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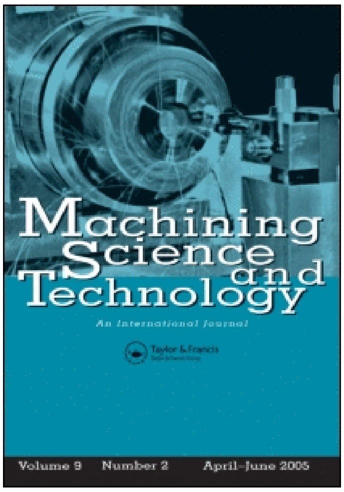

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MACHINABILITY IMPROVEMENT THROUGH HEAT TREATMENT IN 8620 LOW-CARBON ALLOYED STEEL

Luis Felipe Verdeja [a]; José Ignacio Verdeja [a]; Roberto González [b]
[a] Cátedra de Siderurgia, E.T.S.I.M.O., Universidad de Oviedo, Oviedo, Spain [b] School of Engineering, Universidad Panamericana, Augusto Rodin, DF, México

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MACHINABILITY IMPROVEMENT THROUGH HEAT TREATMENT IN 8620 LOW-CARBON ALLOYED STEEL

Luis Felipe Verdeja[1], José Ignacio Verdeja[1], and Roberto González[2]
[1] *Cátedra de Siderurgia, E.T.S.I.M.O., Universidad de Oviedo, Oviedo, Spain*
[2] *School of Engineering, Universidad Panamericana, Augusto Rodin, DF, México*

□ *The effect of different heat treatments is evaluated on SAE 8620 low-carbon alloyed steel by means of drilling tests. Improving machinability through prior heat treatment in steels used for nitro-carburizing surface treatments is very important in the manufacturing of large series of parts, due to its impact in production costs. This is the case for the commonly used SAE 8620 grade, in its carburized and quenched and tempered state, for the production of gears, shafts and other transmission box components for the automobile industry. The machinability of the steel, determined by simple drilling tests (which are typical in industry labs), is a function of microstructure, which is determined by the state in which the steel is received and/or heat treatments prior to carburizing. This work shows that by employing some inter-critic annealing treatments, followed by sub-critic isothermal ones, the machinability of 8620 steel can be improved by ∼16% over the typical as-received cold drawn state.*

Keywords chip morphology, drilling test, heat treatment, machinability, metallography, 8620 steel

INTRODUCTION

The productivity of manufacturing of steels by a machining route is not only determined by the use of low cost-high performance alloys, but also by the capability to transform a specific steel alloy to the required surface finish and geometry by machining at sufficiently high speed.

Machinability Rate (MR) in steels (including low-carbon alloyed ones) is related both to microstructural and processing characteristics, though machinability indexes are relative and vary with each machining operation (Jin and Sandström, 1994; Murphy and Aylward, 1998). The need for more efficient and low-cost processes (Hawkins, 1989), especially in the automobile industry, requires good MR steels in order to reach higher cutting velocities without changing the cutting tool, and maintaining

Address correspondence to Roberto González, School of Engineering, Universidad Panamericana, Augusto Rodin 498, 03920 DF, México. E-mail: robglez@up.edu.mx

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excellent surface finish. The use of thermal, thermo-mechanical or thermo-chemical treatments in order to modify microstructural features in low-carbon low alloyed steels, allows a higher MR (Abeyama et al., 1983; Araki et al., 1975) and cost reduction. Such heat treatments, including isothermal annealing and normalizing, are frequently used to control machinability in automobile parts (Funatani, 2004).

The efficiency of machining is expressed as a function of specific operations, such as drilling, turning, milling and others (Jin and Sandström, 1994; Murphy and Aylward, 1998). In any case, it is required for the steel to have an adequate microstructure to optimize machinability (Araki et al., 1975; Abeyama et al., 1983), which is achieved by thermal treatments and may be of the following three types (Pero-Sanz, 2006):

- Supercritic annealing. Carried out at temperatures above A_3 of the steel, followed by slow or moderate cooling until room temperature is reached, or by isothermal subcritic treatments below A_1, in the range of 600–700°C.
- Intercritic annealing. Performed between the temperatures A_1 and A_3 of the steel followed by continuous cooling or subcritic thermal treatment just as the prior case.
- Subcritic annealing. Carried out at temperatures below A_1, followed by slow or moderate cooling.

