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Original Article

Effect of intercritical annealing with high cooling rate associated with cold deformation and subcritical annealing on microstructure and mechanical properties of SAE 52100

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ABSTRACT

Conventional spheroidization heat treatments of bearing steels are long-term, therefore it is necessary to study alternatives to decrease the heat treatment time to save energy consumption. This work aimed to develop a new manufacturing route in order to obtain a completely spheroidized microstructure. The microstructure and mechanical properties of SAE 52100 steel were evaluated after intercritical annealing with higher cooling rate than the conventional one, followed by cold deformation with different area reductions, and subcritical annealings with different soaking times. It has been observed that the route considering the intercritical annealing with cooling rate 8 times higher than the conventional one, followed by a high cold reduction and subcritical annealing for 1 h turns feasible the complete spheroidization of the material.

1. Introduction

Bearings must present high wear and fatigue resistance, besides microstructural stability at high temperatures. Most of the bearings are manufactured by using seamless tubes of cold drawn SAE 52100 steel. The microstructure of this steel in the as-rolled condition consists of pearlite and proeutectoid cementite formed at previous austenite grain boundaries. In order to facilitate drawing and machining the tubes, spheroidization annealing is usually performed aiming to obtain a microstructure of globular carbides in ferrite matrix [1]. Machining spheroidized steel may increase the tooling life 5 times compared to the non spheroidized steel [2].

The driving force for cementite spheroidization is the reduction of interfacial ferrite/carbides energy by the formation of globular particles of cementite, since those have lower surface area/volume relationships [3]. The literature [4] indicates that for complete spheroidization SAE 52100 steels should be heated up to 795 °C, fast cooled to 750 °C and then slowly cooled to 675 °C using a cooling rate that does not exceed 6 °C/h. This rate corresponds to at least 12.5 h during the cooling process. Another possibility is heating the material up to 795 °C, followed by fast cooling to 690 °C and keeping at that temperature for 16 h.

To increase the productivity and reduce the energy consumption related to the high heat treatment time, it is necessary to study alternatives to decrease the spheroidiza-

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Table 1 – Nominal chemical composition (weight %) of SAE 52100 steel [6].

%C	%Mn	%P	%S	%Si	%Cr
0.93 – 1.05	0.25 – 0.45	max 0.025	max 0.025	0.15 – 0.35	1.35 – 1.60

tion time for bearings steel. For low and medium carbon steels, it has been observed that plastic deformation before the subcritical annealing has a significant effect on spheroidization kinetics [5]. However, a similar cold deformation effect in SAE 52100 steels before spheroidization has not yet been reported, probably because they have high mechanical resistance in the as-rolled condition.

In this context, the objective of this work was to identify a new manufacture route in order to obtain a fully spheroidized microstructure at a lower heat-treatment time. Therefore, the microstructure and mechanical properties of SAE 52100 steel were evaluated after intercritical annealing using a higher cooling rate than the usual one, followed by cold deformation with different reductions in area, and finally subcritical annealing at different soaking times.

2. Materials and methods

Seamless hot rolled tubes in SAE 52100 steel manufactured at Vallourec Soluções Tubulares do Brasil were used in this research. The nominal chemical composition of the steel is given in Table 1. The microstructure of the hot rolled tube was characterized by scanning electron microscopy (SEM). Tensile tests and Brinell hardness (HB) measurements were employed to evaluate the mechanical properties of the hot rolled tube.

A schematic representation of the heat treatments and cold deformation applied to the hot rolled tube is shown in Fig. 1. Samples were submitted to intercritical annealing in a muffle furnace and then cooled at two different cooling rates: two times and eight times the conventional rate employed in the literature. Microstructure and mechanical properties were evaluated as before.

It was reproduced in industrial scale the heat treatment with higher cooling rate and later the tubes were cold drawn in two different area reduction, that were named “low” and “high”, considering that the high reduction is equivalent the double of the low reduction.

Finally, new samples of both routes were submitted to subcritical annealing with soaking time of 1 h, 2 h and 3 h and they were characterized mechanically and metallographically.

