Materials Research. 2023; 26:e20230179
DOI: https://doi.org/10.1590/1980-5373-MR-2023-0179

Fracture Toughness of Vacuum Sintered AISI M3:2 High Speed Steels

Moisés Euclides da Silva Junior[a]*, *Wanderson Santana da Silva*[b], *Mauricio David Martins das Neves*[c], *Hélio Goldenstein*[d], *Oscar Olimpio de Araujo Filho*[a]

[a]*Universidade Federal de Pernambuco, Departamento de Engenharia Mecânica, Recife, PE, Brasil.*
[b]*Universidade Federal de Santa Catarina, Departamento de Engenharia de Materiais, Blumenau, SC, Brasil.*
[c]*Universidade de São Paulo, Instituto de Pesquisas Nucleares e Energéticas, São Paulo, SP, Brasil.*
[d]*Universidade de São Paulo, Escola Politécnica, Departamento de Engenharia Metalúrgica e de Materiais, São Paulo, SP, Brasil.*

Received: March 24, 2023; Revised: September 27, 2023; Accepted: October 20, 2023

The aim of this investigation was to study and evaluate the fracture toughness (K_{ICV}) of an AISI M3:2 high speed steel that was prepared by powder metallurgical processing, which consisted of uniaxial cold compaction of irregularly shaped water atomized powders, without and with 0.3% of carbon in the form of graphite, followed by vacuum sintering to obtain compacts with densities close to its theoretical value. The sintered steels were then hardened by austenitizing, quenching and triple tempering. Chevron fracture toughness test samples were prepared from the compacts and the tests conducted to determine K_{ICV}. The microstructures of the specimens were examined by scanning electron microscopy (SEM), and the composition of the phases determined by x-ray diffraction analysis (XRD). The sizes of the primary carbides and of the austenite grains were determined using Quantikov digital analysis software. No significant difference in fracture toughness (K_{ICV}) between the two high speed steels AISI M3:2, austenitized at the different temperatures, was observed.

Keywords: *M3:2 High speed steel, powder metallurgy, K_{ICV}, characterization.*

1. Introduction

High speed steels (HSS) is steels capable of cutting other materials at very high loading rates compared to carbon tool steel. They have been used for several decades as unique materials for drills, broaches, and blades. In other words, applications where the material must exhibit oxidation resistance, high heat resistance, and hardness[1,2].

High speed steels can be produced by conventional processing that consists of stages such as melting followed by die casting, forming, heat treatments (annealing, austenitizing, quenching, tempering) and machining. Powder metallurgical processing can also produce these steels, and this is useful when conventional processing becomes ineffective with formation of eutectics during solidification and the final product has a coarse and non-uniform microstructure from dendrite formation and segregation[3-5].

Often, large-scale carbide segregation in conventional processing causes embrittlement. These carbides align at times to form paths that favor crack propagation[4-6]. The presence of these cracks reduces the energy required for fracture and decreases the fracture toughness of the steel[7,8]. Fracture toughness of high speed steels is an important property with practical implications and generally refers to the steels capacity to absorb impact loads without significant plastic deformation or catastrophic failure. A cutting tool should maintain precise dimensional tolerances, often under conditions of intermittent cuts, involving repetitive impact loads and during which, irreversible or inelastic deformation should not occur. Therefore, ductility is not the correct criterion for tool performance. Published literature on fracture toughness testing of high speed steels is quite limited. Toughness, in the context of high speed steels can be defined as:

1) The capacity to withstand deformation before fracture (bend test).
2) The capacity to resist to permanent deformation (creep resistance).

An alternate definition was offered by Johnson, who defined toughness as the amount of energy measured during plastic deformation in a static bend or torsion test[5]. Johnson demonstrated that there is no essential correlation between toughness, as defined by him, and the life of a tool executing intermittent cuts.