The best treatment considering the MR of the steel, is a function of chemical composition (C concentration and alloying elements), correlation of microstructure and hardness, and energetic cost (temperature and time) of the chosen thermal treatment. Also, heat treatments on the 8620 Steel (UNS number G86200, AISI 8620), whose composition ranges are: 0.18–0.23% C, 0.70–0.90% Mn, <0.035% P, <0.040% S, 0.15–0.35% Si, 0.40–0.70% Cr, 0.40–0.60% Ni and 0.15–0.25% Mo, are common in order to avoid low hardness and bad surface finishing, so normalizing or isothermal annealing are used, along with austenitizing to obtain coarse austenite grains, and also heat treatments below Ar_3 to form coarse lamellar pearlite (lamellar annealing). Though there are numerous data on the machinability of 8620 steel (Davis, 1989), the optimum heat treatment to increase MR is not considered and only general indications, such as tool life versus C content are reported.

Although the steel hardness is an indication of the abrasive capacity towards the cutting tool or potential problems during machining, judging the MR includes analyzing the cutting chips, tool life, cutting energy, surface stresses, surface finish and other parameters. Some of the factors related to choosing a good MR steel are chemical composition, inclusions, grain size, and phase distribution. It is generally reported (El-Hofy, 2006) that an increase in grain size reflects in a better MR as well as good

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tempering, though the fracture toughness of the part, and thus, its fatigue life resistance are diminished. Another important microstructural aspect is the presence of inclusions, which can be beneficial for machining in the case of sulphurs, acting as lubricants and chip breakers, or detrimental, such as alumina or silicate particles (Eleftheriou and Bates, 1999; Ramalingam and Wright, 1981; Yaguchi, 1986).

When considering steel parts that have to be machined prior to carburizing (or nitriding) and quenching and tempering, $0.1 < \%C < 0.25$, as in the selected 8620 steel, the best microstructures from a machinability point of view are usually the ferritic-pearlitic ones, with large ferrite grains and partially globulized pearlite, and inclusions that, in a complementary way, facilitate lubrication during material removal by the machining tool (for example *MnS*, *Pb*, etc.). Very soft microstructures are undesirable, such as the ones with globular pearlite (gummy microstructures such as coagulated pearlite), and also the presence of hard and fragile inclusions, (for example SiO_2 and Al_2O_3).

In the cold drawn (CD) state, 8620 steel has a machinability of about 65% compared to the 12L14 steel (leaded carbon and resulphurized steel), whose chemical composition margins are as follows (Davis, 1990): <0.15% *C*, 0.85–1.35% *Mn*, 0.04–0.09% *P*, 0.26–0.35% *S* and 0.15–0.35% *Pb*. The 8620 steel may reach hardness ranges (and microstructures) between 445 HV (as quenched) and 158 HV (as annealed) (Vander Voort, 1991).

In the case of low alloy steels with more than 0.5% *C*, the preferred microstructure to increase MR is globular pearlite in a ferrite matrix. On the other hand, for steels with lower carbon content the preferred microstructures are soft materials with globular cementite, which is considered better than lamellar pearlite. All these microstructures are sought when the objective is to remove as much material as possible and when superficial conditions (surface finish) are not critical. It is important to take into account that for many machining operations in low-carbon steels though the uniform and well distributed pearlite is sometimes beneficial, many such steels present a very low hardness, which results in very poor MR, and so the bainite microstructure is preferred (Davis, 1989).

The best results for low-carbon steels are obtained considering the following: coarse pearlite in a ferrite matrix, cold work hardening, a high yield stress/tensile stress relation, manganese or sulphur particles, and tempered martensite (especially when a good surface finish is required).

EXPERIMENTAL PROCEDURES

During this work, different heat treatments were performed on 8620 steel samples, as indicated in Figure 1 and specified in Table 1, in order to reproduce typical microstructures in industrial applications and evaluate

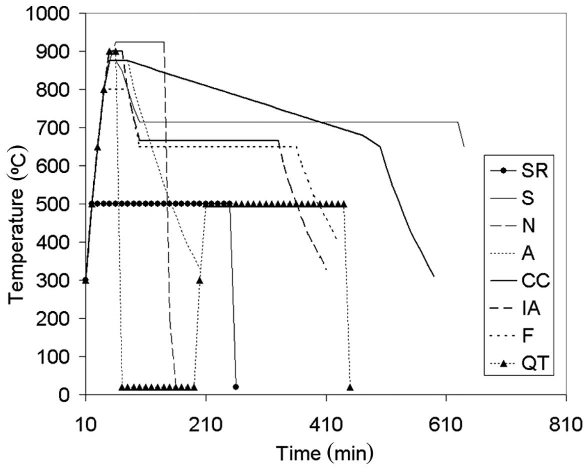

FIGURE 1 Heat treatments applied to 8620 steel samples.

the machinability of the samples and the type of microstructures by means of drilling tests in each of them.

