The achieved cooling rate for each pressure is given on Table 2 bellow. After quenching, the specimens were tempered, twice for 2 hours, at 560 ºC; hardening temperature was fixed at 1200 ºC, for 3 min.

Table 2. Cooling rate between 1200 and 650ºC, for each cooling pressure. This temperature range was chosen because bellow it no precipitation is due to occur[13]

Pressure	**2 bar**	**6 bar**	**9 bar**
Cooling Rate	380 ºC/min	470 ºC/min	580ºC / min

2.2 Second Experiment – Effect of Bar Size

The second approach to simulate the effect of cooling rate was the evaluation of large diameter bars. This is mainly important because many tools, special for cold work tooling, may employ large pieces, with 1 inch thick, and the effect of grain boundary precipitation embrittlement might be stronger for these tools.[14,15] The specific design of this experiment is shown in Figure 1, where several specimens were introduced inside different positions of two bars with different sizes: approx. 2 in and 4 in. Two main advantages regards to this idealization: i) that large high speed steel bars are quite difficult to be evaluated, regarding to specimens preparation, due to the high hardness after hardening and tempering and thus poor machinability; ii) in "real bars" the distribution carbides would be different in small, medium and large bars, which affect considerably the final toughness as determined in previous paper.[16] So, the introduction of small specimens inside big parts (Figure 1) solves both problems of specimens preparation and carbide distribution, representing only the effect of quenching speed.

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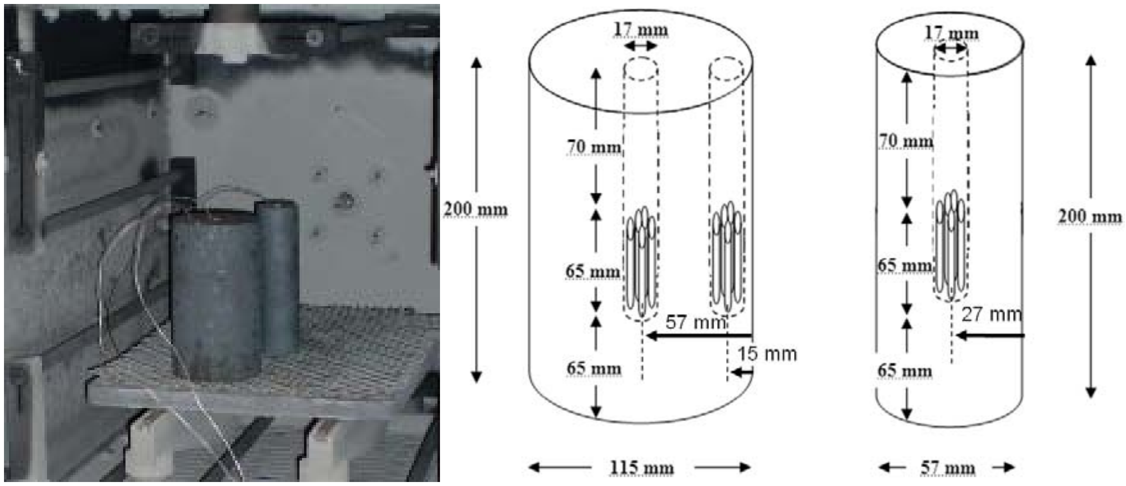

Figure 1. Second experiment: for each condition was used five samples, located as described below: free specimens placed inside the furnace, some inserted in the center of the block of 57.0 mm, others in the central region of the block and, finally, five in the surface region of the block. The drill holes were filled with wood chips and the hole was sealed with a thermal blanket. In each hole, a thermocouple was inserted to monitor and record the temperature.

The details of each sample are given as follows, being the measured cooling rate shown in Table 3 and actual cooling curves are shown in Figure 2.