At present, there is a general acceptance that fracture toughness of high speed steels is an important property. According to studies[1,9,10], the influence of microstructure parameters, such as grain size, fine carbides, microcavities and impurities promote failures in the material, affecting its fracture toughness.

Increase in fracture toughness of high speed steels requires optimization of alloy design and heat treatment procedures[8]. In this investigation, the fracture toughness (KICV) of these steels was determined using the Chevron methodology, which has the advantage of avoiding fatigue pre-cracks (ASTM E 1304-89)[11,12].

*e-mail: juniormoises7@hotmail.com

Chevron specimens to determine fracture toughness of metallic alloys and other materials such as ceramics and glasses are cheaper compared to specimens with other configurations. This stems from the type of equipment required and the reduced time required preparing chevron specimens. Specimens of this type were previously used to determine the fracture toughness of brittle materials, wherein introduction of fatigue pre-cracks was a problem. These materials exhibited a near-ideal linear elastic behavior and only required the maximum load to failure to determine their fracture toughness. Use of the Chevron methodology was extended to ductile materials when very large specimens were needed to determine its fracture toughness by other methods.

Thin Chevron specimens ensure adequate planar deformation at the crack tips, permitting thus the use of small specimens to obtain valid fracture toughness results. Chevron specimens can also be used to determine the fracture toughness of materials that are not available as thick sections (or large) and of expensive materials, where costs become prohibitive to conduct fracture toughness testing using other specimen configurations. Use of this methodology simplifies interpretation of results, and the specimens are just 40% as thick, and about 2% as heavy as specimens with other configurations used to determine fracture toughness.

2. Methods and Materials

The AISI M3:2 high speed steel was prepared by the powder metallurgy route using water atomized irregularly shaped metal powders. These powders were uniaxially cold compacted at a pressure of 700 MPa and sintered at 1263°C under vacuum 10^{-5} (Torr), sintering was carried out in a vacuum chamber furnace with mechanical pump and diffuser and resistance to tungsten, the temperature was controlled by a type B thermocouple (platinum-rhodium). Resulting in obtaining a compact with acceptable microstructure and density greater than 98% of the theoretical value for this type of steel. Table 1 shows the chemical composition of the AISI M3:2 high speed steel supplied by Coldstream Inc. To this powder, 0.3 wt% of carbon (graphite) was added as graphite to help correct the carbon content to ASTM standards. The steel powder to which 0.3% carbon was added was also uniaxially cold compacted and sintered at 1240°C (The microstructure (by SEM), density determination and 3-point bending test were also evaluated in order to determine this sintering tempeture), these temperatures were studied in the work On Sintering of an AISI M3:2 High Speed Steel. The tests were carried out on high-speed steel specimens compacted and sintered under vacuum at temperatures of 1230°C, 1240°C, 1250°C, 1260°C and 1270°C and the best densification results were obtained for the temperature 1260°C. The microstructure (by SEM), density determination and 3-point bending test were also evaluated. A 3° window was chosen and the test was carried out at 1263°C. The steel specimens, with and without carbon added, were submitted to the same experimental procedures[12].

The specimens were subsequently submitted to hardening heat treatments which consisted of austenitizing at 1140°C, 1160°C, 1180°C and 1200°C followed by triple tempering at 540 °C. The following parameters of the specimens were determined: Vickers hardness, Rockwell C hardness, primary carbide size and austenite grain size. These data were presented elsewhere[11], the measurement of austenitic grain size was carried out using the Snyder-Graff Method (Intercept Grain Size). Figure 1 and Table 2 show the details of the Chevron specimen geometry and dimensions, Figures 2 and 3 show fractured TRS specimen and the apparatus used to carry out the fracture toughness (KICV) tests, respectively. The fracture

