THE STUDY OF FRAGILE DUCTILE TRANSITION IN METALLIC MATERIALS USING IMPACT TESTS

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ABSTRACT: The ductile/fragile character is a characteristic of materials that describes how they behave when subjected to external forces. A material is neither completely ductile nor brittle but follows a unique curve (the ductile-brittle transition curve) where the character of its deformation varies depending on the temperature. One method of checking the ductility of materials is the impact test. With the help of such a test, mechanical characteristics such as tenacity, resilience, elastic limit and yield limit, as well as hardness, ductility and ductile/brittle transition temperature can be checked. This transition temperature represents the limit temperature to which a material can be subjected to in order to preserve its mechanical properties.

KEYWORDS: fracture, temperature, impact, deformation, brittleness

1. Introduction

This paper aims to test the capabilities of an impact test developed in the 20th century and establish its relevance. We considered that the theoretical analysis would not provide the necessary details to support such an experiment, so we made a rudimentary test device with which to support the test in a more practical way. For economic reasons, the type of test we chose for analysis is the one inspired by Charpy's model [1]. The test consists of a body of high mass striking a sample of standardized sizes from the material under test. By calculating the energy absorbed by the sample during the impact and analyzing the fracture area, we can establish the type of fracture to which the material was subjected.

2. The test apparatus

The test device (hammer-pendulum, fig. 1) was constructed of rectangular metal profiles, made of construction steel S235J2. The exact dimensions of the frame do not have a major impact on the experiment, but we took into account the final length of the pendulum (from the axis of rotation to the point of impact). Then, the support table for the sample where the impact will happen was attached to the frame (fig. 2) and a metal chisel was mounted on the base of the pendulum that would act as the impact point. Finally, the entire construction was mounted on a rigid surface. The attachment of the parts was made by MAG welding (metal - active gas) and the stainless-steel rotation axis of the pendulum was provided with bearings to minimize frictional forces.

Fig. 1. 3D representation of the device

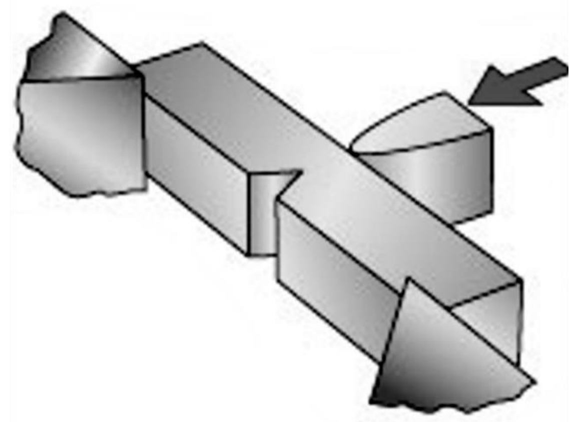

Fig. 2. The point of impact

Since the energy absorbed by the sample on impact is the first step in obtaining our results, the height and mass of the pendulum were chosen to maximize the impact energy and minimize costs. After an online study we found out that most of the metallic materials that we could subject to testing will absorb 200-300 J upon impact [3]. Starting from a reasonable length of 80 cm, the mass required to generate sufficient energy was calculated by the following method:

$$E_i = E_f \to E_p = E_c \to Mgh = E_c \quad (1)$$

$$h = l + l\cos\alpha\,;\ (\alpha = the\ angle\ with\ the\ vertical) \to h = l + l \to h = 2 \cdot l \quad (2)$$

$$E_c = M \cdot 9{,}81 \cdot (0{,}80 \cdot 2) \to E_c = M \cdot 15.69\,J \quad (3)$$

From the calculations it follows that any mass greater than or equal to 20 kilograms will develop the energy necessary to break. However, such a high mass could distort the entire test system. Wanting to use only the materials at our disposal and trying not to compromise the integrity of the instrument, we chose as a “high mass" element a hammer head with an exact mass of 4950g, creating together with the pendulum, a hammer with a total mass of 5200g.

$$E_c = M \cdot 15{,}69 \to E_c = 5{,}2 \cdot 15{,}69 \to E_c = 81{,}61\,J \quad (4)$$