The tests were made in 25.4 mm diameter bars in the CD (cold drawn) state. The chemical analysis was performed in two samples for each measurement in the following way: *C* and *S* were analyzed by combustion method in a Leco CS-200 equipment; the rest of the elements were characterized by optical emission spectroscopy in an ARL 3460 system. The resulting data, expressed in weight % is: $C = 0.22$, $Si = 0.22$, $Mn = 0.76$, $S = 0.01$, $P = 0.013$, $Cr = 0.45$, $Ni = 0.44$, $Mo = 0.14$, $Al = 0.025$, $Cu = 0.22$, which is consistent with the expected values of this 8620 steel. Thermal treatments were made in a Carbolite HTC1500 furnace, with an electronic controller that allows the achievement of heating ramps,

TABLE 1 Description of Heat Treatments in 8620 Steel Samples (Cooled Inside Furnace at Approximately 150°C/hour, Unless Specified Otherwise)

Sample	Name	Heat treatment
CD	Cold drawn	
F	Ferritic structure	800°C for 45 min + 650°C for 4.5 hours
IA	Isothermal annealing	900°C for 30 min + 665°C for 4 hours
N	Normalized	925°C for 1.5 hours, cooled in air at 700°C/hour
A	Annealed	875°C for 40 min
CC	Controlled cooling	875°C for 40 min, cooling at 30°C/hour
SR	Stress relieved	500°C for 4 hours
S	Spherodized	875°C for 15 min + 715°C for 9 hours
QT	Quenched and tempered	900°C for 15 min + water quenched + 500°C for 4 hours

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temperature maintenance and controlled cooling. Samples were 100 mm in length and treated as specified in Table 1.

The heat treated samples were cut in half to avoid analysis in decarburized layers, and then prepared by grinding, polishing with diamond paste and finishing with gamma alumina (0.05 μm in size). The chemical etchant used was 2% nital and the metallographic observations and microstructural characterizations were made in a Nikon Epiphoto optical microscope coupled with a Buehler Omnimet quantitative metallography image analyzer. This equipment allows the automatic or semi-automatic counting of pearlite, and automatic determination of grain size (mean linear intercept, $\overline{L_\alpha}$) over the lines traced at 0, 45, 90 and 135° of a reference diameter, chosen randomly over the sample, in accordance with ASTM E-112 and ASTM E-1181-02 standards (Vander Voort, 1999).

Using the metallography samples, hardness was measured in the transverse section using a GMEM OM-150 universal durometer, using the Vickers scale with a 10 kg load, except in the case of the QT sample where, because of the higher hardness, a Galileo durometer in the Rockwell C scale was used. In each sample, five indentations were made, eliminating the maximum and minimum values, and reporting the mean value of the other three. The test procedures follow the ASTM E-92, A-370 and E-140 standards.

In order to determine the Machinability Rate (MR) index in different steel samples, controlled drilling tests were performed using a standard bench drill specifically prepared for the test (Burke et al., 1999; Eleftheriou and Bates, 1999; Yaguchi, 1987). The results were based on the amount of material removed during drilling, while applying a constant load (approximately 25 N) at 450 rpm for a lapse of 45 seconds.

The tests were made using HSS M2 4 mm diameter drills using a new drill (as-received) for each sample to be measured, and always using drills from the same supplier in order to maintain the test repeatability. The drills used had a point angle of 118°, a helix angle of 30°, a chisel edge angle of 145° and a lip length of 2.33 mm. The drilling tests were performed in the following way: using samples of 8620 steel alloy with 25 mm diameter and approximately 90 mm in length, which were cut; different heat treatments were performed in order to reproduce normal industrial heat treatment procedures (Figure 1 and Table 1). After heat treatment, samples were machined and polished in their surface to remove the decarburized layer. The samples were fixed to the bench drill and the surface of the sample was drilled eight times. Each time one perforation was made, the weight of the samples was measured in order to evaluate the performance of the drill. As expected (Schey, 1983) and due to the wear of the cutting edge of the drill during the test, the first operation was always more efficient in removing material, while the last was less efficient. The total amount of material removed was considered and compared to the amount extracted in the CD sample, for which a 100% MR was assigned.