- Samples positioned freely inside the furnace: they represent small tools made with high speed steel, with dimensions near 6.0 mm, conditions typical used in cutting tools such as drills. They will be referred to as small parts.
- Samples inside the block with ∅57.0 mm: represent midsize tools such reamers and counter sunk. The samples were inserted in the central block position.
- Samples inside the block with ∅115.0 mm: represent large tools, as tools for cold working, such as extrusion or forming. The samples were inserted in the central block, referred to as core, and surface region of the bloc.

For each condition, it was used five samples and the average result of this study can be followed on the items below.

Considering the cooling rate data of Table 3, it is interesting to note that the cooling rate is not only related to the position of the thermocouple, but also depends on the total weight of the piece. For a large piece, the distance between the surface and the core is bigger. This promotes the formation of a temperature gradient between these regions, where the surface transfers heat to the core, in what is known as a conduction. I. e., the cooling rate depends on furnace convection for the heat extraction is more effective and at the same time, depends on the mass being cooled so that heat transfer between the surface and core is the most quickly as possible. As larger pieces have a core/surface distance area greater, heat conduction is governed more significantly the cooling rate, resulting in a drop representative of their value. The same occur for the heating step. These results are important to understand why large parts result in lower hardness, and promote the grain boundaries precipitation of carbides.

As showed, the mass affect the cooling rate in a strong way. For example, when compared cooling rate for the thermocouple inside the core of the medium piece, this result is twice de value register in the thermocouple into de core of large piece. But, this difference is bigger when used small piece is. It results in almost ten times.

Hardening and tempering procedures (temperature and number of treatments and time) were the same of the first experiment. In this case was used 6 bar of pressure. However, due to the different size of bars, the austenitizing time and temperature varied from each of the conditions, which led to differences in final hardness, as shown in the next section. In Table 3, the data of austenitizing and cooling rate for each position of Figure 1 are shown. And the results will be described according the cooling rate data.

After hardening, all specimens were double tempered at fixed temperature of 560 ºC. Bend toughness, hardness and microstructure on optical microscope were compared.

Table 3. Cooling rate between 1200 and 650ºC, for each conditions of Figure 1. Due to the differences in size, time at austenitizing temperature was different, which is also shown. For the isolated specimens, it is considered the 6 bar value from Table 3

Specimen Position	Single Specimens	27 mm from surface of 50 mm bar	15 mm from the surface of 115 mm bar	57 mm from the surface of 115 mm bar
Cooling Rate	470 ºC/min	123 ºC/min	75ºC / min	57ºC / min
Austenitizing	16 min at 1200 ºC	6 min at 1200 ºC	3 min at 1190 ºC	1 min at 1190 ºC

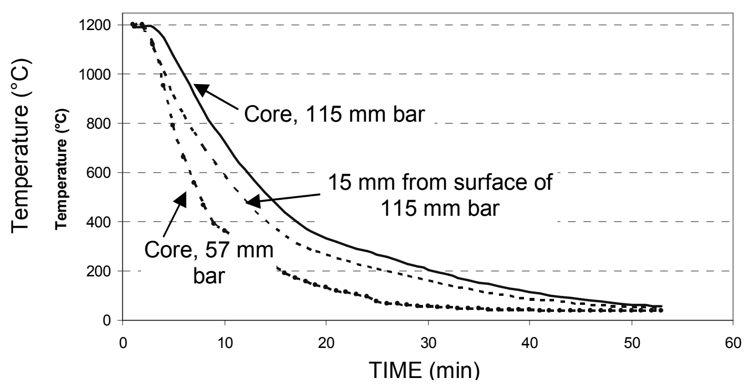

Figure 2. Cooling rate data (°C/min) as function of pieces' size for M2 high speed steel. Each curve correspond one thermocouple inside the blocks, how as showed in Figure 1.

