academicJournals

Vol. 12(23), pp. 322-328, 16 December, 2017
DOI: 10.5897/IJPS2017.4687
Article Number: 1B3EE9466949
ISSN 1992 - 1950

http://www.academicjournals.org/IJPS

International Journal of Physical Sciences

Full Length Research Paper

Microstructure and mechanical properties correlation for the steel: A comparative methodology of educational research for physics and mechanical engineering trainings

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Received 7 September, 2017; Accepted 31 October, 2017

An academic methodology based for experimental evaluation of materials treatment is presented. The study is centered in an educational research emphasis about microstructure evaluation and heat treatments in steels samples machined according to ASTM E8 specifications. The uses of metallographic techniques and hardness/tensile tests for analyzing experimental variations due to structural changes are included. Different thermal treatments were applied on AISI-SAE 1018 steel specimens by raising the temperature until it reached the austenization state. Images were obtained with a Nikon NIS Elements computer programming, in order to observe the microstructure and identify the phases involved in each of the thermal treatments. For the hardness analysis, the round indenter of 1/16 in of Tungsten Carbide with a preload of 100 kg was used. A grain diameter of 3 to 4 µm was observed in both annealed and normalized sample, so it is assumed that the cold rolled or reference sample had a normalized condition. Both 41 and 67% in elongation and area reduction percentages, respectively, in the normalized samples were observed. The results allow identifying the correlation between microstructures and mechanical properties, providing an engineering educational approach for metallographic analysis and heat treatment schemes focused on the grain size interpretation, resilience and stress-strain curves. The described methodology provides an academic reference for the didactic evaluation of the main techniques associated with the treatment of materials for physics and mechanical engineering training.

Key words: Heat treatments, microstructure, tensile test, hardness, educational research.

INTRODUCTION

Since the beginning of civilization, materials have been used by humanity to improve their standard of living, being it the substances that make up any structure or product (Daunton et al., 2012; Whitesides and Wong, 2006). Engineers design most products and the processes required for their manufacture are invoiced, so students of engineering must get acquainted with the internal structure and properties of the materials, as well as the techniques of thermal treatments, stress tests, hardness and metallographic analysis (Selfridge, 1985;

Williams and Starke, 2003; Parkinson, 1995). The engineer should be able to select the most suitable for each application and be able to develop the best processing methods.

Considering the role of the engineer training to meet such needs, important studies have been conducted to identify strategies and reflections that promote a more solid formation in the area of design (Atman et al., 2007; Schaefer et al., 2008; Szykman et al., 2000; Dym et al., 2005), as well as in the implementation of the scheme and learning project-based (Dutson et al., 1997; Mills and Treagust, 2003).

The thermal treatments constitute procedures to improve materials properties or achieve characteristics for specific purposes (Calik, 2009; Kuśtrowski et al., 2005; Fadare et al., 2011; Daramola et al., 2010; He et al., 2010) and these in turn, depend on the structure and the type of material in a piece, which is achieved with the precise handling of temperature and cooling rate. A recent study about the impact of intercritical annealing temperature and microstructure, including optical microscopy and point count method using stereology to evaluate martensite volume fraction, can be consulted in the report of Ikpeseni et al. (2015). Also, a description about the main heat treatment problems can be found in ASM Handbook, chapter 1 (ASM Handbook, 2014).

Other properties associated with the materials, such as the structural characteristics and it's relation to the physical, mechanical and chemical properties are usually evaluated through metallography studies (Stobrawa et al., 2007; Cwjna and Roskosz, 2001; Frade-Drumond et al., 2014; Castillo and Marin, 1985; Dobrzański et al., 2007; González et al., 2015; Wojnar, 2016); grain size, distribution of contraction cavities and manufacturing processes, which affect the mechanical properties of the material, are commonly feasible determined from such techniques (De-Cooman and Speer, 2011; Dieter and Bacon, 1986).