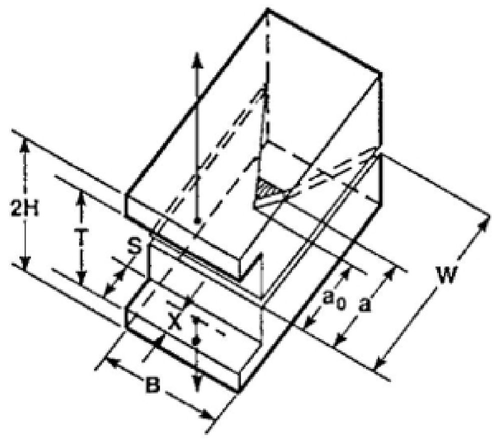

Figure 1. Geometry of fracture toughness test specimens, as per Chevron methodology.

Figure 2. Chevron notch specimen machined from fractured TRS specimen.

Table 1. Chemical composition of AISI M3:2 high speed steel, (mass %) and the balance is iron.

AISI M3:2	C	Mo	W	Mn	Cr	Si	V	Fe
Mass (%)	0.98	6.12	5.68	0.3	3.97	0.2	2.92	Bal.

toughness of the specimens was determined using the Chevron methodology, as per ASTM 1304-97 (Reapproved 2002) standard. The procedure used in the Chevron methodology, from specimen preparation until test validation is discussed in the Technical Bulletin BT/PMT/0501[13,14].

The tests were carried out with a Universal testing machine Instron Model-5567, with a 5 kN load cell, at the University Center of FEI. A strain rate of 0.2 mm/min and data collection frequency of 10 Hz were used. To determine the fracture toughness (K_{ICV}) of the material, using the Chevron methodology, the following equation was used:

$$K_{ICV} = \frac{P_{max}}{B\sqrt{W}} Y_C^*$$

Where, P_{max} is the maximum load obtained during the test, B and W are dimensions of the specimen (Table 2) and Y_c^* is the minimum geometric stress intensity factor, (defined by specimen geometry) and is independent of the material. To determine Y_c^*, ASTM norm 1304-97 was used[11], where the value of Y_c^* was obtained from the W/B ratio (specimen dimensions).

3. Results

Tables 3 and 4 shows the Vickers hardness (HV), Rockwell C hardness (HRC), primary carbides sizes, austenite grains sizes and fracture toughness (K_{ICV}).

The fracture toughness (K_{ICV}) results for the vacuum sintered high speed steel AISI M3:2, with and without 0.3% of carbon (graphite), and after specific heat treatments mentioned above are shown in Figure 4.

Figures 5 to 20 show pairs of scanning electron micrographs (SEM) and x-ray diffraction (XRD) profiles of the vacuum sintered high speed steel AISI M3:2, with and without 0.3% C, after hardening heat treatments mentioned before.

4. Discussion

The SEM micrographs of the high speed steel M3:2 revealed a bimodal distribution of primary carbides, containing very large carbide grains of about 17 μm and other smaller carbides

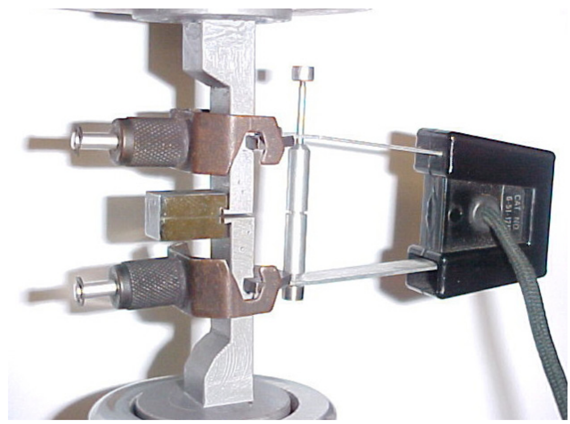

Figure 3. Apparatus used in the KICV test.

Table 2. Dimensions of fracture toughness test specimens, as per Chevron methodology.

