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Viability Assessment of Replacement of Rolled and Machined Bars by Rolled and Drawn Bars of Steel SAE 5140

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***Abstract*—The optimization process allows the manufacturing industries to produce more at lower costs. It is necessary to analyze the properties of the product, verifying that the process changes do not affect its use. The standard steel bar manufacturing process has a machining step to reduce the bar diameter. The proposed manufacturing process is intended to eliminate the machining process by replacing this forming process (drawing and upsetting). The aim of the paper is to evaluate the replacement of the conventional manufacturing process bars by an alternative process. It was characterized the microstructure of the bars produced in each of the processes, checking the existence of decarburization, analysis of the austenitic grain size of each process and the influence of quenching in three cooling media: salt, polymer solution and oil. The sample evaluations were performed in optical microscopy, scanning electron microscopy and Vickers microhardness tests. After these analyses, it was concluded that the formed samples obtained a more homogeneous microstructure, but with decarburization, especially the sample tempered in salt. All bars reached an acceptable grain size but with non-normal grain growth attenuated in the formed samples and the cooling media influenced in different ways the formed and machined bars, and the new process presented a reduction of approximately 30% of the material in each piece.**

Keywords— Aluminium alloy; Heat treatment; Deformation.

I. INTRODUCTION

The link between technological and manufacturing costs represent a significant challenge for the survival of companies. Cost reductions can lead to drastic savings, making the company more competitive and forcing competitors to invest in the same way, generating a demand for technological innovations, aimed at optimizing manufacturing and improving tool and component performance.

The specification of the raw material, as well as the use of the right manufacturing process, directly influence the quality of the products and their manufacturing costs, and any alteration of the process must be analyzed in detail to verify its viability.

The microstructural analysis is necessary for the identification of the properties that the final product possesses. It is possible to identify problems such as inclusions, decarburization, unfair thermal and thermochemical treatment, use of incorrect material, among others, which compromise the level of quality and reliability that the company Is delivering to the customer with your product. Microstructural analysis by microscopic optics and scanning electronics as well as hardness and microhardness analyzes raise the quality of the product that a company can offer and are indispensable tools for quality control.

This work analyzes the feasibility of manufacturing considering the mechanical and metallurgical characteristics of the production of SAE 5140 steel bars used in the manufacture of concrete and wood drills only by mechanical forming processes. For replacement of the current form of production, machining is necessary, generating a high loss of material. The change of manufacturing process aims to reduce the waste of material produced by this machining process.

II. REWIEW

A. *Alloy steel SAE 5140*

SAE 5140 steel is a steel alloy for mechanical construction. It can be formed hot, warm or cold, depending on the temperature, used in the production of spindles, springs, high strength bolts, spring bundles and tools such as drills [1].

According to SAE J404: 200, the composition of SAE 5140 steel (Table 1).

Table 1. Chemical composition of Steel SAE 5140.

Steel	C	Mn	P	S	Si	Cr
SAE 5140	0.38 - 0.43	0.7 - 0.9	≤ 0.03	≤ 0.04	0.15 - 0.35	0.7 - 0.9

Source: SAE Standard J404: 2000 [2].

It can be obtained high hardness by the beneficiation of the same, reaching values around 60 HRC on the surface, besides being a versatile steel, it can be used in different thermal treatments and also in thermochemical treatment of nitriding.

B. *Heat treatment*

The characteristic TTT curve of SAE 5140 steel, where lines A_1 and A_3, which indicate the chief temperatures of the steel heat treatment, besides showing the hardness obtained referring to the temperature used for the cooling (Fig.1) [1].

The heat treatment concept is a set of heating and cooling operations for controlled times and temperatures determined to obtain certain mechanical and microstructural characteristics in a material.

Low and medium-carbon steels are standardized after forging since high-carbon steels, and steels with alloying elements need to undergo a heat treatment process of annealing and co-firing before the machining step.

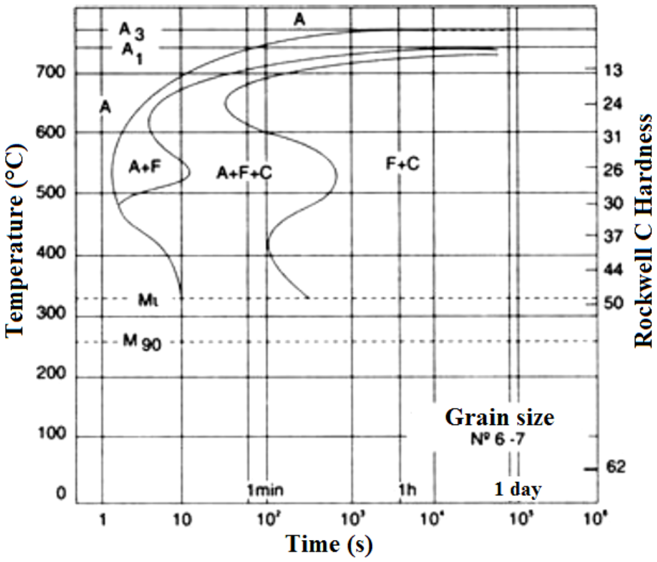

Fig. 1. TTT Diagram of SAE 5140 Steel [1].