Finally, a third aspect considered in the preparation of this report, is related to the choice of steel 1018, which is a sweet and low carbon steel widely known for its good combination of strength, ductility and hardness. Several contributions associated with mechanical properties and heat treatments have been reported for steel 1018 (Suzuki and Mcevily, 1979; Jayaraman et al., 1997; Topçu and Ubeyli, 2009; Doong and Tan, 1989; Clough et al., 2003; Akkurt et al., 1996). Being the most common steel of cold-rolled steel, it is a very useful product due to its typical characteristics of good mechanical strength and good ductility. In general terms, this metal has excellent weldability and better machinability than most carbon steels. Similarly, its alloy with tin (Noguez et al., 2002) allows the strengthening of its mechanical properties, especially with respect to ductility.

The mechanical properties of 1018 steel, such as its hardness (126 HB), creep yield (370 MPa), maximum effort (440 MPa), modulus of elasticity (205 GPa) and machinability (76%), among other, make it ideal for a wide range of components such as pins, rods, shafts, gears and sprockets. While it is true that other steels can exceed their mechanical properties, the 1018 has the advantage of easier, machine-made production, presenting a low cost in the market.

The main objective of this report is to describe a methodology with educational research reference for the didactic evaluation of the main techniques for treatment of materials. Experimental work was realized with participation of student of investigative exercise, research assistantships and linkage projects as other learning modalities.

As part of the experience in academic training, it has been perceived that the study of heat treatments and properties of materials usually presents a certain level of difficulty in the students' learning, mainly due to the number of standards (ASTM, ASM), techniques and criteria in which is based. In this sense, the methodology provides a reference for the academic evaluation of the main techniques associated with the treatment of materials. The report includes experimental evaluations that allow identifying microstructure, mechanical properties, hardness and thermal treatments in samples machined according to the heat treater's guide (Harry, 1995).

MATERIALS AND METHODS

Sample preparation begins with cutting the specimen 1 "in diameter and 1" in length. Subsequently, the sample is tilled with silicon carbide abrasive paper (sandpaper) number 80, 160, 240, 400, 600, 1000, and 2000, using water as lubricant and a flat surface as carrier. It should be noted that in each change of abrasive paper, the sample is rotated 90° so that the stripes generated are perpendicular to those generated by the new abrasive paper. After the AISI-SAE samples have been tilled, the polished process was applied, which consists of the elimination of all the stripes generated by the abrasive papers, using abrasive powder "alumina" of 3 microns and water as lubricant. Subsequently, the microstructure is cleaned and revealed by chemical attack with 5% Nital (5 ml nitric acid, 95 ml alcohol). Samples were cleaned with ethyl alcohol to remove residues and stains in the sample as indicated by ASTM standard (ASTM E3, 2017).

Different heat treatments were applied to AISI-SAE 1018 steel specimens (Chemical Composition: 0.15 to 0.20% C; 0.60 to 0.90 Mn; 0.04% P; 0.05% S) with a C401 H-PM3E Cress furnace. The temperature was raised at intervals of 250 to 930°C (Austenization temperature), according to Szykman et al. (2000) and Harry (1995).