For each heat treatment described in Table 1, at least two samples were drilled to confirm the results. Considering that the rise of temperature of the samples has been reported to produce variations in MR indexes, some tests were conducted and it was verified that the variations were small enough to allow the drilling test to be performed without coolant fluid (Davis, 1989).

Also, the chips produced during drilling were saved and analyzed with magnifying lenses, to characterize if fine or gross particles were produced, the length of the chips, the uniformity in size, and the size of the spiral geometry.

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RESULTS AND DISCUSSION

Table 2 presents the values of the hardness obtained with different heat treatments performed in the 8620 steel in its CD state, to which the following data has been added: the G state, equivalent to S plus 15 h of isothermal treatment at 715°C, which results in a practically total globulization of the lamellar pearlite (Figure 2) and the minimum hardness value (107 HV10); and the NA state, equivalent to N but followed by air-cooling (Figure 3), where the microstructure presents a ferrite-pearlite-bainite steel, with an intermediate hardness (202 HV10) between S and QT.

TABLE 2 Amount of Chip Extracted During Drilling Tests on Heat-Treated Samples, Resulting Machinability Rate, Hardness, Amount of Pearlite and Ferrite Grain Size

Sample	Amount of chip (g)	MR (%)	Hardness (HV 10)	Pearlite amount (%)	Ferrite $\overline{L}_\alpha$ (μm)
CD	16.73	100.0	135	10.6	33
F	16.08	96.1	128	3.7	17
IA	13.95	83.4	135	5.3	28
N	12.73	76.1	135	4.7	28
A	15.17	90.7	135	5.0	23
CC	15.76	94.2	133	5.3	30
SR	13.40	80.1	135	10.3	28
S	19.47	116.4	143	3.9	23
QT	12.08	72.2	274		
G			102		
NA			206		

(CD: cold drawn, F: ferritic structure, IA: isothermal annealing, N: normalized, A: annealed, CC: controlled cooling, SR: stress relieved, S: spherodized, QT: quenched and tempered, G: totally globulized, and NA: normalized and air-cooled).

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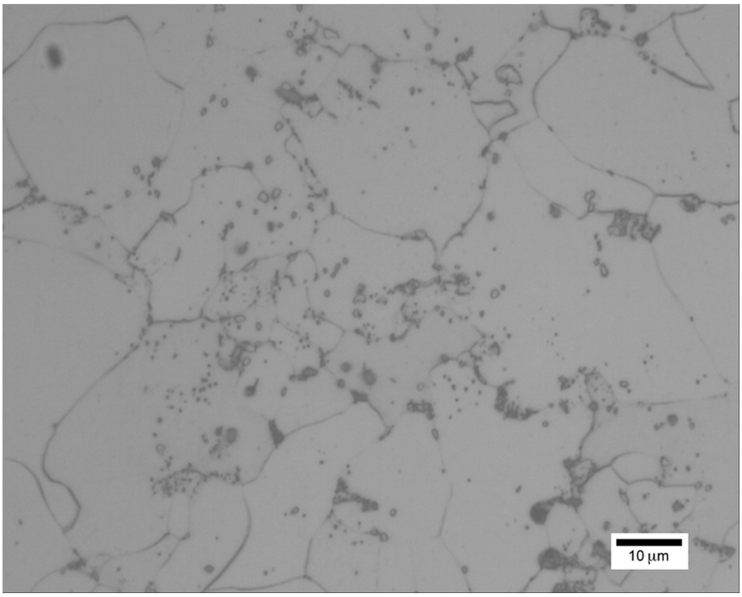

FIGURE 2 Completely globulized pearlite microstructure (G).

