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IMPACT RESISTANCE OF QUENCHED 1045 STEEL PINS FOR QUICK STOP DEVICE APPLIED IN TURNING OPERATIONS

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Abstract. *The main variables of the machining process depend on the chip formation process and therefore, the tribological conditions of the chip-tool interface. To study the phenomena involved, a quick-stop device is used, for instantly interrupting the cut by applying a sudden impact on a swiveled toolholder. The toolholder is supported by a fusible pin, made of a brittle material that is rigid enough to withstand the machining force, but breaks easily under the impact of the quick-stop. This work consists of studying the brittleness of SAE 1045 steel pins through impact tests (Izod-type) on quenched and tempered samples, in addition to the correlation of data generated by the spring brake. The bars used as fusible pins were quenched, after heated in a muffle furnace, under different conditions of temperature, time and cooling method. The results showed that the way to produce pins with the most suitable properties for their application is through quenching at 900 °C for 60 minutes and water cooling. In this way, it is possible to optimize the use of this equipment, as by producing pins with the most appropriate properties, problems with activating the quick-stop during turning tests are avoided.*

Keywords: *turning, quick-stop, impact test, 1045 steel, impact resistance.*

1. INTRODUCTION

The material is removed from the surface of the part during machining in the form of chips, which is the final by-product present in all cutting operations, and can vary (in type, shape and extent) between machining processes or in the same process altered according to the cutting conditions. It can be said that the chip formation is influenced by the tool geometry (rake angle, relief angle, edge inclination angle and tool nose radius), workpiece material (yield strength, hardness, toughness and ductility), cutting fluid (type and method of application), tool material (hardness, wear resistance and toughness), cutting conditions (feed rate, depth of cut and cutting speed), chipbreaker (dummy or integral) and machine-tool (static and dynamic characteristics) (Ferraresi, 1977).

The study of the chip-tool interface is a great challenge, since it is not possible to directly evaluate the chip-tool interface during the cutting process, since the chip exit speeds are very high, the chip-tool interface has a small area of contact and is subjected to very high pressures in the secondary shear zone (Chern, 2005). To carry out a study of the chip (adherence zones, curvature, etc.) it is necessary to evaluate its interface with the tool at the exact moment of the cut. If a cut is interrupted in the traditional way, with a progressive deceleration, as the speed drops, the chip shapes itself to the respective cutting speed, in which the characteristics differ from those prevailing during the cutting process. Therefore, the last chip formed will not be useful as an object of study. So, to solve this issue, machining research uses a device capable of instantly interrupting the cut. This device is known as quick-stop, which applies a sudden impact on the tool holder, forcing it downwards at a speed higher than the cutting speed, so that the remaining chip root keeps the characteristics of the cutting process performed at the real cutting speed of the process investigated.

Thus, the intent of the quick-stop method is to “freeze” the cut during machining to obtain more detailed information about the structure of the deformed material at the chip root. Thus, theoretical analyses, together with direct observations of the deformed microstructure contribute directly to the understanding of the chip formation mechanism. In quick-stop devices, the cutting tool is retracted at a speed greater than the cutting speed (two to three times greater), leaving the root of the chip in conditions for detailed analysis by means of microscopy. Basically, these devices have the function of establishing the cutting operation with the tool support resting on a hardened steel pin. This pin has enough stiffness to withstand shear forces but has low impact toughness to fracture without deformation. When chip formation is taking place, due to the action of a sudden external action/load (which can be delivered manually or by a pneumatic device, by the action of a spring or even by a gunpowder-based projectile), the pin breaks and the tool is pulled away from the workpiece at high speed, almost instantly.