As for semi-finished steels, they can receive the heat treatments of tempering, tempering, solubilization and aging, carbon recovery, etc. Thermochemical treatments of carburizing, carbonitriding, nitriding, oxy nitro carbonation [3].

Tempering is an important heat treatment and widely used, to obtain a martensitic microstructure in the steel which consequently increases its hardness and tensile strength limit. It consists of two stages, austenitization, and rapid cooling. In austenitization, the steel heated until it reaches the particular temperature in the austenitic field and is maintained in it for a sufficient time so that all material is homogenized. After austenitization the material is cooled rapidly in a medium, being it oil, polymer solutions, salt bath or high-pressure gasses.

The great increase of hardness caused by the microstructural transformation of austenite (FCC) in martensite (BCC), also causing the appearance of residual stresses and reduction of ductility. To avoid these drawbacks, the temper accompanied by another heat treatment, the tempering, in which the material reheated to a subcritical temperature for a particular time. To transforming the structure into fresh martensite, relieving internal stresses, minimizing the brittleness and dimensional stability of structure, reaching the optimum point between hardness and ductility of the martensite [4-5].

C. Cooling

The cooling curve can be characterized by several cooling mechanisms, being possible to divide the process into at least three stages: vapor phase, bubble nucleation phase and convection phase, each with very different cooling rates [6].

In the first stage due to the high temperature of the austenitization, a stable vapor film is formed in the surroundings of every piece, playing an insulating role that prevents a rapid cooling, making the radiation the main means of heat transfer.

The second stage characterized by a large increase in the rate of heat transfer in which the vapor film formed in the first stage broken when the temperature of the metal reaches the Leidenfrost Temperature, and the temperature fluid which comes in contact with the metal is Instantly evaporated causing a reliable transfer of heat.

The third stage begins when the temperature of the metal surface is below the boiling temperature of the cooling fluid. This stage is characterized by a much lower heat transfer than the previous stage, with convection being the main transfer mechanism. The transformation of the austenite into martensite occurs at this stage. Therefore a slow cooling can minimize the possible cracks and undesirable distortions in part. Because it is a predominantly convective stage, the degree of agitation, the viscosity of the fluid and bath temperature are important factors to consider to avoid such drawbacks [6-4-7].

D. Immersion

Various fluids used for the tempering process, among the main oils and polymer solutions. The way in which the cooling takes place has a great influence on the final characteristics of the element.

Salt immersions are water-based solutions with sodium chloride (NaCl) or calcium chloride (NaOH), because of the corrosion effect, often have additives to inhibit such a drawback. They have higher cooling rates than water, which allows a lower degree of agitation in comparison.

The salts present in the solution promote the breakage of the vapor film in part during the first step, because small crystals of salt settle on the surface of the component, with the high temperature, these crystals break up violently, causing a stirring that destroys the film, thus increasing the cooling rate.

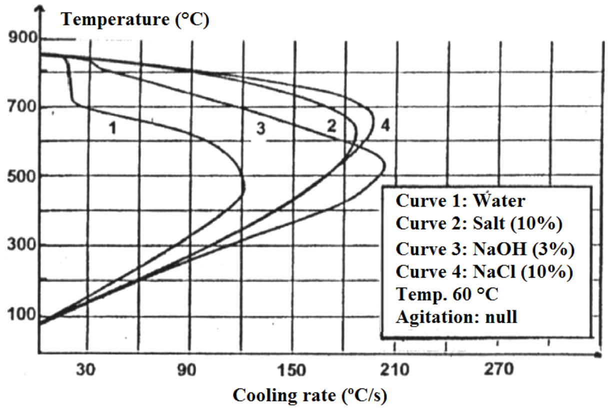

Fig. 2. Cooling curves for different salt immersions as a function of the cooling rate [6].

Oils for tempering have a large number of variations, from conventional oils to fast-cooling oils with special additives to increase cooling, each with very different characteristics and components. The volatility of these components influences the flash point of the oil, the lower temperature at which the fluid produces enough vapor to form a flammable mixture with air, directly influencing the ability to draw heat from the element, being oils with low flash point harmful to certain heat treatments. There are some important properties that oils must possess to be competitive quenching cooling forms [7].

Acceptable flash points and combustion points;
Low degradation rate;
Do not stain the tempered elements;
Appropriate heat removal properties.