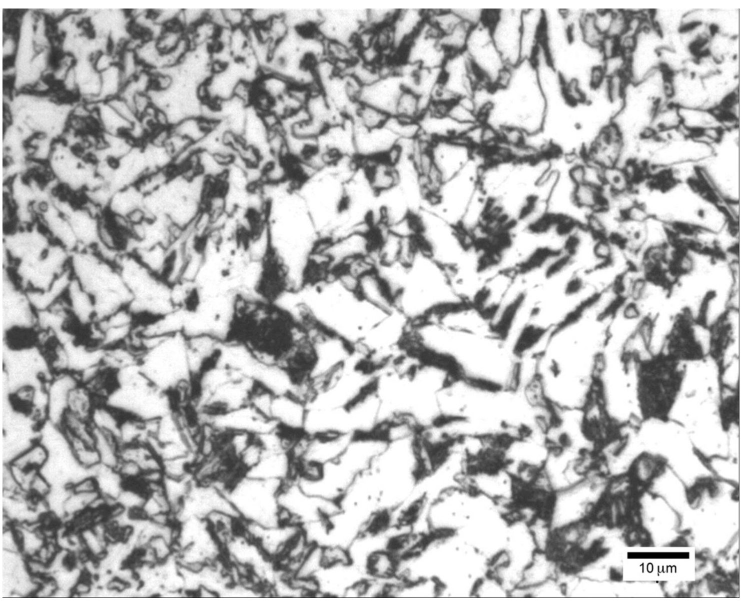

FIGURE 3 Microstructure of the 8620 steel sample in the normalized and air-cooled (NA) state.

It may be confirmed that the obtained hardness for most of the different heat treatments are in a relatively narrow margin of 128–143 HV10, which is not the case for the MR index (Table 2). Also shown are the lamellar pearlite volume fraction F_p and mean intersected length (grain size) $\overline{L}_\alpha$ for the ferrite phase. The following results and tendencies may be deduced:

Samples F, A and S, submitted to intercritic annealing, $725 < T < 875°C$, maintain and even improve machinability compared to the reference CD state. The S sample with a ferritic-partially globulized pearlite (Figure 4), 3.7% lamellar pearlite fraction and a 23 μm ferrite grain size, improved machinability by 16%.

Samples IA and N (Figure 5), submitted to supercritic annealing, $T > 875°C$, present a machinability approximately 20% lower than the reference state with 28 μm grain size and ~5% of pearlite fraction, which is higher than the ones submitted to intercritic annealing (F, A and S).

Reference CD and SR samples (Figures 6 and 7) with pearlite fractions $F_P \approx 10\%$ and ferrite grain sizes $\overline{L}_\alpha \approx 30\,\mu m$ are alike because the 500°C stress relieving heat treatment is not sufficient to significantly alter the initial microstructure, but induces a 20% machinability loss. This indicates, on one hand, the sensitivity of this steel in particular, and of steels in general to heat treatments even if allotropy and/or solid state solubility changes are not experienced (Pero-Sanz, 2004); on the other hand, the difference in machinability may be explained considering that the SR

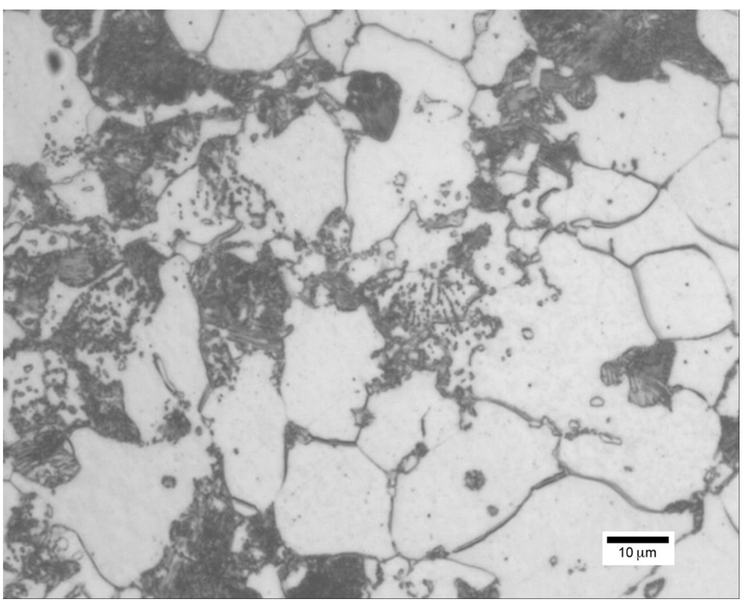

FIGURE 4 Microstructure of the 8620 steel sample in the spherodized (S) state.