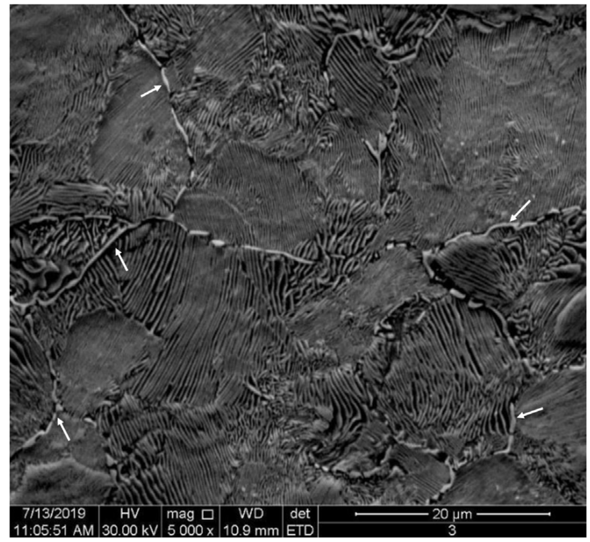

Fig. 2 – Microstructure of hot rolled tube in SAE 52100 steel. White arrows indicate proeutectoid cementite at the prior austenite grain boundaries.

3. Results

The microstructure of the hot rolled tube is shown in Fig. 2, while Table 2 presents the average values of its mechanical properties measured in tensile and Brinell hardness tests. Pearlite and proeutectoid cementite at the prior austenite grain boundaries are the constituents present in the steel after hot rolling and cooling to room temperature. The material exhibits high strength and hardness, while elongation is low.

The microstructure and mechanical properties after intercritical annealing using both cooling rates are shown in Fig. 3 and Table 3. After intercritical annealing the microstructure is majority spheroidized carbides in ferrite matrix. For both cooling rates evaluated elongated carbides were identified. However, the sample submitted to higher cooling rate showed more heterogeneity regarding the carbides morphology and greater amount of elongated carbides. Partially spheroidized

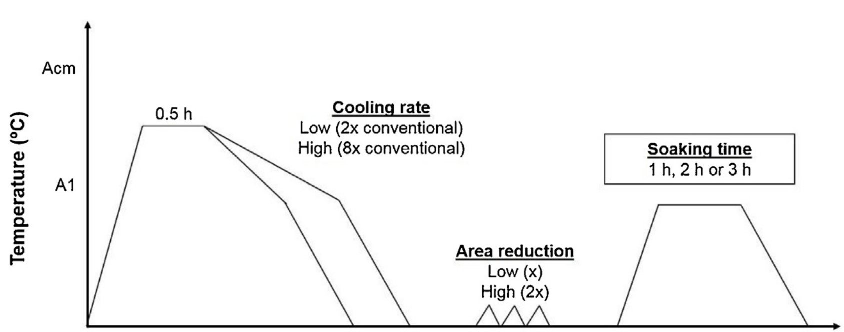

Fig. 1 – Schematic representation of heat treatments and cold deformation applied to the hot rolled tube.

Table 2 – Mechanical properties of hot rolled tube in SAE 52100 steel.

Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Hardness (HB)
622	1121	10	320

Table 3 – Mechanical properties after intercritical annealing.

Cooling rate	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Hardness (HB)
2x conventional	405	648	39	196
8x conventional	410	696	31	196