The use of quenched polymer solutions has taken significant importance in industrial thermal treatment, its superior fire resistance, biodegradability, the ability to not produce toxic fumes, among other characteristics, make polymer solutions a more interesting option compared to oils.

These solutions offer ranges of water-oil tempers, which are required by many applications, without the inconvenience of cracking and distortion due to water severity, as well as avoiding the abovementioned oil-related problems [6].

When the part is immersed in the solution, a continuous film of polymer is formed separated from the surface of the metal by an overheated vapor, during the cooling the film collapses simultaneously throughout the part, resulting in high cooling rates. After the surface temperature of the material falls below the boiling point of the water, the same convective process occurs in the other media. In the oil cooling phases and in a polymer solution (Fig. 3) it is possible to observe that in the oil the collapse of the vapor layer does not occur entirely, causing a less uniform cooling [4].

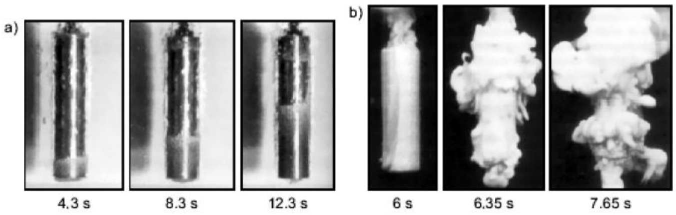

Fig. 3. Comparative of the cooling process: a) Oil, b) Polymer solution [7].

The cooling rate of the polymer solution is strongly influenced by the polymer concentration and bath temperature (Fig. 4), the type of polymer and the degree of agitation are also factors of extreme influence.

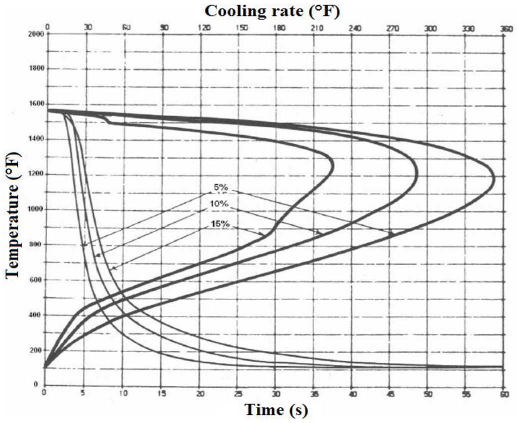

Fig. 4. Cooling and cooling rate curves for different polymer conc. [6].

III. MATERIALS AND METHODS

This work aims to analyze the feasibility of replacing SAE 5140 rolled metal bars. They undergo a machining process to obtain the initial dimensions and will be replaced by metallic bars of the same material, laminated and drawn with subsequent upsetting process. The same dimensions are obtained, but without the waste of material caused by the machining. Such replacement must meet the existing mechanical and microstructural requirements of the process. For this, the analysis of the microstructures, verification of decarburization, microhardness profile, austenitic grain size and microstructural changes were performed due to the different cooling media.

A. Samples

The SAE 5140 steel in the form of a metallic bar, formed (Fig. 5) and machined (Fig. 6) both with a length of 160 mm, a diameter larger than 10 mm and smaller than 7.5 mm.

Fig. 5. Formed bar obtained by the alternative method.

Fig. 6. Machined bar obtained by the conventional process.

B. Preparation of Samples

Two specimens with their mechanical and metallurgical properties were characterized and then tempered in the three cooling medias discussed in the paper.

The machined bars were initially obtained by cold forming, straightening to the final 10 mm diameter, with a subsequent machining process to reduce part of their section to a diameter of 7.5 mm (Fig 7).

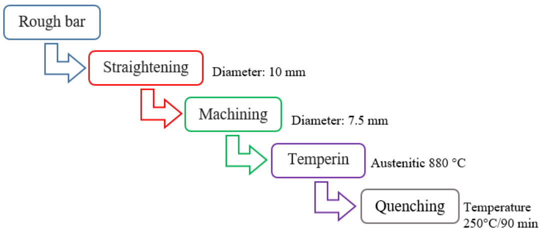

Fig. 7. Manufacturing process diagram of the machined base bar.

The formed bars were obtained by the same rolling process with a subsequent cold drawing process to obtain the diameter of 7.5 mm and subjected to an upsetting process at 1190 ° C, increasing the diameter of a portion of the length to 10 mm (Fig 8).

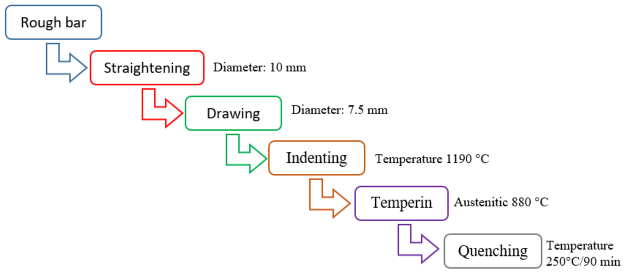

Fig. 8. Manufacturing process diagram of the formed bar.