Parameters	Symbol	Dimension	Tolerance
Thickness (mm)	B	6.3	0.005
Useful length of specimen (mm)	W	9.135	0.005
Distance from specimen end to load line (mm)	X	0.63	0.005
Total length of specimen (mm)	(W+X)	9.765	0.005
Height of specimen (mm)	2H	5.481	0.005
Distance between load line and notch tip (mm)	a_0	3.0303	0.005
Distance between specimen end and notch tip (mm)	$a_0 + X$	3.6603	0.003
Grip groove depth (mm)	S	0.945	0.003
Grip groove width (mm)	T	2.205	0.005
Thickness of notch (electrical discharge machining with wire) (mm)	t	<0.189	-
Chevron notch angle	Φ	54.5°	0.5°

Table 3. Vickers hardness (HV), Rockwell C hardness (HRC), size of primary carbides, size of austenite grains and fracture toughness (KICV) of AISI M3:2 high speed steel.

M3:2 SV	HV	HRC	Primary carbide size (μm)	Austenite grain size(μm)	Fracture toughness, K_{ICV} (MPa × $m^{1/2}$)
1140/540	690± 6	60 ± 0.6	2.161 ± 0.124	11.8 ± 0.2	21.6 ± 0.4
1160/540	690 ± 4	60 ± 0.4	1.921 ± 0.078	9.5 ± 0.2	21.7 ± 0.9
1180/540	690 ± 6	60 ± 0.6	2.280 ± 0.123	11.7 ± 0.2	20.7 ± 1.3
1200/540	740 ± 4	62 ± 0.4	2.056 ± 0.086	12.4 ± 0.6	21.3 ± 1.5

Table 4. Vickers hardness (HV), Rockwell C hardness (HRC), size of primary carbides, size of austenite grains and fracture toughness (KICV) of AISI M3:2 high speed steel with 0.3% carbon.

M3:2 +0.3%C SV	HV	HRC	Primary carbide size (μm)	Austenite grain size(μm)	Fracture toughness. K_{ICV} (MPa × $m^{1/2}$)
1140/540	836 ± 3.4	62.7 ± 0.3	1.812 ± 0.302	11.3 ± 0.5	18.45 ± 0.39
1160/540	898 ± 5.6	62.9 ± 0.2	1.677 ± 0.123	11.5 ± 0.3	16.52 ± 1.26
1180/540	902 ± 13.8	63.9 ± 0.5	1.855 ± 0.131	11.6 ± 0.4	15.54 ± 1.33
1200/540	907 ± 2.2	63.6 ± 0.5	1.466 ± 0.153	12.6 ± 0.8	18.45 ± 1.26

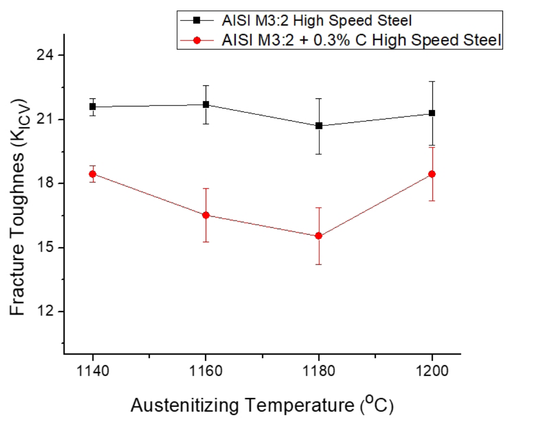

Figure 4. Fracture toughness (K_{ICV}) test results of vacuum sintered AISI M3:2 high speed steel.

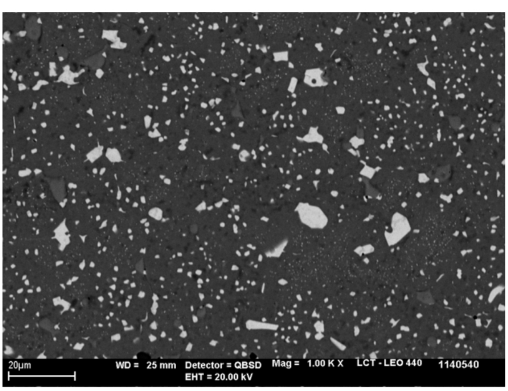

Figure 5. SEM of M3:2; 1140°C/540°C.