However, the results we obtained at this point do not take into account frictional forces. Thus, in order to compensate them, we launched the pendulum without placing a sample (eliminating the energy variation at impact) and measured the total energy variation from the launch point (160cm) to the maximum point reached by the hammer. To calculate the final height, we first found out the angle that the pendulum makes with the vertical. This measurement was carried out by filming the pendulum with a camera with the "slow motion" function and by digitally measuring the angle with the help of a protractor type function (fig. 3).

$$\Delta E = Ef - Ei \to -L_c = E_{p_f} - E_{p_i} \to L_c = Mgh_i - Mgh_f \to L_c = Mg\left(h_i - h_f\right) \quad (5)$$

$$h_f = l + lcos\alpha; (\alpha = with\ the\ vertical) \to h_f = 80 + 80 \cdot \cos 1\,5° \to h_f = 157{,}27cm \quad (6)$$

$$L_c = 5{,}2 \cdot 9{,}81 \cdot (1{,}6 - 1{,}57) \to L_c = 1{,}39\,J \quad (7)$$

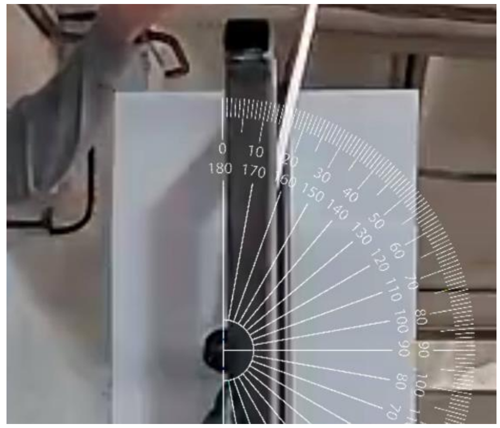

Fig. 3. Measuring the angles using the frames from the "slow motion" footage

Thus, the completed pendulum hammer develops over 80 J at the moment of impact (table 1). Although the obtained value is not close to the desired energy, we decided to conduct the experiment paying attention to this deficiency to see what kind of conclusions we can state.

Table 1. Characteristics of the test device

The mass of the pendulum	The length of the arm	The maximum angle before release	The maximum height before release	Total energy developed
5,2kg	80,0cm	180^0	160,0cm	>80,0 J

3. Tested materials

From the very beginning we noted the impossibility of testing samples made out of construction steel S235J2, the most common steel on the market, due to its property of resisting impact, including at temperatures below 0^0C. So, without the possibility of lowering drastically the temperature of the metal, making the transition curve for construction steel was not easy. However, analyzing the characteristics of the alloy, we managed to draw conclusions regarding possible materials with which we can verify this method of impact testing.

From the chemical composition of S235J2 steel [2] (table 2), two primary elements attract attention: the low carbon concentration (0.17%) and the high manganese content (1.40%).

Table 2. Composition of construction steel, S235J2

C	Mn	P	S	Cu
0,17%	1,40%	0,030%	0,030%	0,55%

Knowing that the tendency of ferrous alloys is to increase their hardness with increasing carbon concentration (fig. 4), the next step was to find a metal alloy with at least a medium carbon content (0.30 < % < 0.50). As for the manganese concentration, a brief online overview showed that a high manganese content "moves" the ductile-brittle transition temperature towards negative degrees (fig. 5). This feature gives our construction steel its high impact resistance, property caused by ductility.

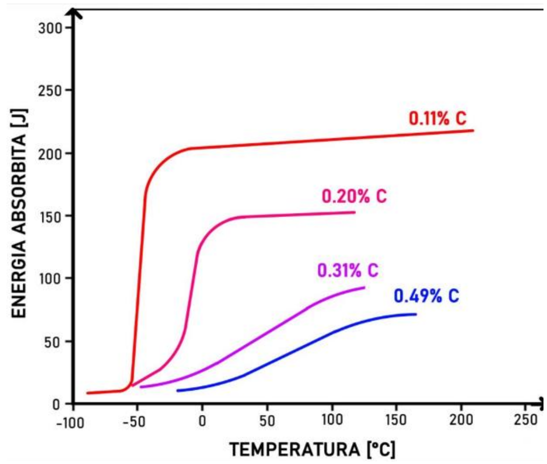

Fig. 4. Transition curve after %C [3]

