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To cite this article: Habid Santiago Méndez *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **872** 012042

Experimental determination of resistance to penetration by dynamic action of a body made entirely of iron oxide and iron oxide and chip alloys

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Abstract. The present article arises from the study of the mechanical behavior of a body composed entirely of iron oxide and iron oxide and chip alloys through the experimental determination of resistance to impact by dynamic action through the application of loads of impact provided by a Charpy pendulum. The resistive evaluation will be useful for the development of new engineering materials, either to design structures or to design and manufacture machine parts. The study also evaluates the materials' level of absorption of impact energy, or their capacity to partially absorb the energy from the impact loads. Possible applications include the design of new materials for use in the automotive industry, for example for collision protection systems for vehicles, among others. The tested materials are derived from metallurgical processes that involve various stages of iron smelting, from melting and casting of the metal until obtaining the test specimens.

Keywords: Resistance, impact, iron oxide, impact energy.

1. Introduction

The study of the effects of impacts on bodies is of utmost importance for structure design, because impact loads are dynamic demands that, though infrequent, may produce catastrophic consequences [1]. Impacts on structures are short-lasting but highly intensive dynamic loads that have substantial effects of stability.

Over their life cycle, structures are often subject to dynamic or impact loads, which implies that the behavior or performance of the materials is of critical importance [2]. Additionally, certain atmospheric conditions accelerate oxidation or other corrosion processes that reduce the structure's resistance to dynamic or impact loads [3, 16]. Minerals and scrap metal are usually transformed by means of foundry processes into pure metals, which are subsequently used to manufacture structures or elements required by other industries [4]. In this field, progress has been made to obtain materials and alloys that produce substantial savings in raw materials because of their longer useful lives [5].

Standard foundry processes have been used to improve the quality and properties of materials used for structural applications. Given that safety is a top priority, it is necessary to improve the capacity of machine parts and structures to absorb impact energy, which implies a substantial modification of their mechanical properties [6]. For this reason, the purpose of this study is to analyze the mechanical performance of metal specimens made through smelting of iron oxide mixed with chips in different proportions, in order to assess their performance and capacity to absorb large impacts.

2. Methodology

The methodology of this study focuses on an assessment of the mechanical properties of materials derived from foundry processes (iron oxide derived from structures made of AISI 1020 steel and chips from manufacturing of structures of the same material), specifically evaluating any changes in chemical composition in terms of molecular structure, based on the understanding that certain materials may be combined with others, i.e. alloys are used to obtain a material based on the combination of two or more solid metal elements [4].

The materials were obtained by smelting prismatic materials of uniform cross-section made up entirely of iron oxide, and other compound materials with a percentage of iron oxide and a percentage of chips, i.e., one material that is 100% iron oxide, another that is 80% iron oxide and 20% chips, and lastly another material that is made of 50% iron oxide and 50% chips, which were obtained as mentioned above through metal foundry processes.

The foundry process involved the following stages:

1) Casting of metal.
2) Making the molds.
3) Molding process.
4) Unmolding by vibration.
5) Grinding of metal parts.
6) Cleaning the parts.

The foundry process was performed in the city of Barranquilla, and each process was performed simultaneously.

Figure 1. Casting of the metal test specimens. Source: Prepared by the authors.

Once the test specimens were obtained, they were submitted to load impacts using a Charpy pendulum, in order to assess and compare the mechanical characteristics of both materials. The impact tests were performed at the Materials Resistance Laboratory of Universidad de la Costa, using an impact machine. The material is expected to absorb the impact energy through deformation [7].

The MT3016 impact machine set up at the materials resistance laboratory consists of a robust and compact Charpy pendulum. The equipment is set up on a heavy and stable cast iron base with screw holes for affixing to the bench. The pendulum is mounted on ball bearings and is precisely balanced. It has a graduated scale in Joules and directly displays the energy required to fracture the test piece [8]. The Charpy pendulum (Figure 2) is a mechanically simple testing machine, but it allows designing several types of impact tests to didactically view the different factors that affect the mechanical behavior of materials, as in the case of the test specimens designed for this project.