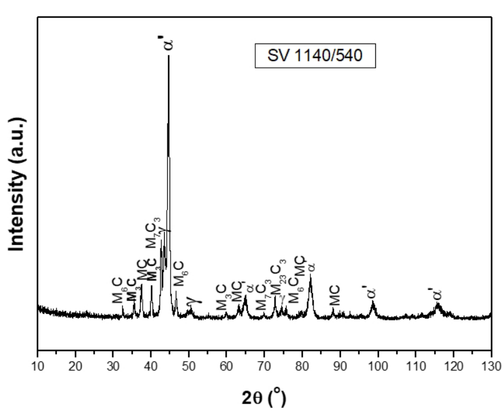

Figure 6. XRD of M3:2; 1140°C/540°C.

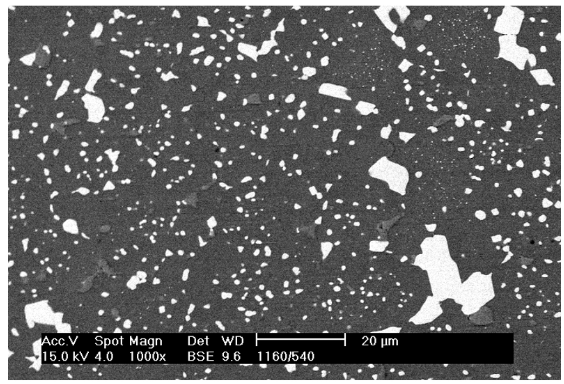

Figure 7. SEM of M3:2; 1160 °C/540 °C.

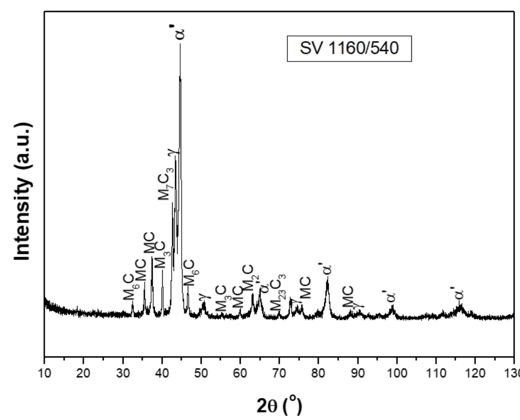

Figure 8. XRD of M3:2; 1160 °C/540 °C.

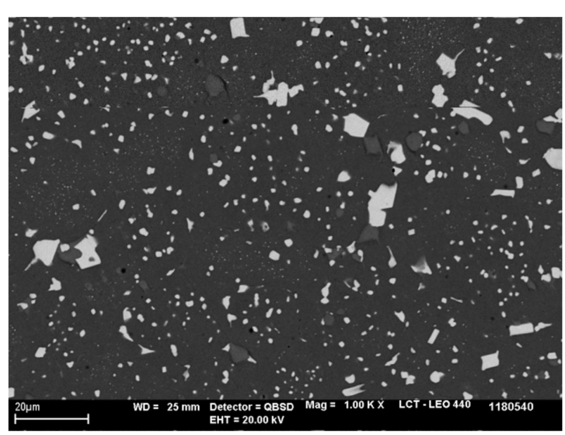

Figure 9. SEM of M3:2; 1180 °C/540 °C.