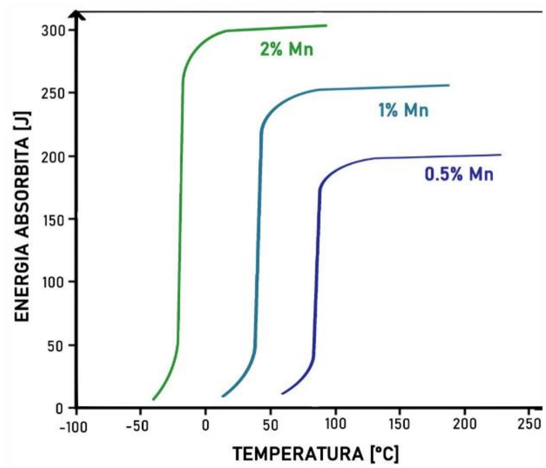

Fig. 5. Transition curve after % Mn [3]

Summing up what we learned, we concluded that the material we will test must have the following properties: medium to high carbon content, low manganese content, high hardness at room temperature (since heating the metal to reach the ductile character was not a problem).

The material we decided to test is a quality 10.9 steel [4] (according to the Romanian standard: SR EN ISO 898-1) with a high hardness and a medium carbon content (table 3). A problem arose when we discovered that the alloy is only used for screws and threaded rods. Trying to minimize the processing time and the amount of wasted material, we chose to work with DIN 933 screws (with thread up to the head) (fig. 6) to use the entire body of the screw.

Table 3. Composition of quality steel 10.9 [4]

C	P	S	B
0.40%	0.025%	0.025%	0.003%

The new sample will have to be adapted to the helical shape of the screw. After trying several variants, we decided on a final sample that is easy to process, to minimize the possibility of errors between different samples. The final shape involves removing the screw head (to obtain a 6cm threaded bar), cutting the thread on two opposite sides (to create a straight surface in contact with the pendulum and the support pillars) and making a cut centered on one of the flattened faces (like Charpy's model with a "V" cut, but with a "U" cut) (fig. 7).

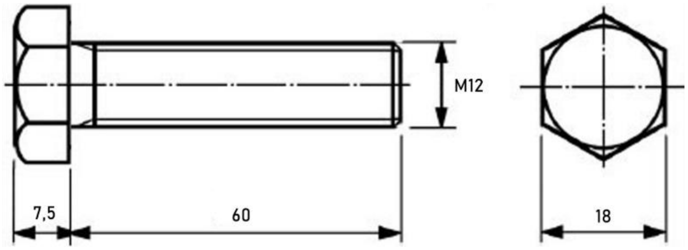

Fig. 6. Screw

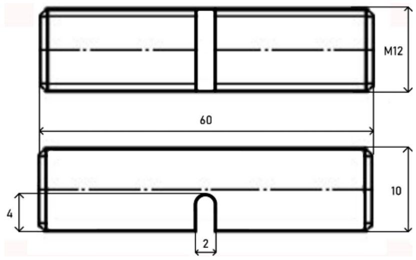

Fig. 7. Sample.

4. Testing

The testing of the samples takes place in the same way as the determination of the frictional forces in the system (this time with the sample positioned at the 0^0 point of the pendulum). The temperature of the metal sample is measured immediately before the hammer is launched. The pendulum is launched under the action of gravity and fractures the metal. Depending on the height to which the hammer-pendulum rises after the impact, the energy absorbed by the tested metal is calculated. After 3 tests at similar temperatures, the results are averaged and entered in a table to be represented later in a graph E[J](T[^{0}C]) (Energy absorbed/Temperature) (fig. 8). Each fractured sample is analyzed visually. Depending on the appearance of the fracture surface, we draw conclusions on the type of fracture (ductile/brittle).