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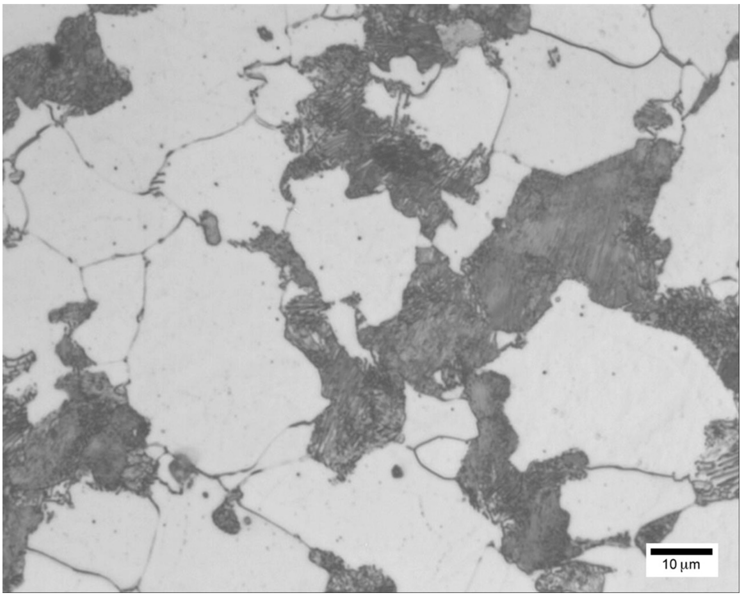

FIGURE 5 Microstructure of the normalized (N) 8620 steel sample.

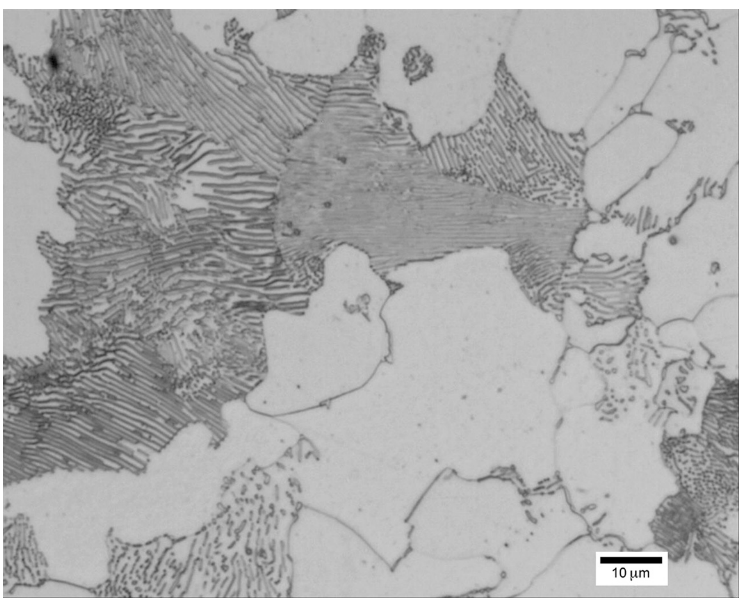

FIGURE 6 Microstructure of the cold drawn (CD) sample initial state.

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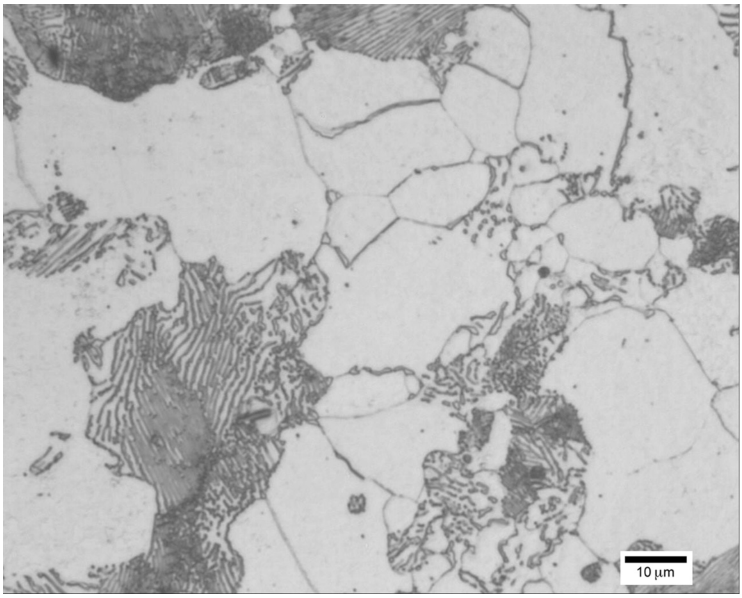

FIGURE 7 Microstructure of the 8620 steel sample in the stress relieved (SR) state.