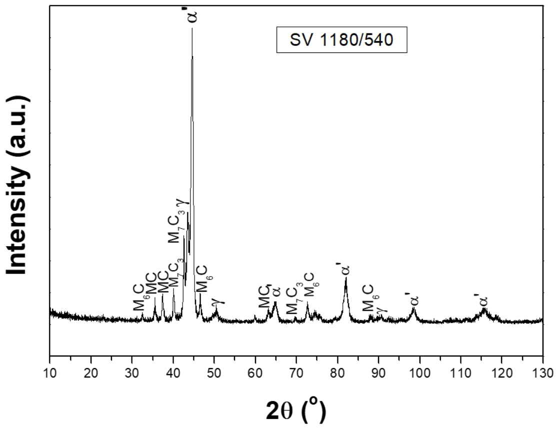

Figure 10. XRD of M3:2; 1180 °C/540 °C.

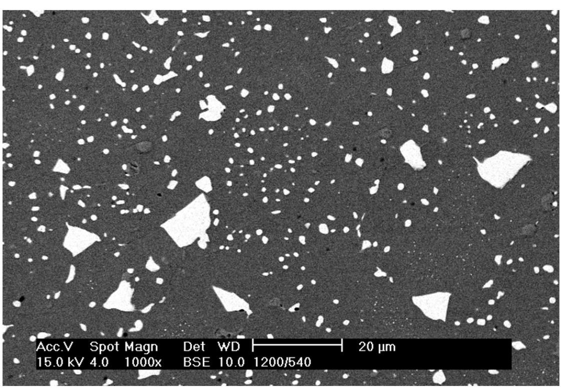

Figure 11. SEM of M3:2; 1200 °C/540 °C.

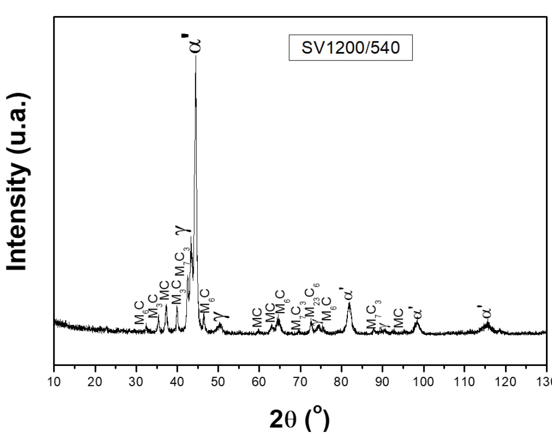

Figure 12. XRD of M3:2; 1200 °C/540 °C.

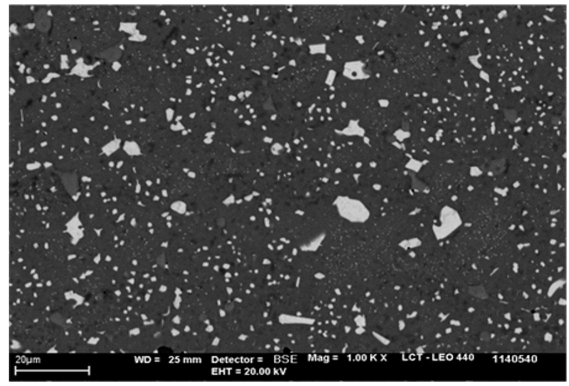

Figure 13. SEM of M3:2; 1140 °C/540 °C.

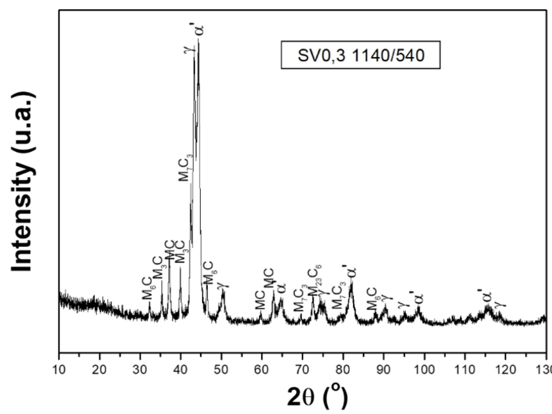

Figure 14. XRD of M3:2; 1140 °C/540 °C.