3 RESULTS AND DISCUSSIONS

3.1 Effect of Quenching Pressure

The cooling pressure is one of the most important variables associated to cooling rate of high speed steels, considering heat treatment in gas quenching vacuum furnaces. Although with excellent hardenability, high cooling rate is still important in high speed steels hardening, in order to avoid carbide precipitation on grain boundaries, which may cause material embrittlement. Therefore, this effect was investigated by the present work, for an industrial furnace; the results are given in Figure 3. This data indicates certain increase in toughness values from 2 to 6 bar pressures (even being the 2 bar specimens with about 0.7 HRC lower hardness) and smaller differences between 6 and 9 bar quenching pressures.

One can notice that the differences are not big, especially if compared to data scattering (pointed in Figure 3 subtitle). According to literature, cooling rate is directly related to nitrogen pressure, and the apparent low sensitiveness to cooling pressure may regard to the low susceptibility of such small specimens to grain boundary

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precipitation embrittlement; this is in agreement to what observed by reference 15. For larger tools, with 1 inch thick (or larger), this effect might be stronger. From literature,[17,18] pronounced grain boundary precipitations were observed in hardened tools about 100 mm thick; but even using 3 bar quenching pressure, no differences were observed between salt bath and vacuum treated tools, regarding toughness and cutting performance. Another important fact is the gas flow conditions inside the vacuum furnace. For all experiences, this flow was kept in a high level, contributing to a high cooling rate even when using lower quenching pressures.

Nevertheless, based on the present data accuracy, it is possible to affirm that 6 bar pressure is enough to promote adequate cooling rate in hardening of small diameter tools (~ 6 mm), when proper flow conditions exist in furnace chamber. For such conditions the attained bend strength values are very close to laboratory heat treated specimens,[19] meaning proper quenching conditions (the comparison of fracture energy cannot be done due to the different size of specimens, but at such high hardness bend strength and fracture energy have the approximately the same indications, as pointed before). The increase of cooling pressure over 6 bar, under these situations, would not lead to important benefits and may cause unnecessary furnace "degradation".

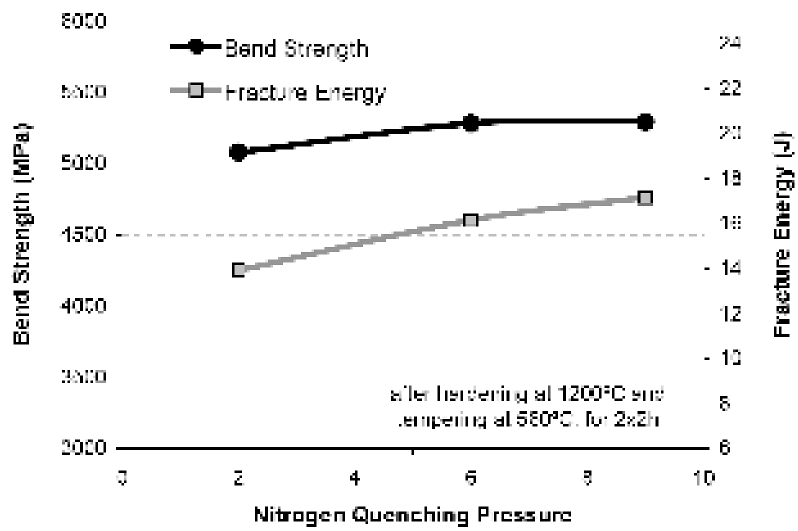

Figure 3. Bend test results for M2 specimens (∅ 6.0 mm from a 6.2 mm bar), hardened in a vacuum furnace with different nitrogen cooling pressures. Relative standard variation is around 9% for bend strength values and 17% for fracture energy. Hardness: 2 bar = 64,8 HRC, 6 bar = 65,5 HRC, 9 bar = 65,8 HRC.

3.2 Effect of Cooling Rate from Different Bar Sizes and Positions

The following were classified according to their cooling rate or specimen position in large bars, but further details are given in the item 2.2.