C. *Heat treatment*

For the thermic treatment and tempering process, three samples were heated at 880 ºC over a period of one hour for homogeneous austenitization of the parts and then separately cooled in three media:

1) Polymer solution of 30 to 50 degrees;
2) Oil (32 Houghton KB) at 60 ° C;
3) Martempering AS140 at 140 ° C.

Tempering at 250 ° C for 90 min.

D. *Metallographic analyzes*

After cutting, the bars were sanded in the following order of granulometry: 120, 220, 400, 500, 600, 800, 1000, where the samples were rotated 90 ° at each change of sandpaper. After this procedure, the samples were polished in a 1 μm alumina mixture with water until a polished surface was obtained.

E. *Analysis of decarburization on the surface of samples*

For decarburization analysis, a chemical attack of the Nital reagent 2% was performed and analyzed under a microscope with a maximum magnification of 1,000 times. Scanning electron microscope in high and low vacuum mode, Jeol with magnification of 2,000.

The Nital reagent 2% is usually used in the development of steel microstructures, it shows the contour of ferrite grains and provides a contrast of martensite, where light structures indicate ferrite and martensite. The samples had their surfaces submerged in this reagent for a certain 30 seconds, with subsequent cleaning with water for the interruption of the attack, then ethyl alcohol was applied and dried in hot air [8].

F. *Analysis of austenitic grain size*

In the analysis of austenitic grain size, the same sanding and polishing process and chemical attack with a reagent variation were carried out, after which the samples were analyzed in the same optical and electronic microscope.

The reagent is composed of 75 ml of distilled water, 55 ml of liquid soap and 3 g of picric acid. This reagent is used in a wide group of steels and is very effective in steels with a martensitic structure, providing information on grain size without new austenitization. The samples had their surfaces attacked by scrubbing for 15 minutes, with subsequent application of tap water for the interruption of the attack, followed by jetting of ethyl alcohol and drying in a hot air jet [8].

Through the optical microscope, with a magnification of 400 times, the austenitic grains were measured by the comparative method according to ASTM E112 [9].

G. *Microhardness profile analysis*

The microhardness analysis was performed with a 0.3 kg Vickers type penetrator with a duration of 10 seconds, from the outside of the piece to its center, at a rate of 0.05 mm, with a horizontal distance of 0.15 Mm to avoid the influence of the previous penetration. The microhardness profile representative of the entire section was then obtained. Samples were sanded and polished by the same method as before before the tests were performed. To obtain a profile of microhardness more representative of the sample, four profiles were made, and the profiles were plotted with the mean value between them (Fig 9).

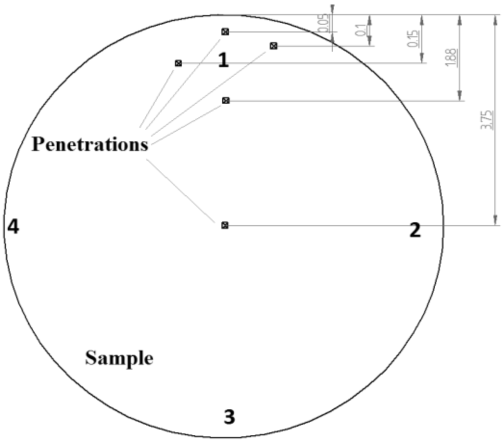

Fig. 9. Scheme penetrations to obtain the microhardness profile.

IV. RESULTS

A. *Microstructural characterization*

In the first stage the results obtained by the chemical attack of the Nital reagent 2% are presented and discussed, referring to the microstructure of the samples without heat treatment of the formed and machined bars. Subsequently with the tempering in the three media and tempering of both were analyzed their differences. Next, the decarbonization analyzes obtained in both optical microscopy and SEM are presented, as well as the microhardness profiles of the samples.

At the end, results are presented regarding the austenitic grain size of the samples and what caused the presented results.

B. *Microstructures of machined and formed samples without tempering and quenching*

The samples without tempering were attacked by the 2% nital reagent for about 30 seconds by submersion, which revealed very different microstructures between the machined bar and the shaped bar (Fig. 10).

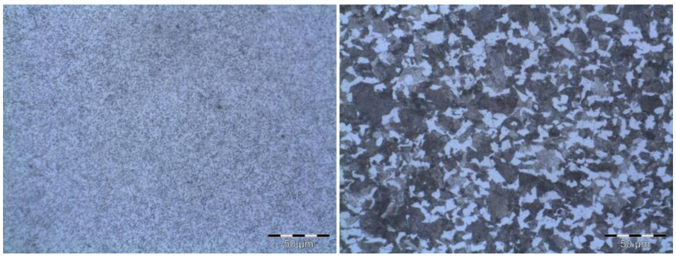

Fig. 10. Amostra conformada (esquerda) e usinada (direita) sem tratamento térmico atacadas com reagente Nital 2%.