The metal test specimens have a notch in the middle that acts as a concentrator of forces and induces failure of the material, in order to subsequently assess the type of material failure, providing in this manner a measurement of the material's resilience in a temperature-controlled environment. The test specimens are simply placed in the equipment's holders, and they are then tested in such a manner that the pendulum's impact originates on side of the test piece that has the notch. Afterwards, the pendulum is allowed to drop freely, and the energy absorbed by the material is recorded in Joules [9].

Figure 2. Charpy pendulum impact machine [10].

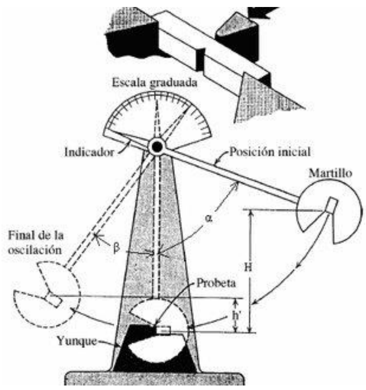


Figure 3. Charpy Pendulum. Oscillation before and after the impact [11].

Figure 4. Test specimens tested in the Charpy pendulum impact machine [10].

3. Theoretical Basis

The Charpy pendulum is a machine that is simple to operate from a mechanical perspective (Figure 2). Despite its simplicity, this instrument enables testing machine parts through impact tests that quickly show the influence certain factors have on the mechanical behavior of materials [7, 9].

The test is named after its French creator, Augustin Georges Albert Charpy (1865-1945). The equipment enables knowing the behavior of materials when they are subject to impact loads, based on a test specimen held in a simple holder. Mass M is affixed to the end of the pendulum of length L, and it is allowed to drop freely from height H. The energy absorbed (Ea) by the test specimen to produce its fracture is determined by the difference between the pendulum's potential energy before and after the impact [12].

For this test, an initial height of the pendulum H1 before impact and the final height H2 after the impact were determined based on the expressions (1) and (2) below.

$$H_1 = R * (1 + \mathrm{sen}(\alpha_1 - 90°)) \quad \text{(Ec. 1)}$$

$$H_2 = R * (1 - \cos(\alpha_2)) \quad \text{(Ec. 2)}$$

In expression (Ec. 1), R is the pendulum's arm, which is 39 cm long, and $\alpha_1$is the maximum angle of opening from which the pendulum is allowed to drop, which is a constant equal to 161°. In expression (Ec. 2), α_2 is the angle after the impact.

The total energy of the test (Et) in Joules is determined based on the values determined in H1 and H2, as calculated in the following expression (Ec. 3):

$$E_t = m * g * (H_1 - H_2) \quad \text{(Ec. 3)}$$

In expression (Ec. 3), m is the mass of the pendulum's hammer, which is given at 2.5 kg, and g is gravitational acceleration equal to 9.81 m/s2. The energy absorbed (Ea) is determined as the difference between total energy Et calculated in expression (Ec. 3) and friction energy Ef, which is the energy produced by the interaction between the machine's components [12].

Fracturing depends on whether the materials are ductile of brittle, and on their capacity to absorb energy during the test. However, it should be noted that in this study no quantitative criteria have been set to differentiate between ductile or brittle fracturing, but as a general approximation it is established that ductile behavior is characterized by greater capacity of the material to absorb energy compared to a more brittle behavior. According to expression (Ec. 3), two of the factors that have an effect of maximum test energy are the mass (m) and the length of the pendulum's arm. Consequently, the study's results are linked to the specifications of the equipment used, which has maximum capacity of 15 Joules.

Based on the tests performed, we also determine the impact energy Ei (Ec. 4) expressed in Joules, the speed of the load drop V (Ec. 5) in m/s, the force of impact Fi in Newtons (N) (Ec. 6) and the stress of impact τi (Ec. 7).

$$E_i = \frac{E_a}{s} \quad \text{(Ec. 4)}$$

$$V = \sqrt{2 * g * H_1} \quad \text{(Ec. 5)}$$

$$F_i = 2 * m * g \quad \text{(Ec. 6)}$$

$$\tau_i = \frac{F_i}{s} \quad \text{(Ec. 7)}$$

The Charpy impact tests are performed in accordance with standard ASTM-E23, which specifies test specimen sizes and results reporting.