3.2.1 Hardness

Through Figure 4 data, it is clear that the final hardness is dependant of the parts size that is heat treatment. Highest hardness was found to small piece and the lower was to large piece. In this last case, the hardness was homogenous to surface from core. Even the medium piece showed higher hardness than the surface of large piece. The explanation of such differences in hardness are more likely related to austenitizing time and temperature than to the hardenability considerations. As shown in Table 3, specimens from bigger parts and isolated specimens were austenitized in the same cycle, which inevitably lead to different degree of dissolution of carbides, which thus converted in distinct precipitation hardening during tempering. Therefore, the isolated specimens which were austenitized for 16 min at 1200ºC are thus coherently harder than the specimens from the core of 115 mm bar, austenitized only for 1 min at 1190 ºC.

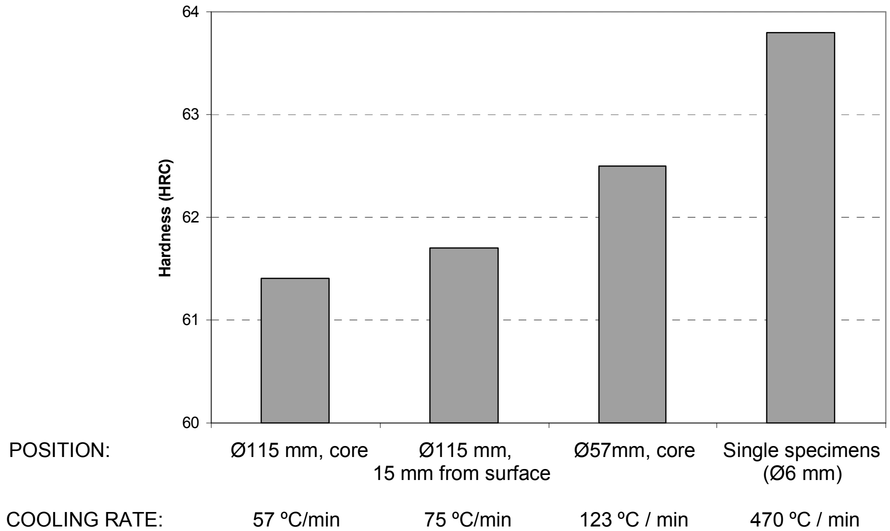

Figure 4. Hardness data versus bar size and position in which specimens were considered.

3.2.2 Toughness

Bend test results are shown in Figure 5. In spite of the higher hardness, the single treated specimens showed the highest toughness values, as can be seen in Figure 5. This fact may be considered as a result of the high cooling rate, reducing the precipitation on grain boundaries and thus increasing the toughness. So, tools with high hardness and also better toughness are possible to be produced. The reduction in toughness for large parts mainly regards to undissolved carbides and grain boundary precipitations discussed previously. These microstructure constituents act as metallurgical notches, weakening the grain boundaries interfaces. Thus, the tool when applied mechanically begins to lose coherence between the interfaces at these points that could enable an intergranular fracture, which requires less energy to promote crack propagation.

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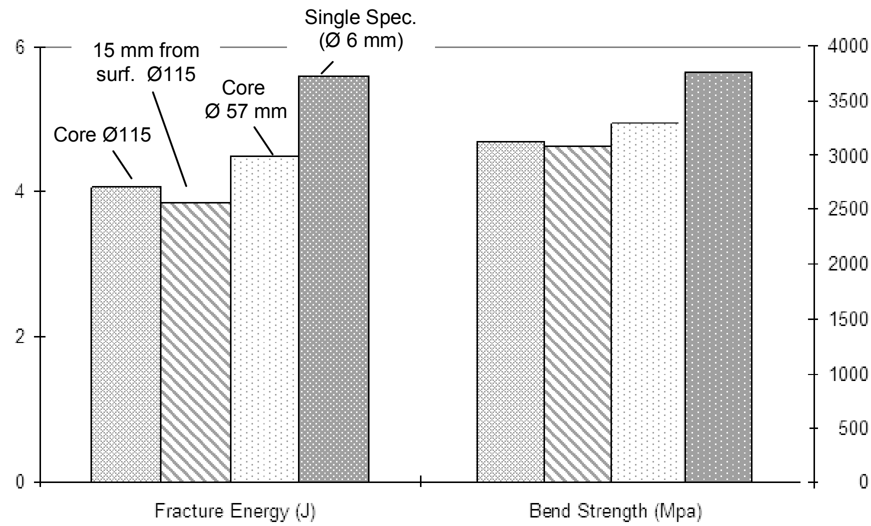