In the machined sample, the nital reagent revealed a microstructure composed of ferrite (light grains) and perlite (dark grains) characteristic of a cold-cooled hypo eutectoid steel [10]. In the shaped sample, a spheroid sized (or coalesced) microstructure was observed, composed of spheres of cementite in a ferritic matrix. The microstructural difference is due to the hot forming processes that the shaped bars are subjected to, and the spheroidization raises the ductility of the material making such processes easier [1].

C. *Microstructures of machined samples without tempering*

The samples tempered in salt, oil and polymer solution analyzed separately from those formed in this step to identify the influence of the cooling medium, all of them attacked with 2% of nital (Fig. 11).

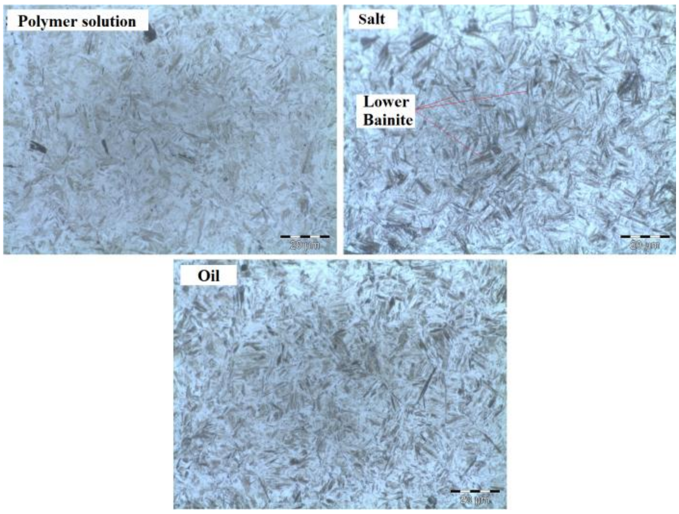

Fig. 11. Microstructure of machined bars tempered in different cooling and tempering media.

Both the sample tempered in a polymer solution and oil had a fine-grained martensite. The sample tempered in salt presented martensite with free ferrite and traces of lower bainite (dark regions) [8], and the oil sample had a predominantly martensitic microstructure.

D. *Microstructures of formed samples without tempering*

The mechanical conformation contributes to a new nucleation of more refined austenitic grains due to the active recovery stages and the recrystallization of the high efficiency, which gave rise to a more refined microstructure of the machined samples.

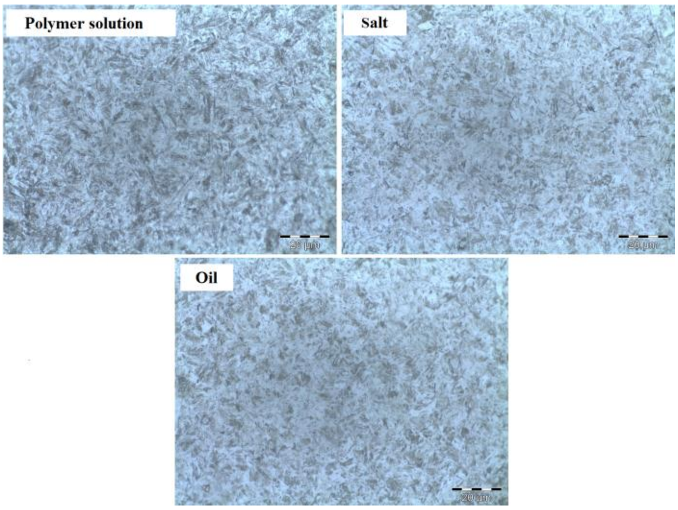

Fig. 12. Microstructure of the formed bars tempered in different cooling and tempering media.

Studies in rolling steel showed the influence of cold deformation on grain refining, the initial microstructure (spheroidal carbides in ferritic matrix) after forming has enough energy to form a substructure during heating for tempering, a more refined grain obtained and consequently fragmented martensite crystals [11].

E. *Analysis of decarburization of the machined and shaped specimens treated thermally in an optical microscope*

In this analysis, samples of the same cooling medium obtained from machined and formed bars did compare. The decarburizing is a phenomenon that occurs on the surface of the bar, so the use of an aluminum foil around the part, as well as the inlay, was intended to reduce bulging during the sanding and polishing process. In the captured images (Fig. 13), it focused as close to the surface of the sample, to verify whether decarburization occurred.

