Magnetic system for the quality control of specimens for Charpy impact test

R V Martin¹, M A P Castanho²
¹,² Instituto de Pesquisas Tecnológicas do Estado de São Paulo - IPT, Cidade Universitária, São Paulo, SP, 05508-901, Brasil

E-mail:¹ ramon@ipt.br

Abstract. It was developed a non-destructive testing system based on magnetic methods for characterization of steel specimens, used in calibration of Charpy impact testing machines. The magnetic properties saturation, remanence, coercivity, and the hysteresis curves were used to create a "magnetic signature" of reference to ensure the value of energy absorbed by these standard specimens.

1. Introduction

The Charpy impact test is widely used in mechanical construction industries for verification of mechanical properties of structural steel [1]. Through this test is determined the energy absorbed by the fracture of a sample with well-defined geometry. The amount of the absorbed energy reveals the ability of material to resist to dynamic loads, shock and defines safe operation temperatures (maximum operational temperature lower than the ductile-brittle temperature). The more ductile is the fracture, the greater the energy absorbed. Low energy indicates high hardness, but brittle materials. There is also a correlation between this energy and the tensile strength. The geometry of the specimen, as well as the machinery and procedures for conducting the tests is specified in technical standards [2]. A schematic drawing of the equipment is shown in Figure 1. These machines have to be periodically calibrated [3], and special specimens (standard specimens) are used for this purpose. Through heat treatments it is possible to change the microstructure of the material in order to modify the energy absorbed in the process of rupture. Brittle fractures are obtained in hard materials, as in martensitic steels, while ductile fractures occur in steels with predominantly ferritic structure. The certified test specimens come from metrological institutions like the NIST [4] and ERM [5]. In Brazil there are still no suppliers. Efforts involving the National Metrological Institute - Inmetro and the IPT of São Paulo are being carried out for the development of these reference materials [6]. These test specimens were manufactured for testing machines with swinging hammers schematically shown in Figure 1. The rectangular bars with 10 mm x 10 mm x 55 mm are machined with a V-notch, where it begins to break up due to stress concentration. The schematic drawing of this specimen is shown in Figure 2. Standard specimens should be characterized properly to ensure the value of the absorbed energy at break. The microstructure must also be checked in addition to the dimensional characterization. This microstructure is defined mostly by the chemical composition of the steel and by heat treatments carried out.
The characterization of the material can be made by x-ray scattering methods, Mössbauer spectroscopy, metallographic analysis laboratory, and other techniques such as electron microscopy. In addition to the long times of measurement and sample preparation, these methods are expensive and only provide results from regions near the surface of the specimens. Alternatively, hardness tests are also used, but only at the ends of the specimens to avoid disturbing the material near the area of rupture.

2. Objectives
The aim of this work is the development of non-destructive testing, based on magnetic measurements, to ensure the results of the energy absorbed in the breakage of standard specimens used in the verification of Charpy testing equipment. The implementation of this quality control is made by the rejection of specimens that feature magnetic properties off limits previously established.

3. Magnetic Methods
Magnetic characterization can be obtained from the information extracted from its curves of magnetization and hysteresis, relating the magnetic induction $B$ with the applied field strength $H$. Some notable points of these curves are the polarization of saturation to intense fields $J_{sat}$, the remanence $B_r$ or $J_r$ (residual magnetization when an intense applied magnetic field is zeroed), and the coercivity $H_c$ (magnetic field intensity that nulls the magnetisation). A device usually employed in this kind of characterization is the vibrating sample magnetometer (MAV). The samples used in this
equipment have the shape of small needles, and the impact specimens are too big for this method. Furthermore, the MAV operates in "open circuit"; the magnetic flux passing by permeability transition magnetic regions creates demagnetizing fields within the sample. That means the field intensity inside the material is smaller than the external field applied.

In this work, the magnetic characterizations were obtained by inductive technique (histeresigraph) in "closed loop", and so the field inside the sample is identical to the applied magnetic field. The specimen was positioned in contact with the polar poles of an electromagnet. The magnetic induction was measured with the aid of a coil with 50 turns wrapped around the specimen, and coupled to an electronic integrator (Laboratorio Elettrofisico – Digital Fluxmeter). The magnetic field was measured with a gaussmeter (Lake Shore 475), whose Hall probe was positioned next to the pickup coil. Figure 3 shows a detail of the specimen positioned between the polar poles of the electromagnet.

![Image of specimen between polar poles](image)

**Figure 3.** Impact specimen positioned between the polar poles of the electromagnet.

4. **Microstructure**

There is a correlation between the magnetic properties and the mechanical properties, because both are affected by the microstructure of the material. The typical microstructure of steels with low carbon content usually contains phases as pearlite and ferrite. The pearlite is a lamellar structure composed of ferrite and cementite. The final microstructures, and consequently the mechanical properties, are strongly influenced by heat treatment to which the steel are subjected. Starting from high temperatures (austenitization), the slow cooling results in ferromagnetic phases as cementite + ferrite or pearlite + ferrite. The resulting steel is more ductile, and absorbs more energy on break. In the case of the quick cooling (quenching) is also formed martensite, a ferromagnetic phase, and retained austenite (a paramagnetic phase). In this case the steel is very hard, but more brittle and less energy is absorbed at break.

5. **Results and Discussion**

The standard specimens or SPs were made of ASTM A36 steel with chemical composition C: 0.25; MN: 0.80; Q: 0.04; S: 0.05; SI: 0.40. Nine SPs were tested. Three were measured in the receiving state (SPs 7, 8, 9). The other six were initially heated to 900° C. Three were kept in the oven for slow cooling in distinct rates (SPs 1, 2, 3). Two were quickly cooled down in water (SPs 5, 6), and
one was cooled down in the air (SP 4). All the SPs were broken in the Charpy impact machine after magnetic characterization tests.