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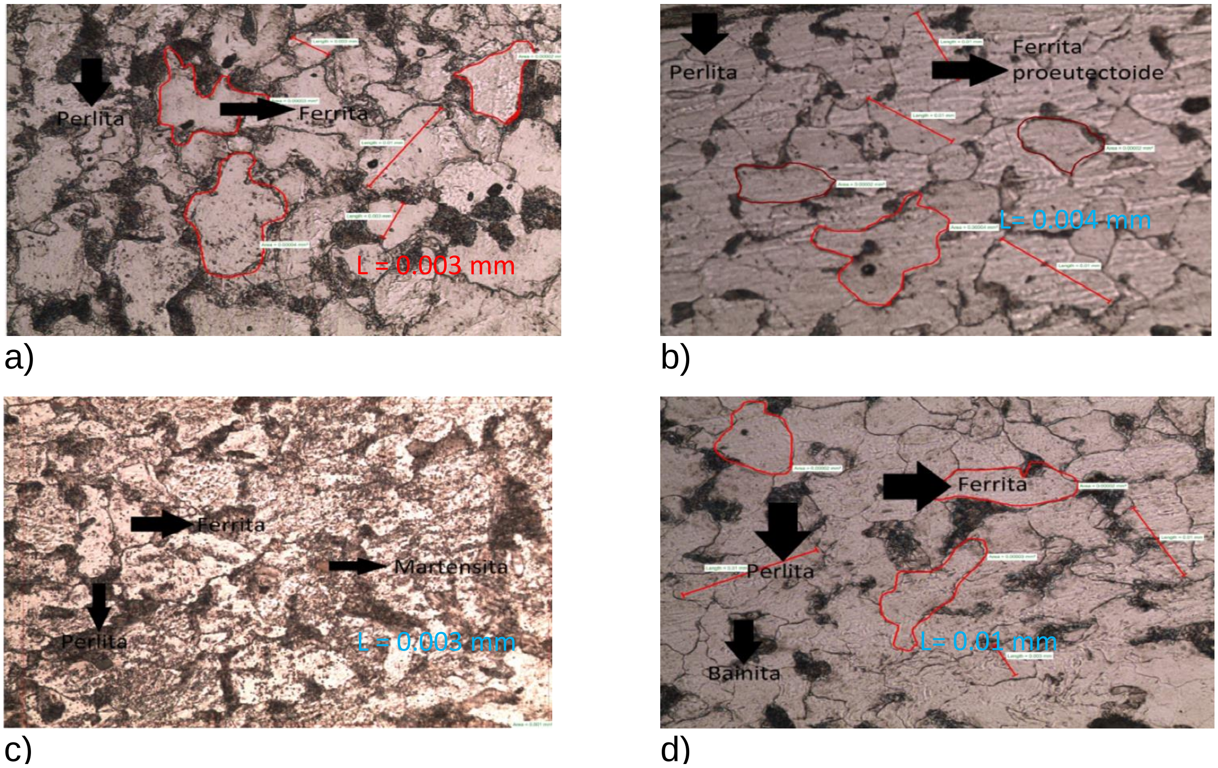

Figure 1. AISI-SAE 1018 steel attacked with 2% Nital in samples with metallographic processes (100x). The phases for control (a), annealing (b), normalized (c), and hardiness (d) are shown. The lines marked in the images highlight the lengths and perimeter of the grains; the arrows identify the phases found in each of the samples.

Subsequently, the specimens were removed and the specific treatment was preceded. In the hardening treatment, they are immersed in water at room temperature for a sudden cooling; for the treatment of normalizing, the test tube is taken and left outdoors. The annealing process was realized placing the sample in the oven with a uniform cooling ramp until it reached the ambient temperature.

For the metallographic analysis, the polished samples were attacked with Nital 2% for 10 s in order to reveal the microstructure. Subsequently, the samples were cleaned with alcohol and observed in the metallographic microscope. The images were obtained with the help of the Nikon NIS Elements computer program (Laboratory Imaging, s.r.o., Za Drahou 171/17, cz-102 00 Praha 10, version 4.10.03). Images with different scales were obtained in order to observe the microstructure and identify the phases involved in each of the thermal treatments, according to ASTM E112 (ASTM E112, 2013) and ASM (Vander-Voort et al., 2004).

In order to perform the stress test on the different test specimens previously machined and according to the specifications of the American Society for Testing Materials ASTM (ASTM E8, 2016), these were subjected to annealing, normalizing and hardening heat treatments. The diameter and length of the calibrated area were dimensioned, as indicated by the standard protocols. Once the specimen was centered and held, *TrapeziumX* computer program (*Materials Testing Software TRAPEZIUM LITE X 349-02788E*) pre-loaded in the system, as well as the diameter and initial length for the development of the test were selected. The loading and displacement positions were tared and the test was performed in accordance with ASTM recommendations.