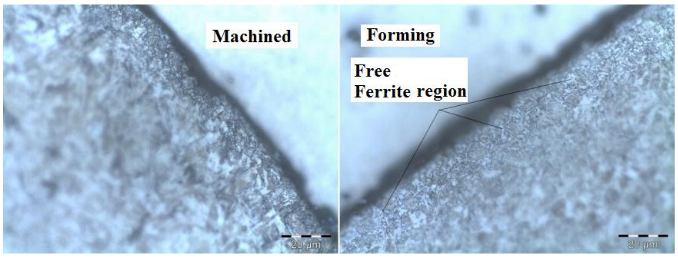

Fig. 13. Sample tempered in polymeric solution and heated with decarburization.

It was observed that the sample produced free ferrite (Fig. 14) characteristic of a decarbonized zone, to which the hardness should be inferior [12]. The machined part showed indications of decarburization, due to the absence of hot forming processes the possible cause is the temperature, which without a controlled atmosphere can cause the loss of surface carbon.

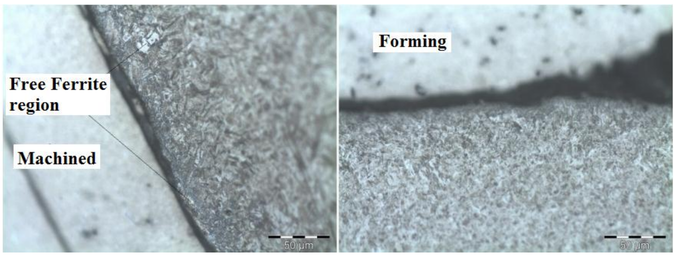

Fig. 14. Samples tempered in salt with decarburization.

Discarded machined sample with regions of free ferrite and shaped sample without apparent decarburization (Fig. 15).

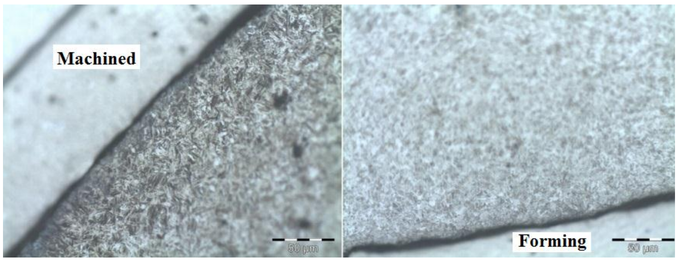

Fig. 15. Oil-tempered samples without apparent decarburization.

Decarburization occurs above 705 ° C, which allows the carbon of the steel surface to react with the oxygen in the atmosphere [13] for the formed samples. The need for heating at high temperatures for the upsetting process is the main cause of decarburization. The machined samples showed evidence of decarburization since in the austenitization stage the material for the tempering process reaches temperatures not as high as the shaped parts. They are still capable of promoting the diffusion of carbon into an uncontrolled atmosphere with the presence of residual oxygen or water vapor because of inadequate air infiltration or purging [10-14].

F. *SEM analysis of decarburization of the machined and formed Samples and with Heat treatment*

The main advantage of the SEM analysis was that even with bulging on the surface of the part the SEM still manages to obtain well-focused images. The magnification of 2000 times was the one that provided the most representative images of the surface of the piece. On the sample surface, a clear layer appeared, characteristic of decarbonated regions [14-15] (machined sample) and (Fig. 16) (formed sample).

In the machined sample it is observed that the grains are deformed, because of the machining itself to reduce the diameter.

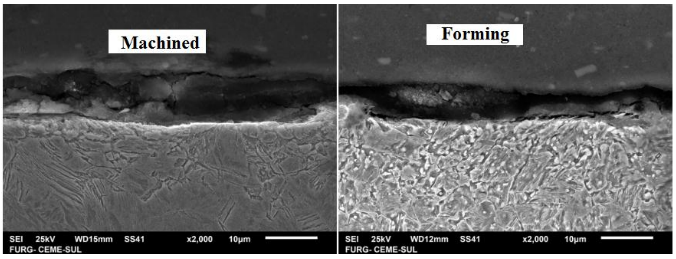

Fig. 16. Tempered samples in polymer solution.

Fig. 17.

Machined sample showed a clear layer, characteristic of decarbonated zone whereas in the formed sample was not identified since in optical microscope was determined a decarbonated zone indicates that the decarburizing at some points throughout the piece located.

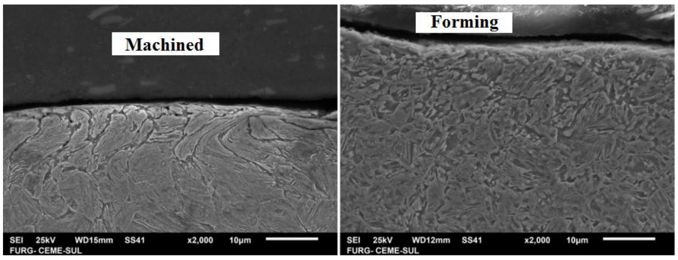

Fig. 18. Salt-tempered samples.