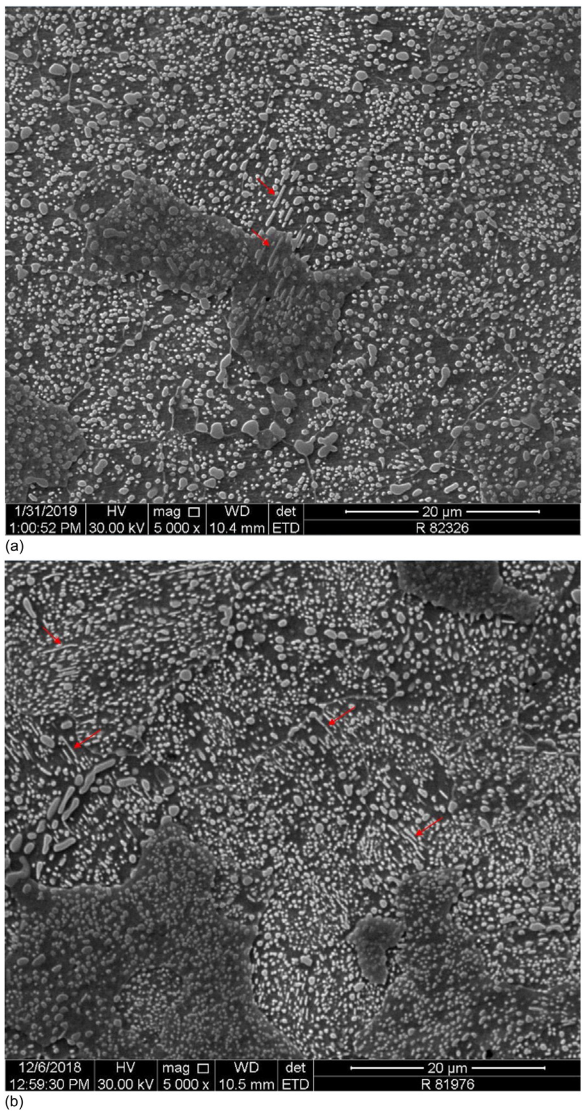

Fig. 3 – Microstructure of SAE 52100 steel after intercritical annealing with cooling rate equivalent the (a) double of conventional one and (b) 8 times higher than the conventional one. Red arrows indicate elongated carbides.

carbides in ferrite matrix gave rise to a decrease in strength and an increase in elongation, in comparison to the as hot-rolled condition. Regarding those results, both evaluated conditions turn feasible to cold drawn the material. Nevertheless, higher cooling rate have been chosen because it is economically more advantageous.

Fig. 4 shows the microstructure after subcritical annealing in different soaking times for the samples submitted to low area reduction and Fig. 5 for the samples submitted to high area reduction. The microstructure of the sample with lower area reduction presented elongated carbides even after 3 h of soaking time during subcritical annealing. But the microstructure of the route with higher reduction indicated fully spheroidized carbides considering soaking time greater than or equal to 1 h.

Mechanical properties after subcritical annealing are shown in Fig. 6 and tensile *versus* strain curves are presented in Fig. 7. It was noticed in the curves the yield point phenomenon. Moreover, considering the same area reduction, it can not be noticed any significant difference of yield strength or tensile strength by increasing the soaking time during subcritical annealing. Finally, Fig. 8 presents HB hardness for the different soaking times in both evaluated deformations.

4. Discussion

Comparing Tables 2 and 3 significant reduction can be observed in yield strength and tensile strength after the intercritical annealing, while the elongation significantly increases. The sample submitted to higher cooling rate showed higher tensile strength compared to that one submitted to lower cooling rate, but significant difference was not found regarding the yield strength.

Mechanical property difference may be justified by the microstructural modifications. The microstructure of hot rolled samples consists of pearlite and proeutectoid cementite (Fig. 2) and after intercritical annealing the microstructure is majority spheroidized carbides in ferrite matrix. For both cooling rates evaluated elongated carbides were identified (Fig. 3). However, the sample submitted to higher cooling rate showed more heterogeneity regarding the carbides morphology and greater amount of elongated carbides.

The samples submitted to higher area reduction exhibited carbides fully spheroidized, while the samples submitted to low area reduction presented elongated carbides even after 3 h of soaking time during subcritical annealing. The microstructural differences observed after subcritical annealing for samples with low and high area reduction may be justified by the difference in previous deformation. It is known that the plastic deformation favors the spheroidization by decreasing the pearlite interlamelar space and increasing the dislocations density in ferrite [5].