The mechanical properties of a steel are directly linked to its microstructure, which influences hardness, ductility, mechanical strength and toughness. The various possible applications for a steel require different combinations of characteristics, which are possible to be obtained through heat treatments such as quenching, in which the steel heated above the austenitizing temperature is rapidly cooled, so that the carbon trapped in the structure Austenitic CFC does not have time to diffuse and form cementite, so it is trapped in the crystal lattice, distorting it. The resulting microstructure is called martensite, a metastable phase supersaturated with carbon, which, due to its transformation by shear, modifies the crystalline lattice, generating internal stresses that hinder the propagation of dislocations and deformation of the material (Callister, 2008). Thus, due to its low deformation capacity, it has greater hardness, but with low toughness, making this treatment ideal to produce quick-stop fuse pins.

The characteristics of quenched parts vary according to the heat transfer rate between the part and the cooling method applied in the treatment. The most used quenching media are water, oil, brine and, more recently, polymeric solutions. The quenching and heating process of steels is directly related to the heat flux density. Several factors influence the hardening mechanism of the heat-treated metal. Conditions internal to the sample affect the diffusion of heat and the surface of the sample and other external conditions can affect the heat extraction potential of the fluid, such as: agitation, pressure and working temperature of the fluids. The severity of the heat treatment refers to the ability of the fluid to extract heat from the heated steel. The greater the severity of the method, the greater the distortion of the part. There are quantitative representations of severity that assume a constant heat transfer coefficient throughout the cooling process, which is often not true. When quenching media such as oil and water are used, for example, vaporization of the solution occurs, modifying the steel cooling rate. A steam bubble is formed that impedes the natural heat flow; therefore, the heat transfer coefficient will be different at that moment, resulting in heterogeneity in the heat extraction (Da Silva Junior et al., 2016). Some references (GGD Metals, 2023) suggest that for 1045 steels, quenching should be done by austenitizing at a temperature between 820 – 850 °C for 1 hour for every 25 mm of thickness of the part. Quenching can be in water or polymer, although oil can also be used for sections smaller than 10mm if quenched from 840 – 860°C.

This work consists of studying the brittleness of hardened SAE 1045 steel pins through impact tests. These pins are an essential part for the operation of the quick-stop device, so their brittleness must be adjusted according to the materials to be machined. This property can be evaluated through the Izod-type impact test, in which the sample is set in a vertical position and hit by a free pendulum, measuring the energy required for the part to fracture. For this, the influence of the main quenching variables on the brittleness of the part must be understood, to choose the ideal quenching condition to achieve the breakage of the pin during the tests.

2. METHODOLOGY

The *Laboratório de Ensino e Pesquisa em Usinagem* (LEPU), or in English Laboratory for Education and Research in Machining, at the Federal University of Uberlândia has already carried out several studies with quick-stop devices, with the pneumatic version being the most used. In this case, an air chamber of a truck brake is used, and activated by opening a compressed air valve, which quickly displaces the bowl piston and causes a quick and strong impact on the tool support, which remains supported on a fusible pin, as shown in blue in the CAD drawings of Figure 1(a). Figure 1(b) shows photos of the real equipment mounted on the lathe.

To evaluate the most appropriate heat treatment to adjust the impact resistance of the fusible pins, samples with the same geometry as the bar used as a fusible pin of quick-stop device were produced. The cylindrical pieces of AISI 1045 steel were prepared by turning to the final dimensions shown in Figure 2, checking them with an analog caliper with a resolution of 0.1 mm and a measurement range from 0 to 150 mm, considering a deviation of up to 0.5 mm to be acceptable in its diameter. Then, the quenching process was carried out following an experimental design of the complete factorial type in 2 levels and 3 variables, according to Table 1, to evaluate the influence of temperature and heat treatment time, in addition to the cooling method. The output variable was the impact energy absorbed by the samples. At least 3 samples for each quenching condition were produced and tested.