Sample machined showed no decarburization while the formed sample can present white decarburized zone.

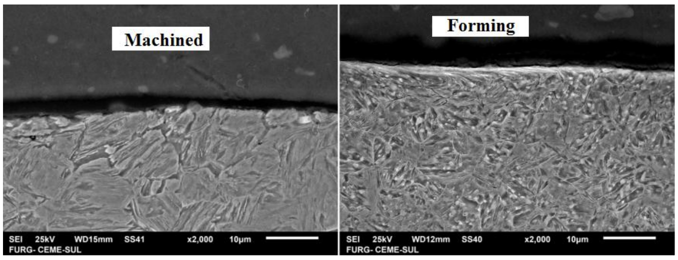

Fig. 19. Tempered oil samples.

G. *Microhardness profiles of Samples machined and formed after heat treatment*

A visual analysis is not sufficient for the identification of decarburization nor its depth. The profiles of microhardness in general, presented hardness in the reduced surface, due to decarbonisation of the samples, indicating that in all parts they had some level of decarburization.

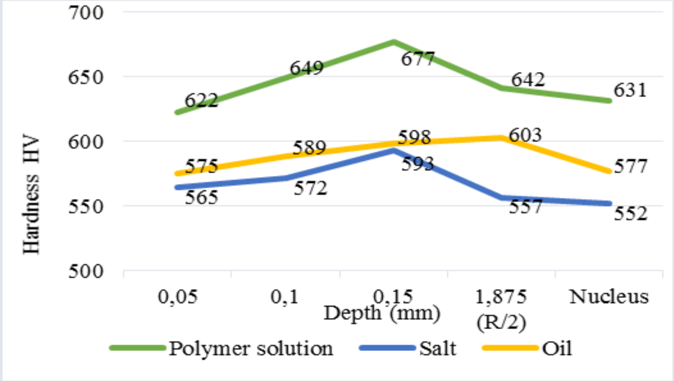

Fig. 20. Microhardness profile of samples machined in HV.

A difference of 30 HV is already indicative of a decarbonized layer; the samples presented hardness higher than its core around 0.15 mm from the surface. The machined samples presented not very uniform results from 0.15 mm of the surface.

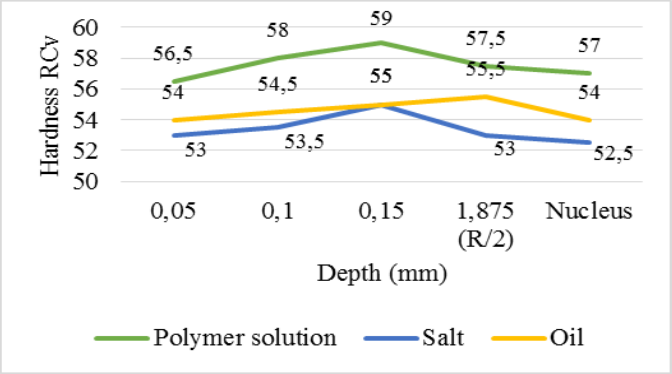

Fig. 21. Microhardness profile of samples machined in HRC.

The sample tempered in polymer solution obtained greater hardness.

H. Formed Samples

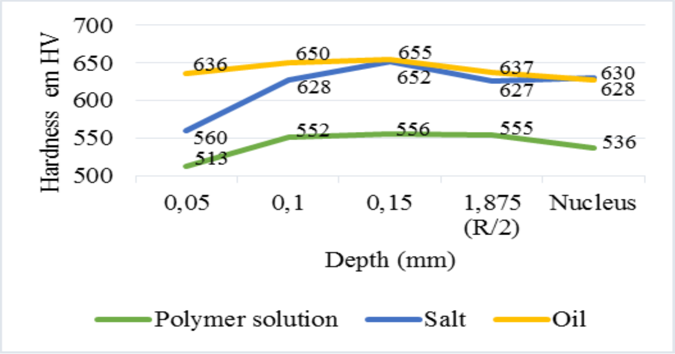

Fig. 22. Microhardness profile of formed samples in HV.

The salt-tempered sample was the one with the most pronounced curve, a variation of 90 HV, indicative of a more intense decarburization.

The oil-tempered sample had no indication of decarburization, and the sample tempered in polymer solution had a less intense and less deep decarburization.