Table 4. Test results

Test number	Temperature	Final angle	Final height	Absorbed Energy	Fracture type
1.	14^0C	82^0	69,41cm	46,21 J	fragile
2.	22^0C	79^0	65,06cm	48,43 J	fragile
3.	220^0C	70^0	52,85cm	54,66 J	fragile
4.	229^0C	81^0	66,87cm	47,51 J	fragile
5.	405^0C	77^0	62,45cm	49,76 J	fragile
6.	428^0C	68^0	50,03cm	56,10 J	fragile
7.	510^0C	43^0	21,88cm	70,46 J	fragile
8.	603^0C	No fracture	-	> 80 J	ductile
9.	652^0C	No fracture	-	> 80 J	ductile
10.	$>800^0$C	No fracture	-	> 80 J	ductile

As the sample heats up, the energy absorbed at impact increases. Given the nature of the material, after the temperature of ~600^0C the fracture with the help of the constructed system proved impossible. However, this impossibility does not in any way compromise the success of the experiment since the samples that were not fractured show severe plastic deformations, and the analysis of the deformation surfaces provides us with all the necessary information for our experiment.

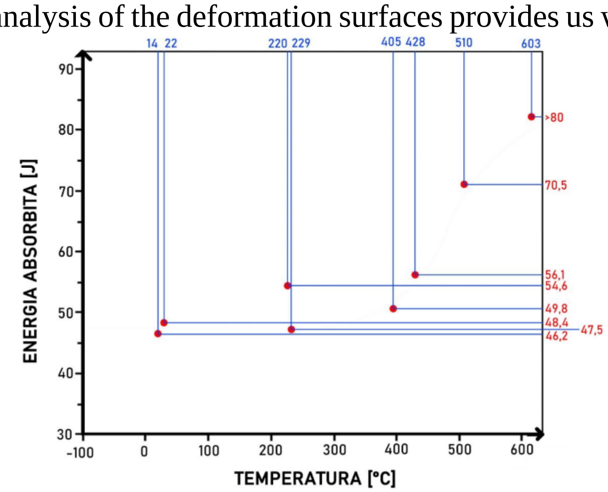

Fig. 8. Points generated by tests

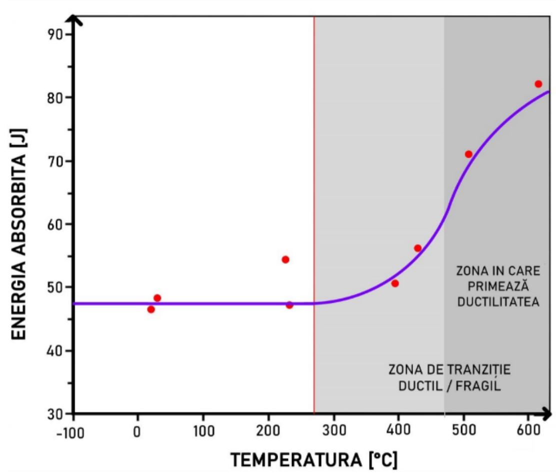

Fig. 9. Illustration of the transition curve

The point generated at the temperature of 220^0C does not follow the usual trend of the curve that we are analyzing, so we chose to ignore it in creating the curve (fig. 9). Following the trend of the graph as a function of temperature, we state that after the temperature of ~300^0C, the material starts to "soften", becoming more malleable (ductile). At temperatures higher than 450^0C-500^0C we can consider the steel to be ductile.

5. Conclusions

Although we failed to generate the desired energy for fracturing the samples, capping at 80 J, we accidentally developed enough breaking power to support our tests. Given the fact that not all the samples were completely fractured, by analyzing the only deformed surface (in the case of ductile samples), we managed to draw the necessary conclusions to state the following:

1. Standardization of the test for finding the ductile/brittle transition curve is not necessary.
2. Through the test in question, it is possible to determine the ductile or brittle nature of tough materials.
3. The analysis of the deformation surfaces is sufficient to characterize the samples (which have resisted the impact).

The Charpy impact test (or the "V" cut impact test), developed at the beginning of the 20th century, is even today the best-known impact test. Due to the simplicity with which it is supported and the low costs, the probability of developing such a test that offers better or cheaper results is small. Summing up the above, the Charpy impact test and its derivatives maintain their level of applicability even today.

6. Bibliography

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7. Notations

E_i = initial energy
E_f = final energy
E_c = kinetic energy
E_p = potential energy
M = mass of the pendulum
g = gravitational acceleration
h = height
l = length of the pendulum arm
ΔE = energy variation
L_c = mechanical work consumed