It was possible to reach the magnetic saturation of the material by applying strong magnetic fields, when the magnetizing curves reach a plateau ($J_{sat} = 2.0$ T). This limit is defined basically by the amount of alloy elements in the steel. All SPs showed saturation curves very similar to those shown in Figure 4. In these charts, the magnetic polarization $J$ is related to magnetic induction $B$ by the relation: $J = B - \mu_0 H$.

![Figure 4. Magnetic saturation curves of the SPs under strong magnetic field intensities.](image)

Figure 4. Magnetic saturation curves of the SPs under strong magnetic field intensities.

The coercivity $H_c$ and the remanence $B_r$ or $J_r$ were obtained from the hysteresis curves measured in low intensity fields range. These curves are shown in Figure 5. The SPs quickly cooled in water show less break energy and an enlargement of the hysteresis curve caused by the formation of martensite. The energy of rupture increases to the SPs slowly cooled down because there was the formation of more ductile phases, such as ferrite and pearlite.

![Figure 5. Hysteresis curves for SPs of the same chemical composition, but subject to different heat treatments. Wider hysteresis curves (red and blue) refer to the SPs quickly cooled in water.](image)

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The appearance of the rupture zone in SP 1 (cooled slowly) can be observed on Figure 6. The rupture is ductile with change of cross section. There wasn’t the complete separation of the parties. Figure 7 shows the most fragile rupture that happened to the SP 6, which was quickly cooled in water.
Figure 6. Fracture aspect of SP with greatest rupture energy (heat-treated with very slow cooling in oven).

Figure 7. Fracture aspect of SP with the lowest rupture energy (heat-treated with quick cooling).

Figure 8 shows the graph of impact rupture energy as a function of remanence, while Figure 9 shows the break energy in function of coercivity for all SPs tested. The SPs cooled slowly are plotted in red, while the ones cooled quickly are in blue, and the ones without any thermal treatment are in black.

Usually, the calibration process of Charpy equipment employs SPs for three different energy bands. In this work there were arbitrarily selected three energy values: low - 50 J, average - 120 J, high - 160 J. In spite to illustrate the procedure of a possible quality control system, three tolerance bands (± 3 %) were created around this mean value of energy. These bands are indicated by the horizontal lines in figure 8 and 9.

Figure 8. Rupture energy as a function of a magnetic property: remanence. The data were obtained from the hysteresis curves. Horizontal lines indicate the band tolerance (± 3 %) for the energies "high", "medium" and "low", while vertical lines show the tolerance ranges of remanence for acceptance of SPs on each band of energy.

Remanence and coercivity were the magnetic properties chosen as parameters to establish the criteria for acceptance of SPs due to major change values in these properties related to different heat treatments. The adopted criteria is composed by two rules: I) If the value of remanence is out of the remanence bands defined for each energy, then the SP is rejected; II) If the value of coercivity is out of the coercivity bands defined for each energy, then the SP is rejected. Graphically: Vertical dashed lines in the figures 8 and 9 show the tolerance ranges of magnetic properties for acceptance of the SPs in each energy level.
Note that only the criterion of coercivity is not sufficient to distinguish samples of high and medium energy, as most of the tested SPs present the coercivity between 200 A/m and 300 Am. The criterion of remanence expands this region of uncertainty, and allows to clearly exclude the SP 7 from the classification of medium energy. In terms of energy, if the tolerance band to the energy value was increased to 5 %, then SP 5 and the SP 3 could be included in the range of medium energy. This is a problem because SP 5 (martensitic), SP 3 (ferritic), and SPs 8, 9 (ferrite + pearlite) have completely different microstructures. The magnetic criteria allow differentiating the SPs by their microstructure. So, the narrower is the tolerance range, the more specific are the microstructures. This is an important issue because the microstructure can affect other properties of Charpy tests as the transition temperature between ductile and brittle rupture.

6. Conclusion
Magnetic characterization tests have great sensitivity, low cost, rapid implementation, and they do not require a previous preparation of the specimens. The magnetic measurements are very affected by the microstructure of the material, and a magnetic signature obtained under the same conditions can be used as a tool for quality control to ensure the results of Charpy impact tests. Although it was not observed significant variation in magnetic saturation in SPs subjected to different thermal treatments, the magnetic properties coercivity and remanence had great variation. Values bands for remanence and coercivity were adopted to set selection criteria to ensure that the specimen is broken at the specified energy. It should be noted that the smaller is the tolerance of the magnetic values, the higher is the rate of rejection of the SPs and the greater is the specificity of their microstructures. The results indicate the feasibility of quality control based on magnetic properties, but the magnetic characterization of a far greater number of SPs should be carried out to ensure the reliability of this method.

References
[1] ABNT NBR ISO 148-1:2013- Materiais metálicos — Ensaio de impacto por pêndulo Charpy
[2] BS EN ISO 148-3:2008 – Metallic materials – Charpy pendulum impact test.
[3] ABNT NBR ISO 148-2:2013- Materiais metálicos - Ensaio de impacto por pêndulo Charpy – Verificação de máquinas de ensaio.
[4] http://www.nist.gov/mml/acmd/structural_materials/charpy-verification-program.cfm
[5] ERM – European Reference Materials (http://www.erm-crm.org)
[6] M. F. F. Pereira, J. A. Paz Cruz, W. Link, L.C.C. Freitas, A. C. M. Garcia, “DEVELOPMENT AND MANUFACTURE OF CHARPY STANDARDS TEST SPECIMENS”, Proceedings of the 18th Imeko World Congress International, Rio de Janeiro, Brazil, September 2006.