The metallographic treated samples were mounted and fixed in a *CV-600A "SPI"* durometer for Rockwell A, B, C and F tests to figure perform the Rockwell B hardness test. For all sample analysis, 1/16 (1.59 mm) tungsten carbide round indenter was used. With 100 kg preload, as indicated by standards (ASTM E8, 2016; DIN-EN-ISO-6508, 2006; ASTM E18, 2017), the load was applied, obtaining the hardness reading on the cover of the durometer. Data were recorded and compared with the hardness range tables, according to literature (ASTM E1140, 2012). Once thermally treated samples were both prepared and conditioned, they were evaluated under ASTM E3 and ASTM E112 considerations.

RESULTS AND DISCUSSION

Figure 1 show the phases presented in AISI-SAE 1018 steel without heat treatment and with treatment at 100x. A metal matrix of ferrite (light zone) and perlite (dark zone) for reference sample (cold rolled or control sample) can be observed (Figure 1a). The microstructure resulting from the heat treatment of annealing is observed in Figure 1b; that is, a metal matrix of ferrite and perlite in the steel. Figure 1c describes the microstructure of annealing; this contains martensite and ferrite grains; while Figure 1d shows the effect of the normalized, where a metal matrix of ferrite can be seen, as well as in the limits of grain, perlite. It should be noted that the formation of 100% martensite is only possible in very thin sections, as well as with a rapid cooling. On the other