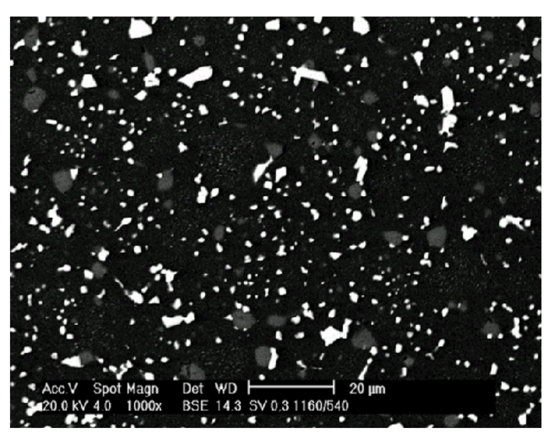

Figure 15. SEM of M3:2 + 0.3%C; 1160 °C/540 °C.

of about 1μm in size[9]. The diffraction profiles revealed a certain quantity of retained austenite (γ phase), which is being quantified in specimens that were given the different heat treatments, as this favors toughening of the material. These observations made from the SEM micrographs and the x-ray diffraction profiles, lend proof to the high fracture toughness K_{ICV} of about 20 MPa × $m^{1/2}$, observed for this vacuum sintered high speed steel, compared to 12 MPa × $m^{1/2}$ of high speed steels of this class (Sinter 23)[13] produced by powder metallurgical processing route that involves sintering by hot isostatic pressing. Further, this high speed steel M3:2, prepared from powders with a low carbon content for this class of material (usually in the range 1.15% and 1.25% (ASTM A600-92a) had lower hardness[14,15]. The retained austenite observed in this fast vacuum sintered steel, despite the low carbon content present, functions as a tenacifier of

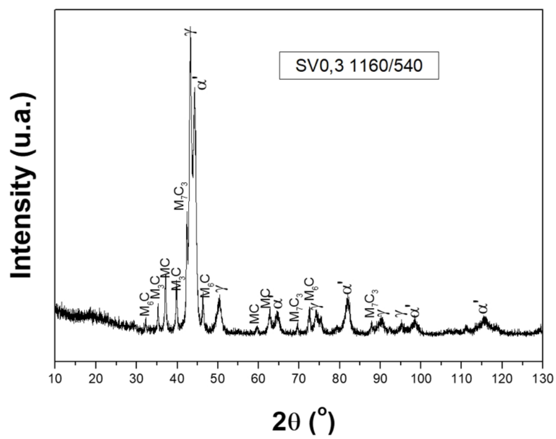

Figure 16. XRD of M3:2 + 0.3%C; 1160 °C/540 °C.

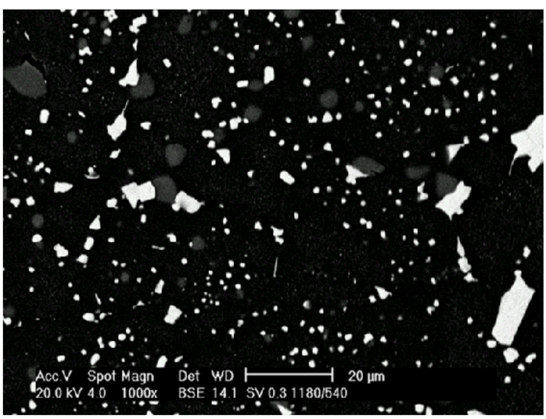

Figure 17. SEM of M3:2 + 0.3%C; 1180 °C/540 °C.