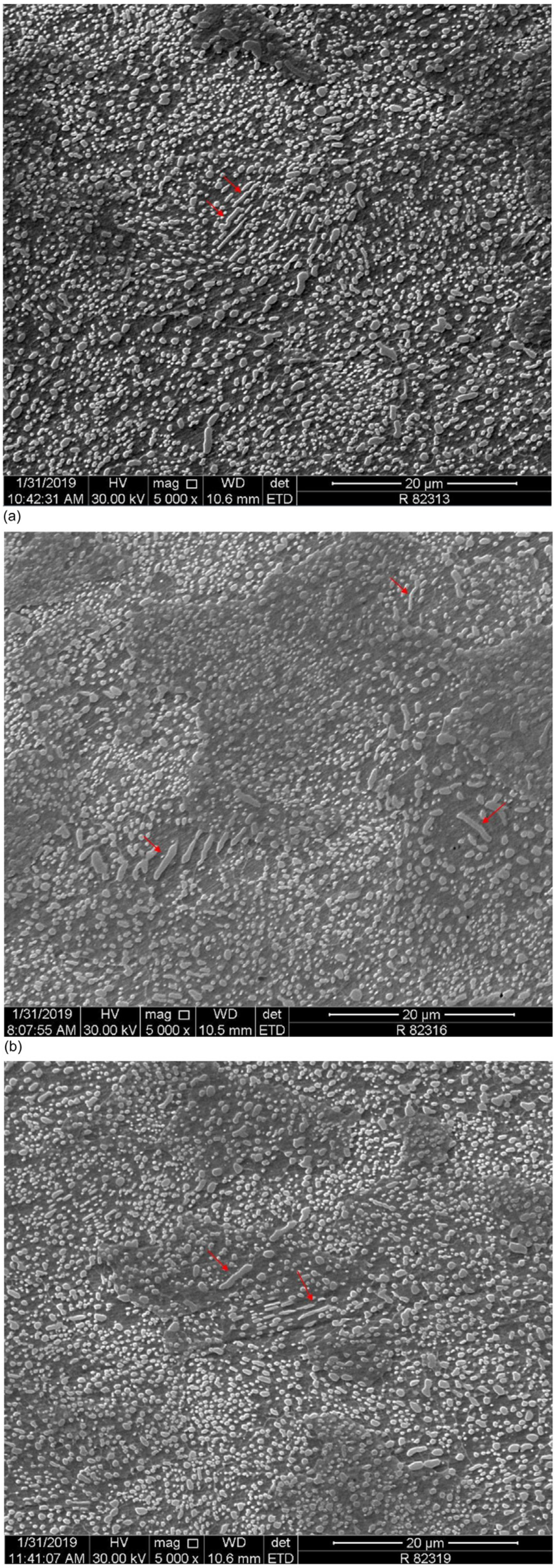

Fig. 4 – Microstructure after intercritical annealing with high cooling rate followed by low area reduction and subcritical annealing for (a) 1 h, (b) 2 h and (c) 3 h. Red arrows indicate elongated carbides.