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sample presents softer and non-deformed ferrite grains compared to the cold drawn sample CD, and the resistance of the material to the removal of those grains makes it more difficult to be machined.

The QT sample (Figure 8), with tempered martensite and elevated 274 HV10 hardness, is the one with the lowest MR (72.2%), though not much different to the N sample (76.1%) which was normalized with a slow cooling rate (Figure 5).

Figure 9 represents the variation and general tendency of the MR index with respect to the lamellar pearlite fraction F_p. It shows that as pearlite fraction increases, MR diminishes. On the contrary, no correlation was found between the MR index and the ferrite grain size, which confirms that the extent of globulization of the lamellar pearlite and its distribution in the ferritic matrix has a very important effect on the amount of material removed, while the specific ferritic grain size is not as important (Jiang et al., 1997).

These experiments consider only the MR index, which is based on the amount (volume) of material removed under constant cutting forces, and may therefore be directly proportional to power consumption during machining. Other aspects such as tool life, surface finish and/or built-up edge formation should be analyzed for specific machining operations.

Figure 10 shows the differences in size and morphology between chips extracted from the S (highest MR index), QT (lowest MR index), and SR

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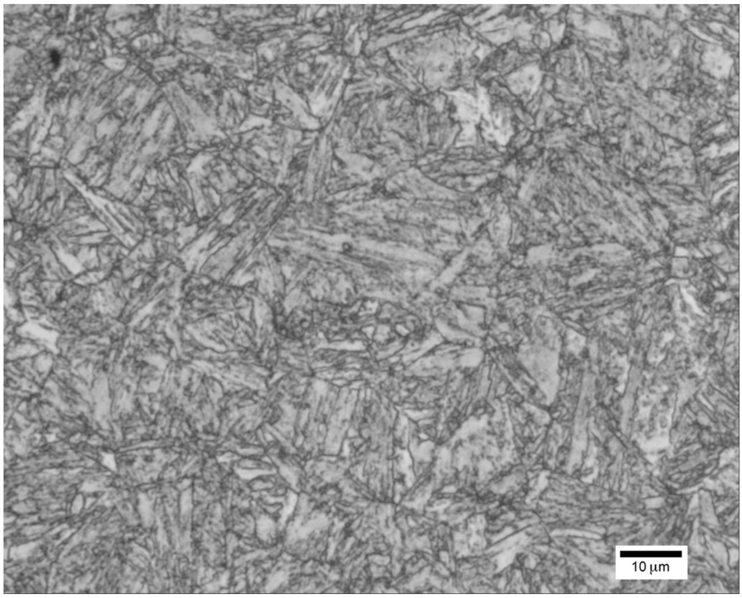

FIGURE 8 Microstructure of the quenched and tempered (QT) sample.

samples. These indicate a better surface finish for QT samples, due to the presence of hard and fine tempered martensite (Figure 10a), compared to the S sample (Figure 10b), where the jagged edges are an indication of built up edge, even though the amount of material removed is the

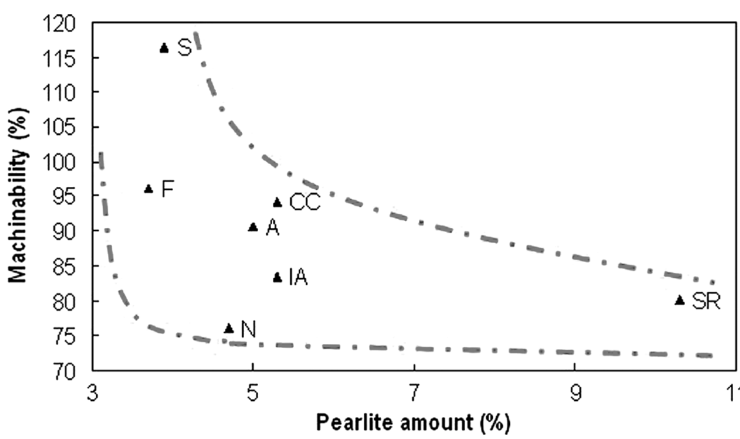

FIGURE 9 Variation of machinability rate (MR) with amount of lamellar pearlite for different heat treated samples. The dotted lines indicate general behavior for this steel: a lower amount of pearlite is beneficial to machinability.