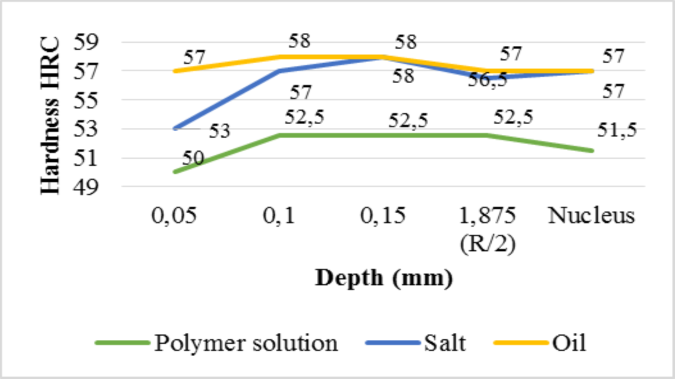

Fig. 23. Microhardness profile of samples conforming to HRC.

The samples tempered in salt and oil obtained higher hardness compared to tempered in the polymer solution.

I. Analysis of austenitic grain size of the machined and formed Samples of the SAE 5140 bars

All samples obtained high grain size, although in all the samples were identified grains with exaggerated size, outside the grain size characteristic of their microstructure.

The machined samples had their grain size lower than the formed samples, even if still high. The abnormal grains presented greater disparity about their microstructure.

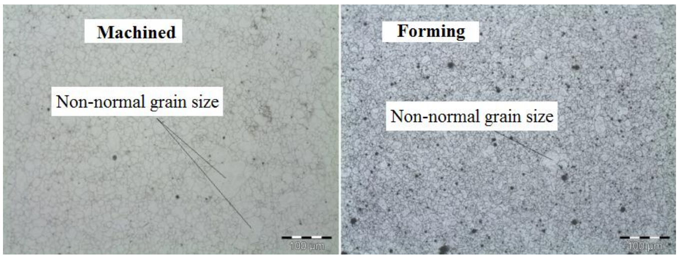

Fig. 24. Tempered samples in polymer solution, machined sample obtained grain size 9 and formed sample grain size 10 according to ASTM E 112-96 - comparative method.

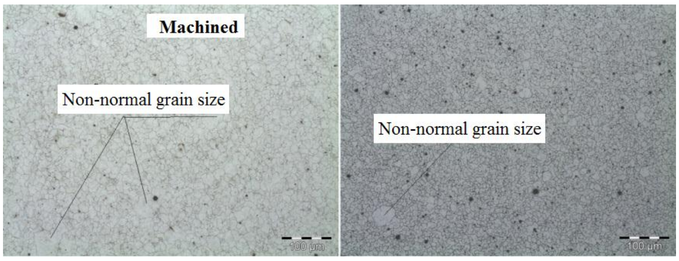

Fig. 25. Tempered salt samples, machined sample obtained grain size 10 and formed sample grain size 11 according to comparative method [9].

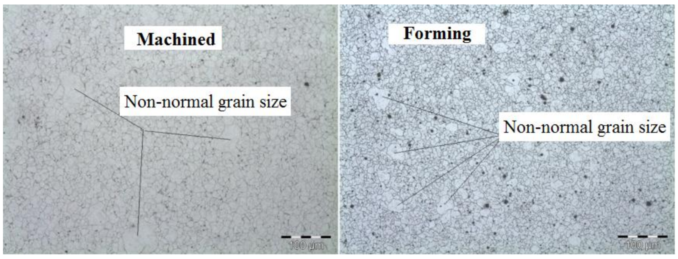

Fig. 26. Oil-tempered and tempered samples, machined sample obtained grain size 9 and formed sample grain size 10 according to comparative method [9].

The formed samples showed a more refined microstructure according to austenitic grain size analysis. The plastic deformation from cold forming processes, such as drawing, refines the microstructure and making it more homogeneous [10]. On the other hand, in all samples with abnormal size grains are present, this abnormal grain growth, also called secondary recrystallization, has as main causes high heating rates, as well as the use of exaggeratedly high temperatures for the process.

V. CONCLUSIONS

The cooling media used showed different results between the machined and formed samples.

In the formed samples, the tempered in polymer solution was the one that reached higher hardness, while in the samples machined, the tempered in oil was the one that reached the highest hardness.

Although the formed samples did not reach the same hardness of the machined samples, it was possible to observe a greater homogeneity of their structures, both in optical microscopy and microhardness profiles, as a consequence of the conformation and recrystallization.

The grain size of all samples was 5 or more thin. However, some grains with abnormal size were present in all samples, larger size in the samples machined.

Both the optical microscopy and SEM analysis of decarburization identified different areas, indicating that the phenomenon occurred in a localized way, in some points of the piece.

The formed samples in salt tempered were the one that suffered most from the decarburization due to the hot forming process necessary to obtain the final dimensions of the bar. In the samples machined, the bar tempered in polymer solution presented a decarbonized layer, but smaller, in the absence of the hot forming process, the possible cause of decarburization is the temperature, which without a controlled atmosphere can cause this effect.

There was an improvement in the homogeneity of the microstructure and also in the reduction of approximately 30% of material in each bar produced.

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