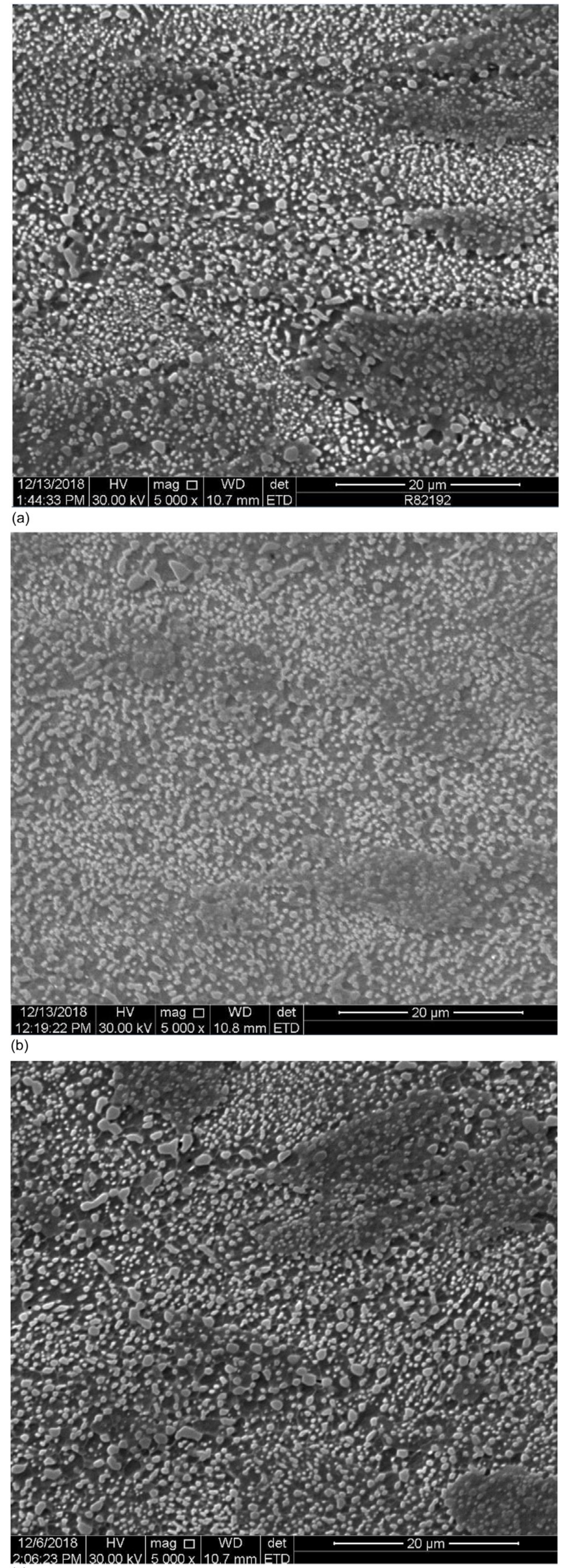

Fig. 5 – Microstructure after intercritical annealing with high cooling rate followed by high area reduction and subcritical annealing for (a) 1 h, (b) 2 h and (c) 3 h.

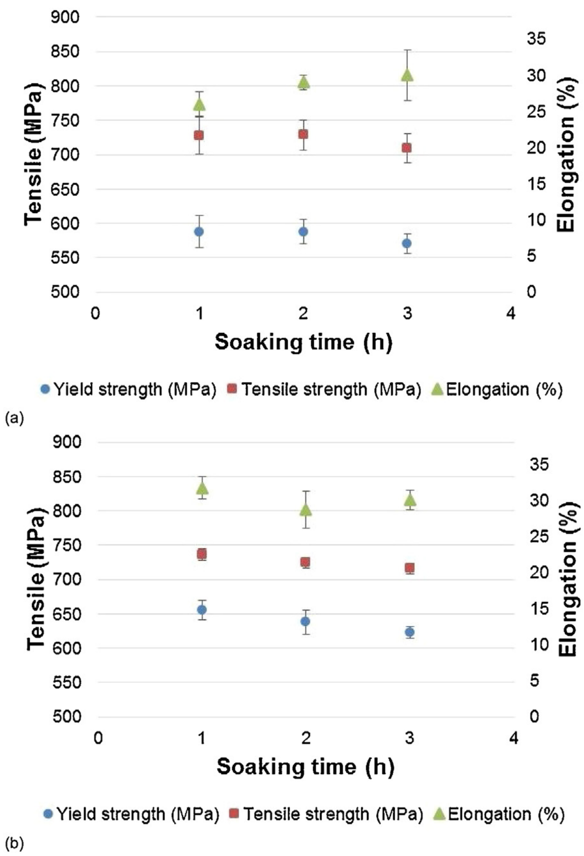

Fig. 6 – Mechanical properties after intercritical annealing with high cooling rate followed by (a) low and (b) high area reduction and subcritical annealing.