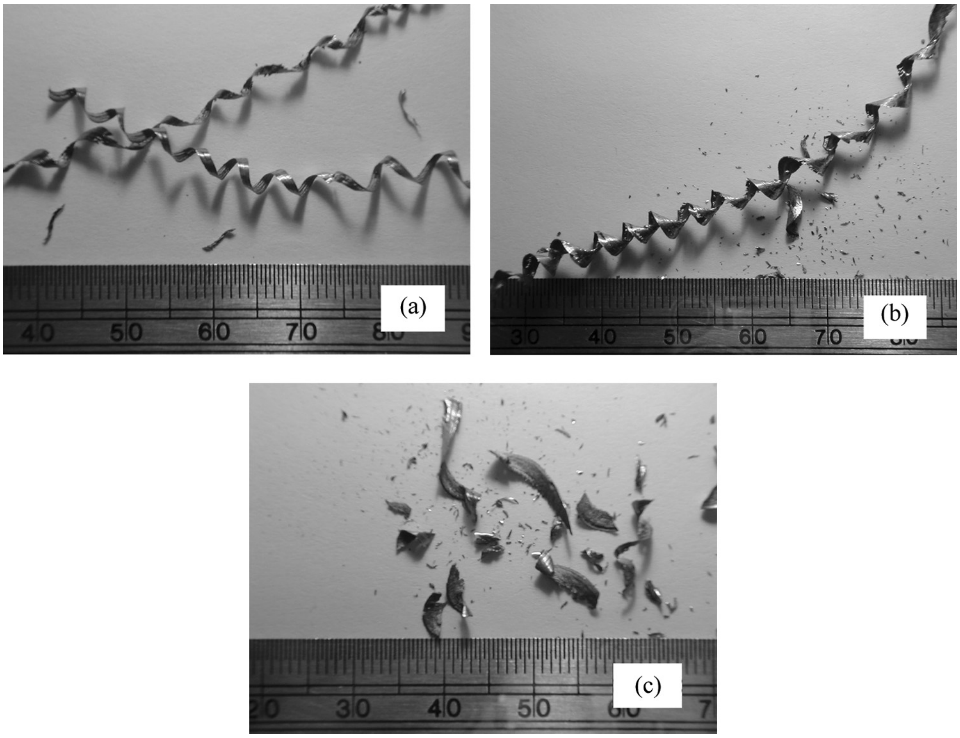

FIGURE 10 Chip morphology for samples QT (a), S (b) and SR (c).

best (good MR). Finally, in the stress relieved state SR (Figure 10c), the increasing amount of pearlite ($\sim$10%) results in discontinuous chips, which are better for high speed operations (Davis, 1989).

CONCLUSIONS

Drill tests may be used to analyze and determine machinability of heat treated low alloyed steels. Also, the drilling test proves to be an efficient method to evaluate machinability, especially in those cases where production requires rough machining. A very good selection of high quality drills is indispensable to obtain good statistical results, and applicable data for industry, where better machinability is needed to reduce production costs.

In the case of an 8620 cold drawn steel, supercritic heat treatments ($T > 875$°C) in the form of normalizing or annealing, as well as subcritic low temperature treatments (500°C stress relieved state) negatively affect the MR index, due to the presence of lamellar pearlite in the range of 5–10%.

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In contrast, intercritic treatments, $725 < T < 875°C$, followed by subcritic treatments at temperatures higher than 650°C maintain or improve machinability of the 8620 steel compared to the as-received cold drawn state. The amount of lamellar pearlite surrounded by globulized pearlite diminishes to ~3%.

The optimum hardness to machine the 8620 steel is placed in a narrow interval of 130 ~ 145 HV10, which corresponds to mixed structures made with gummy ferrite (~100 HV10), and an inteval of 0 to 25% of lamellar pearlite, this last one corresponding to the normalized ferrite-pearlite structure with approximately 25% of lamellar pearlite and 200 HV10. Thus, close attention must be paid to the remaining lamellar pearlite and not so much to the ferrite grain size when machinability is a critical factor.

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