Figure 5. Toughness data (bend strength and fracture energy) versus pieces' size for M2 high speed steel. Bend test specimens ∅ 5,8 mm, machined from a 6.15 mm bar. Mean relative standard variation is about 10% for bend strength values and 20% for fracture energy.

When fracture energy and bend strength was compared for medium and large bars, it can be considered that these properties do not show a classical correlation between hardness and toughness. Although with higher hardness, specimens with higher cooling rate tend to show better toughness. To enable the discussion of toughness levels in different hardness, Figure 6 was prepared. In this graph, the predicted behavior of toughness (represented by fracture energy) and hardness was prepared from data of previous paper and the same trend was applied to the data of present paper. With this comparison, it can be observed that for the same hardness, toughness reduces in larger bars, showing an embrittlement due to slower cooling rate. This is shown by the arrow in Figure 6.

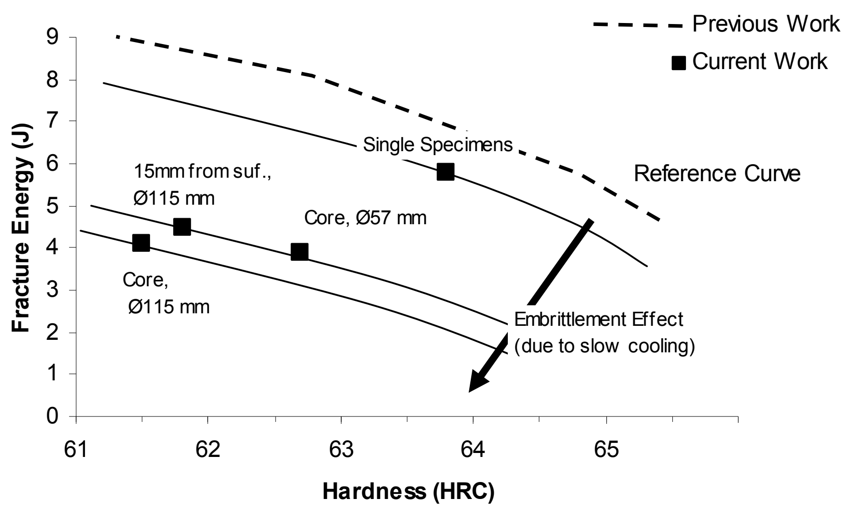

Figure 6. Combination of hardness and toughness values, showing the comprimsse between these two mechanical properties for each bar size (cooling rate) condition. The dashed line represent the expected combination of hardness and toughness, from different hardening conditions, from previous work (reference 7).

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3.2.3 Optical Microscopy

Figure 7 shows typical microstructures for M2 after quenching and tempering heat treatment at each part size studied. It may be suggested that the small piece showered a larger amount of retained austenite, due to the lighter appearance after metallographic etching as well as a greater amount of dissolved carbides. This is clearly related to the higher austenitizing temperatures and longer times involved in the hardening procedure (as shown in Table 3), also explaining the higher hardness. In relation to the specimens from large bars, as the tempering was performed at the same procedure, the darker appearance is related to distinct precipitation – which obviously also cause the hardness variation. For instance, the lower dissolution of carbides enables lower alloy content in the matrix of specimens from the large bars, causing their darker appearance after etching.