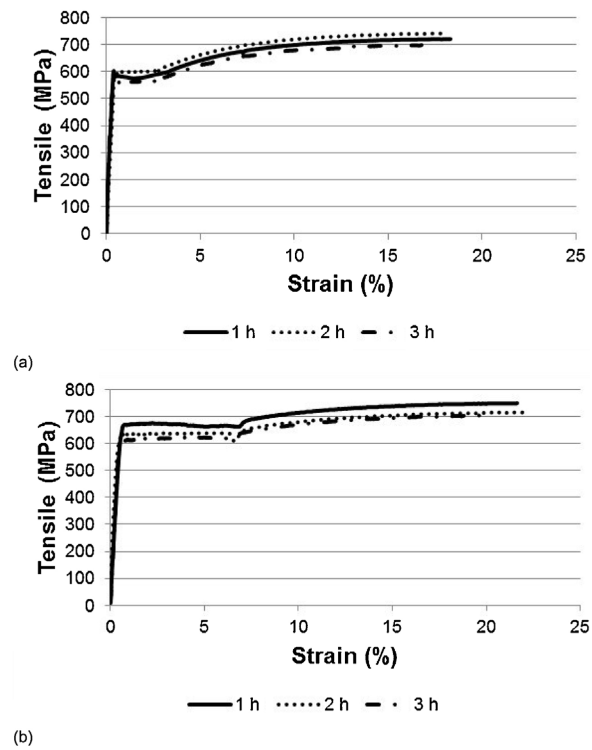

Fig. 7 – Tensile *versus* strain curves after intercritical annealing with high cooling rate followed by (a) low and (b) high area reduction and subcritical annealing.

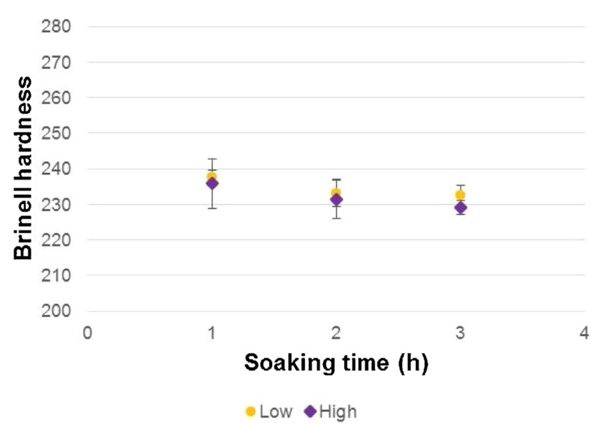

Fig. 8 – HB hardness after intercritical annealing with high cooling rate followed by deformation and subcritical annealing.

Any significant difference was not noticed of yield strength or tensile strength by increasing the soaking time during subcritical annealing, as observed in Fig. 6. Guo et al. [5] noticed as well in 50CrV4 steel that by increasing the soaking time the mechanical properties did not change after subcritical annealing from 2 h up to 8 h. They observed that higher area reduction presented lower mechanical properties after subcritical annealing and they indicated that it was due to greater homogeneity of carbides distribution. However, in the present work it was noticed that the yield strength of samples submitted to higher area reduction are higher than that one of samples submitted to lower area reduction. It may be supposed that the microstructural effect presented before is less significant than that of previous deformation and dislocation increase. Furthermore, it was not identified significant difference regarding HB hardness, as shown in Fig. 8. Guo et al. [5] have observed similar effect for 50CrV4 steel and they have affirmed that the degree of spheroidization, size and distribution of globular carbides have low effect on the material hardness.

After the subcritical annealing it can be observed in Fig. 7 that the higher the previous area reduction the higher the yield point phenomenon. It is known that the yield point phenomenon is caused by the dislocation locking movement. It may be supposed that the microstructural difference can explain that phenomena, since the samples submitted to higher area reduction showed carbides fully spheroidized and more homogenous, which is in agreement with the result by Nam and Lee [7]. They have evaluated high carbon steel wires that were cold drawn at 700 °C with different area reductions and graphically showed that the higher the area reduction the bigger the yield point phenomenon.

Moreover, it can be observed that the tensile *versus* strain curves have indicated similar behavior during elastic regime (Fig. 7). It is expected since the elastic deformation depends on distortions of lattice structure caused by external force [8].

5. Conclusions

Based on this work, the following conclusions can be drawn upon:

- Intercritical annealing with cooling rate 8 times higher than the conventional one provides the beginning of carbide spheroidization and a reduction of the mechanical properties of SAE 52100 steel;
- After low area reduction followed by subcritical annealing with soaking time from 1 h up to 3 h the carbides are not fully spheroidized, in other words, some elongated carbides were present in the microstructure;
- After high area reduction followed by subcritical annealing with soaking time greater than or equal to 1 h provides carbides fully spheroidized;
- Considering the same area reduction, significative difference was not noted for yield strength, tensile strength or hardness by increasing the soaking time during subcritical annealing;
- The higher the area reduction the higher the yield strength, but that was not observed for tensile strength or HB hardness.

Conflict of interest

The authors declare no conflicts of interest.

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