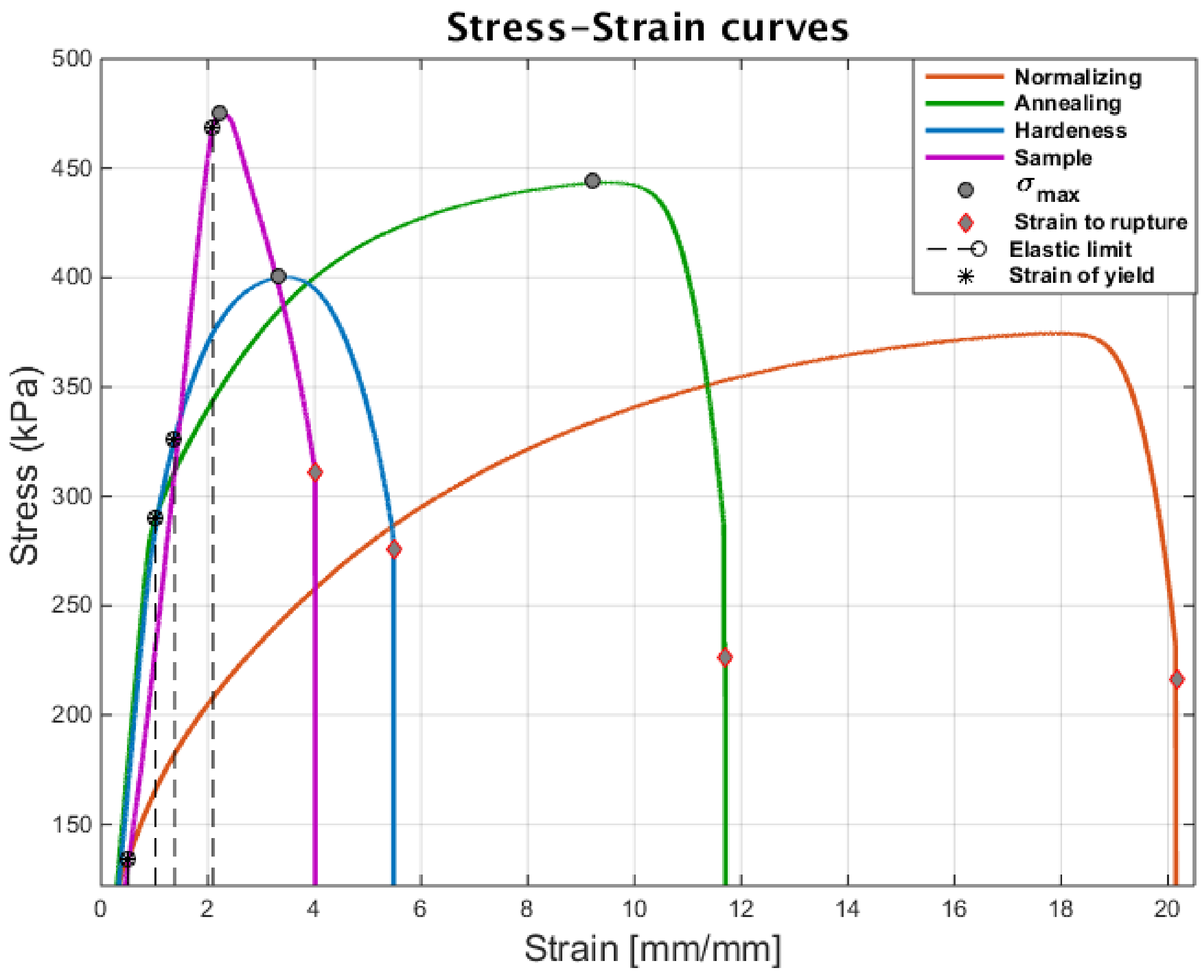

Figure 2. The stress-strain curves obtained from the tensile stress tests.

hand, diameter of the order of 3 to 4 µm can be observed in both the annealed samples (Figure 1b) and normalized (Figures 1d), associated to grain size ASTM 5 to 6 (ASTM E112, 2013), whereby the control sample is assumed to have a condition of normalized. The lines marked in the photographs of Figure 1 highlight the lengths and perimeter of the grains. The arrows identify the phases found in each of the samples.

With respect to the stress test, the comparison of the four stress-strain curves corresponding to each of the thermal treatments performed and the reference sample are recorded in the Figure 2, where it can be seen that the σ-ε curves corresponding to those tempered specimens show higher yield strength and lower elongation percentage. Similarly, the tenacity (area under the σ-ε curve) was higher in the normalized sample. The resilience (area under the curve σ-ε in the elastic zone delimited by the dotted line) was higher in the control sample. The annealed sample presented greater stress at rupture and the plastic zone was higher in the normalized sample; such plastic zone is delimited between the dotted line and the break point in each of the curves.

The values of lengths, diameters, areas, stresses, Young's modulus, percentages of area reduction, elongation, as well as the resilience and average values of the hardness test obtained from measurements in the tensile and hardness tests were recorded in Table 1. Based on the results, it can be observed that in the normalized sample, the percentage of elongation was 67.75% and the area reduction was 79.3%, which indicate a greater tenacity. Also, the Young's modulus of 277.6 kPa turned out to be higher than the other thermally treated samples.

The annealing sample showed a higher maximum stress than the other samples with 444 kPa treatment. For the temperate sample, the maximum stress values were higher with respect to the rest of the samples, both in yield and in rupture, whose values correspond to 326.24 and 91.86 kPa, respectively. Likewise, the calculated resilience was the highest among the heat treated samples with a 223.52 kJ/m^2.

Table 1. Results obtained from the stress-strain curve and the hardness tests.

Parameter	Normalizing	Annealing	Hardness	Sample
l_o (mm)	41.80	40.51	41.91	40.64
l_f (mm)	70.12	57.27	48.99	43.84
$ø_o$ (mm)	6.24	6.22	6.14	6.29
$ø_f$ (mm)	2.84	3.04	3.63	1.47
A_o (mm^2)	30.58	30.38	29.60	31.07
A_f (mm^2)	6.33	7.25	10.34	1.69
Rupture strength (kN)	1.37	2.93	4.22	5.54
E (kPa)	277.59	262.14	250.98	300.18
Strain of yield (kPa)	134.24	290.14	326.24	468.91
Strain at 0,2%	137.20	292.79	317.55	464.51
$\sigma_{máx}$ (kPa)	374.71	444.09	400.65	475.50
Strain to rupture (kPa)	25.10	62.26	91.86	114.75
% of elongation	67.75	41.37	16.9	7.87
% of area reduction	79.3	76.13	65.06	94.56
Resilience (kJ/m^2)	33.92	151.53	223.52	504.37
Average HRB (100 kg, 1/16)	11.8	17.8	73.8	14.6