During the design of machine parts, it is vitally important to understand the mechanical behavior of the materials the parts of structures are made, given that they will probably be subject to substantial stress and extreme service conditions. For this reason, impact tests are often made to search for brittle fractures, where temperature plays an important role, because high temperatures imply ductile materials of low mechanical resistance, whereas low temperatures imply a brittle behavior [13]. For the Charpy test of this study, the following variables that have substantial incidence on the results were defined:

- The speed of the applied load, which is controlled by changing the angle α_1.
- The presence of stress concentrators, which is achieved by placing a notch in the middle of the test specimen.
- Performance of the impact test on materials that have been subject to different temperatures.

Changes in temperature produce the transformation of materials from ductile to brittle as temperature decreases. As a result, several Charpy tests are performed at different test temperatures. "When a material is subject to a sudden and violent impact, in which deformation occurs very quickly, it may behave in a manner that is much more brittle than observed in other types of tests, for example stress tests, as in the case of many plastic materials: when they are stretched slowly, the polymer molecules have time to uncoil and the chains can slide against each other, enabling large plastic deformations" [14]. However, when an impact load is applied, these mechanisms do not have enough time to play a role in the deformation process, and the materials break in a brittle manner. Consequently, impact tests are often used to evaluate the brittleness of a material under such conditions. Unlike the stress test, in impact tests the unit deformation rates are much higher [14].

It should be noted that the test specimens that fail in a brittle manner break into two halves, whereas ductile and less brittle materials bend without breaking. This behavior depends largely on the temperature and chemical composition of the metals, which implies that tests must be performed at different temperatures in order to determine what is known as the "ductile-to-brittle transition temperature" [14].

IOP Conf. Series: Materials Science and Engineering **872** (2020) 012042 doi:10.1088/1757-899X/872/1/012042

4. Experimental procedure

Three test specimens were used for the Charpy pendulum impact tests: one fully made of iron oxide, another made of 80% iron oxide and 20% chips, and a third made of 50% iron oxide and 50% chips.

Initially, the dimensions of the test specimen were recorded along with the notch area. The empty pendulum was measured to determine the friction energy and the friction angle of the interaction between the equipment parts. Then the test specimen is simply placed in its holder and the hammer is lifted to its highest position, and left in place using a security lever. Then the lever is pulled to allow the pendulum to fall freely and produce the impact on the test specimen. Afterwards, all the data obtained from the test are recorded for each tested test specimen.

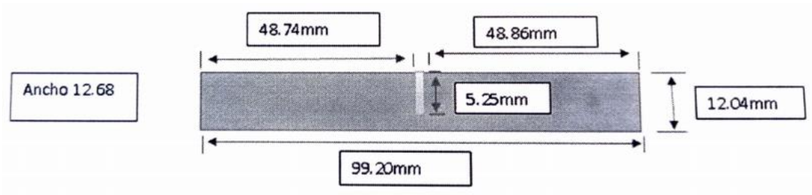


Figure 5. Dimensions of the test specimen bars used for the Charpy pendulum impact test [7].

5. Results

The following test results were obtained:

Table 1. Data obtained from the Charpy pendulum impact test results.

Material	Friction - Prior to impact		After impact		Pendulum arm R (m)	Pendulum hammer mass (kg)	α_1	α_2
	Energy (J)	Angle (°)	Energy (J)	Angle (°)				
100 % Rust	0,5	152°	14,9	11°	0,39	2,5	161°	11°
80% Rust - 20% chips	0,6	152°	14,7	4,5°	0,39	2,5	161°	4,5°
50% Rust - 50 % chips	0,5	152°	14,9	8°	0,39	2,5	161°	8°

Table 1 displays the test data for each tested specimen, including some of the specifications of the tester machine, such as the arm length (R), the mass of the hammer, the friction energy and angle, and the initial angle prior to impact. The data are displayed by type of test specimen, namely: 100% iron oxide, 80% rust and 20% chips, and 50% iron oxide and 50% chips. Afterwards, the results obtained from the mathematical models of the mechanical properties of the materials that underwent impact testing were recorded.