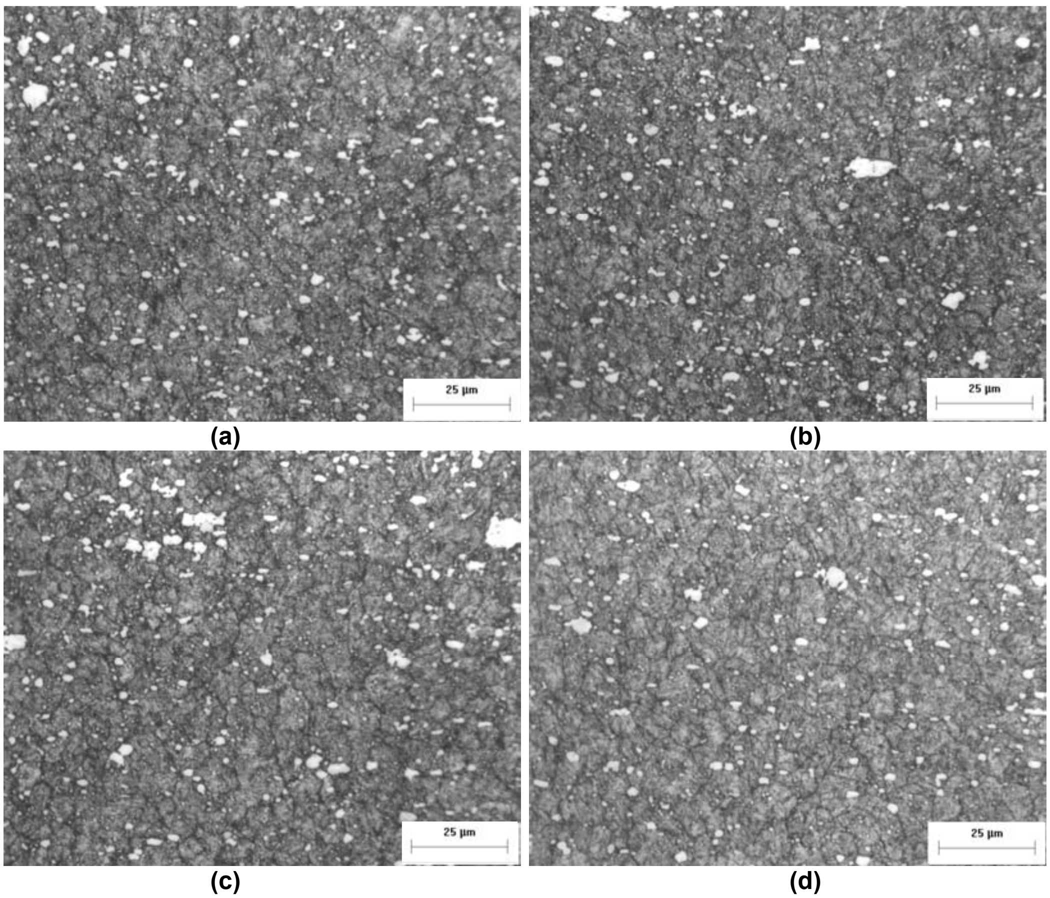

Figure 7. Microstructure results for M2 different sizes hardened in a vacuum furnace with same nitrogen cooling pressure (6 bar). (a) specimens introduced in the core of 115 mm bar, 61,3 HRC; (b) 15 mm from surface of 115 mm bar, 61,7 HRC; (c) core 57 mm bar, 62,5 HRC; (d) single specimens, 63,8 HRC.

5 CONCLUSIONS

- Bend test is shown as a proper tool to evaluate toughness of high hardness tool steels, enabling the understanding of several heat treating variables.
- For small tools, the results do not show strong differences regarding vacuum hardening cooling pressures, especially when comparing 6 and 9 bars conditions; 6 bars is thus considered enough to promote adequate toughness, in a vacuum furnace with proper gas flow.
- In large parts, surface temperature is not a proper control during hardening. Insufficient austenitizing time or temperature may occur in core regions, leading to lower hardness at these positions after hardening and tempering.
- Bar size affects the cooling rate, leading to strong reduction in toughness. This effect is shown important even in the surface regions of large bars of 4 in or in the core regions of 2 in bars.

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