A_o, Initial cross-sectional area; A_f, Final area of the cross-section area at the surface of the fracture; σ, Effort; ε, Unitary deformation; E, Young's Module; δ, Elongation; Ø, Diameter; P, Force/Load; l_o, Initial length of the calibrated zone; l_f, Final length of the calibrated zone; $\dot{\varepsilon}$, Strain speed; ANSI, American National Standards Institute; SAE, Society of Automotive Engineers; ASTM, American Society for Testing Materials; ASM, American Society for Metals; HRB, Hardness Rockwell B; ISO, International Organization for Standardization.

The tempering heat treatment at 930°C for 1 h and with sudden cooling, allows the steel to present more defined characteristics as the greater Modulus of Elasticity, greater ultimate strength, and a greater yielding stress due to the martensite phase (Figure 1d), corresponding to the tempering, values that are congruent with the hardness values. This normalized thermal treatment, but with cooled in the open air, allowed an increase in the ductility and, consequently, its deformation was greater and the yielding effort was low; that is to say, it had less elastic deformation and increased plastic deformation. Given the characteristics obtained in each of the thermal treatments made of steel, it can be concluded that the reference sample has a normalized condition. Based on the circumstances foreseen in the study, the mechanical properties of the AISI-SAE 1018 steel can be correlated with the values of tension; hardness and microstructure differ with respect to the applied heat treatment.

Conclusion

The periodic curricula updating at different levels of education is an evidence of the national effort to improve the skills of engineering graduates. Although the development of traditional courses at different engineering areas continues to be one of the main tools to ensure the preparation of engineers, the implementation of other teaching modalities such as investigative exercise, research assistantships and linkage projects implemented through methodology under study, promote a more direct approach of the student with the technology, motivating their level of participation and professional strengthening.

The mechanic engineering field is centered on a significant number of international norms and regulations associated with testing and evaluations of materials properties, so that students are called to review a number of manuals that allow them to take advantage of equipment and resources. Therefore, the student of engineering requires the consultation of sources that aid mediates between articles of very specialized essays, theoretical courses and manuals of considerable extent, as well as extracurricular activities that allow him/her to develop other competencies associated with the management of techniques and its interpretations.

The study was centered in an educational research emphasis about the material microstructure as well as of the heat treatments in samples machined according to ASTM E8 specifications. The experimental process was developed within the laboratory practice programs for physical and mechanical engineering students of a prestigious university at the pacific.

The methodology provides a reference for the academic evaluation of the main techniques associated with the treatment of materials. The results obtained and the experimental schemes developed describe the correlation between the microstructure and the mechanical properties as a fundamental tool for the comprehension of the treatment of materials in diverse areas of engineering. For the steel AISI-SAE 1018, it was determined that the heat treatment makes possible the change in the mechanical properties of the material, which can be observed in the tests of tension and hardness, as well as metallographic analysis.

The report is an academic reference respect to the experimental mechanical engineering training in an institution of higher education studies at USA-Mexico border.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

ACKNOWLEDGMENTS

The authors express their thanks to the Secretariat of Public Education through the Professor' Improvement Program (PRODEP), for the financial support. Research was conducted throughout the Mechanical Systems Optimization Academic Group (UABC-CA-219). The authors are grateful for the excellent collaboration of Dr. Arturo Baundez Pliego, CENIDET: National Center for Research and Technological Development.

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