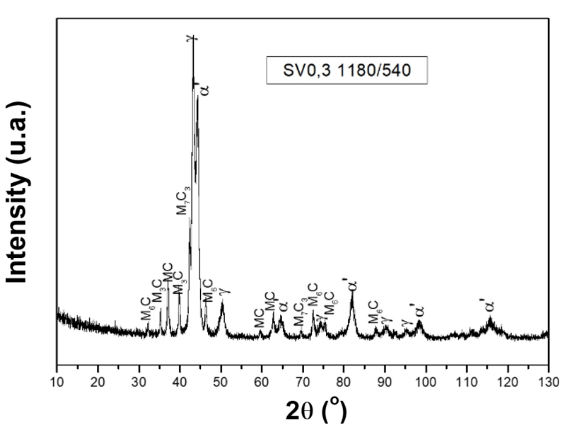

Figure 18. XRD of M3:2 + 0.3%C; 1180 °C/540 °C.

this class of tool steels. The addition of 0.30% of carbon to the powder of this high speed steel added to correct the carbon content in the sintered steel increased the amount of austenite retained, but this tenacifier effect generated by the increase of the retained austenite when faced with the increase in hardness was not enough to produce an increase

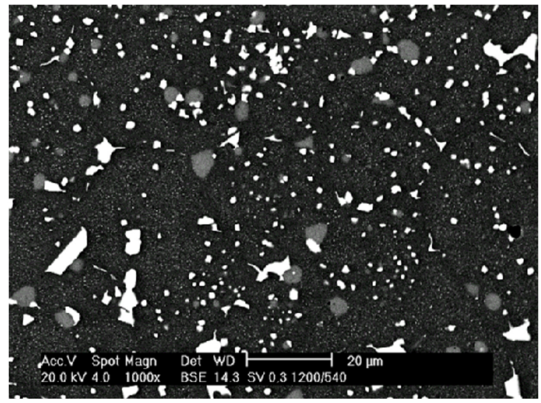

Figure 19. SEM of M3:2 + 0.3%C; 1200 °C/540 °C.

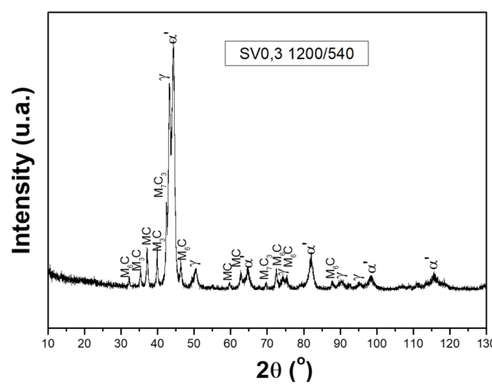

Figure 20. XRD of M3:2 + 0.3%C; 1200 °C/540 °C.

in fracture toughness (K_{ICV}) when compared to steel without the addition of carbon[16]. On the other hand, it's necessary to take in regard that the Chevron Notch technique applied for the evaluation of fracture toughness of brittle materials always tends to overestimate the obtained results.

5. Conclusions

1. The high fracture toughness K_{ICV} of these two vacuum sintered high speed steels M3:2 can be attributed to the bimodal distribution of the primary carbides and the toughening effect of the retained austenite detected even after triple tempering.
2. The lower hardness may have also contributed to the high fracture toughness K_{ICV} values.
3. There was no significant difference in the fracture toughness values, as determined from the Chevron tests, of the different high speed steel specimens, with and without 0.3% C and heat-treated to different austenitizing temperatures.
4. The results presently available are inconclusive in terms of austenite grain size and its influence on K_{ICV}.

6. Acknowledgements

The authors are grateful to IPEN- Institute of Nuclear and Energy Research, the Mechanical Engineering Department

DEMEC of the Federal University of Pernambuco, the University Center of FEI – Department of Metallurgical and Materials Engineering, the Department of Metallurgical and Materials Engineering of the Polytechnique School of the University of São Paulo, The Brazilian National Research and Development Council (CNPq) and the State funding agencies FAPESP and FACEPE.

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