5.1 Stress concentrator

The notch on the test bars produced by a machining process generates a concentration of stress in that area of the material, and consequently the fracture of the test specimen begins where stress concentration is greatest. On the other hand, it should be noted that the notches placed in the material

IOP Conf. Series: Materials Science and Engineering **872** (2020) 012042 doi:10.1088/1757-899X/872/1/012042

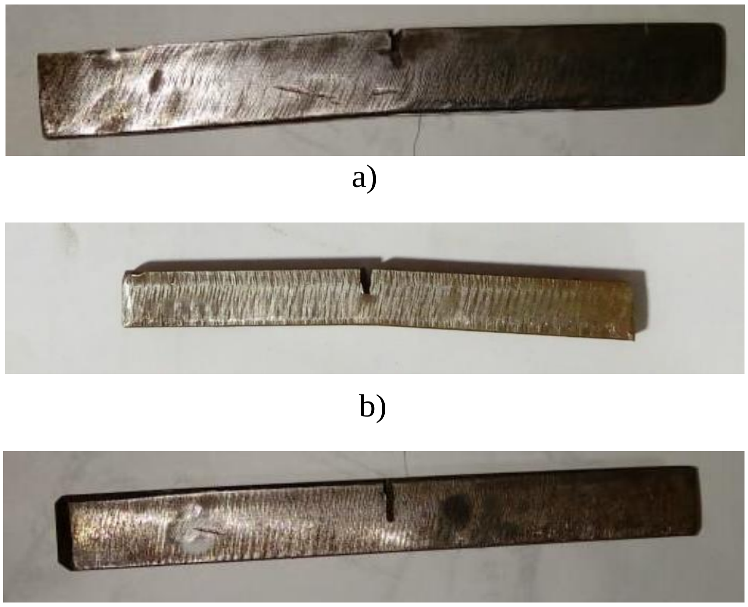
trigger a sharp percent increase in brittleness; similarly, the intensity of the force depends on the stress applied, as well as the geometry of the crack around the notch [15].

Table 2. Charpy pendulum impact test results for each tested material (a).

Material	Initial height	Initial angle	Final height	Total energy	Energy absorbed
	H_1(m)	Ángulo α_1(°)	H_2 (m)	E_t (J)	E_a (J)
100 % Rust	0,76	161°	0,0072	18,49	17,99
80% Rust - 20% chips	0,76	161°	0,0012	18,63	18,03
50% Rust - 50 % chips	0,76	161°	0,0038	18,57	18,07

Table 3. Charpy pendulum impact test results for each tested material (b).

Material	Energy absorbed	Cross section cut area	Impact energy	Impact speed	Force of impact	Impact effort
	E_a (J)	s (mm^2)	E_i (J/mm2)	V (m/s)	Fi (N)	τ_i (MPa)
100 % Rust	17,99	86,10	0,2089	3,86	49,05	0,57
80% Rust - 20% chips	18,03	86,10	0,2094	3,86	49,05	0,57
50% Rust - 50 % chips	18,07	86,10	0,2099	3,86	49,05	0,57



a)

b)

c)

Figure 6. The specimens tested using the Charpy pendulum impact test: a) 100% rust, b) 80% rust and 20% chips, c) 50% rust and 50% chips.

6. Conclusions

Based on the results obtained, we may firstly infer that based on the experience, testing with the Charpy pendulum is useful for the design of machine parts or structures by establishing the relationship between the internal structure of materials and their mechanical behavior when subject to impact loads, which involve grain size and the composition of the alloy.

It was also found that the three tested materials had similar mechanical behaviors when subject to impact demands, and that the test specimen made fully of iron oxide absorbed the least amount of energy compared to the specimen made of 80% rust and 20% chips; this may be influenced by the composition of the internal structure of the material, which is highly resistant because it is made of iron oxide, but it is also highly brittle. When compared to the other materials, it was found that those made of rust and chips were capable of absorbing a greater amount of energy and have a more ductile behavior, which implies that the chemical combination of the two substances changes the mechanical properties. This would suggest that such materials may be used for metal structures in collision safety systems in the case of the automotive industry. It should be noted that a full study of the materials would be required, including an assessment of production costs and the feasibility of mass production, as well as the availability of the required raw materials.

Additionally, knowledge of the mechanical behavior of these materials would suggest their usefulness for use in engineering, though taking into consideration the possible limitations of the tests, and consequently it would be advisable to combine them with others in order to obtain a more complete database.

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