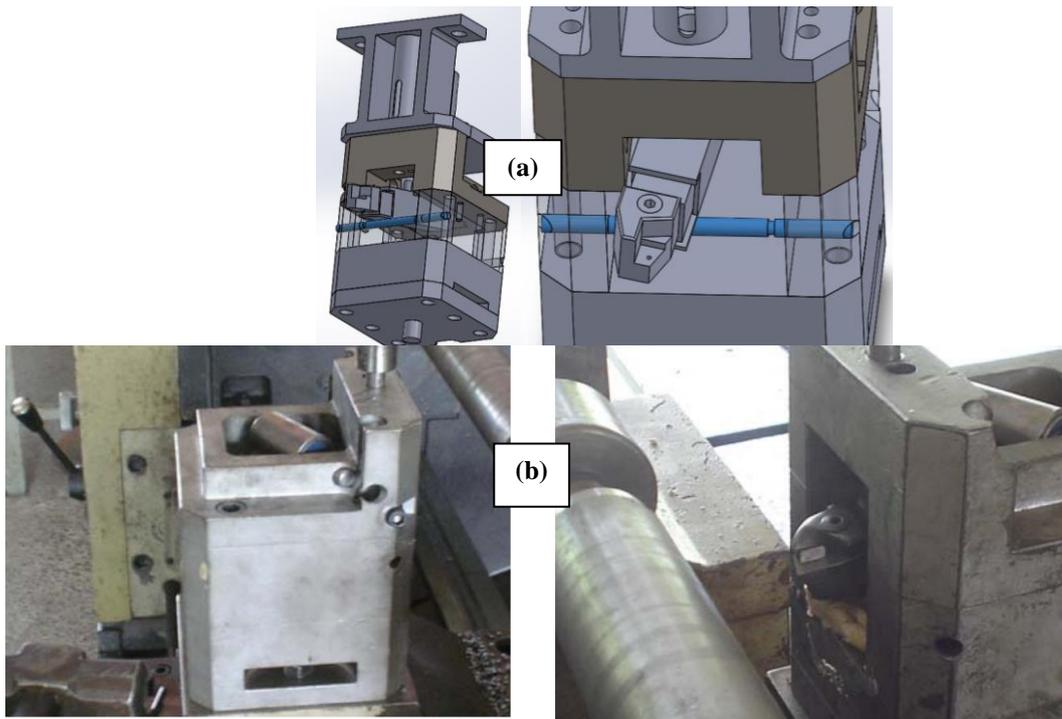


Figure 1. CAD drawing (a, b) and photos (c, d) of the pneumatic quick-stop used in the LEPU. Adapted from Luiz (2007).

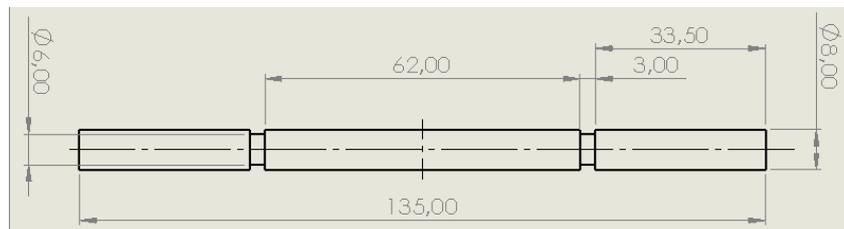


Figure 2. Dimensions of the turned samples, in millimeters.

Table 1. 2^3 full factorial experimental design, indicating the quenching conditions of the pins.

Quenching Condition	Temperature (°C)	Time (min)	Cooling Method
A	800	20	oil
B	800	20	water
C	800	60	oil
D	800	60	water
E	900	20	oil
F	900	20	water
G	900	60	oil
H	900	60	water

During heat treatment, the oven temperature was recorded using a K-type thermocouple sensor, with one end inside the oven next to the samples, and the other end attached to an Arduino and MAX31855 module, for signal amplification and data transmission, as in the work by Campos et al (2020). The acquisition was performed at a rate of 0.2 Hz, through the Serial USB Terminal 1.46 application on a smartphone connected to the Arduino system via USB. The acquisition system used can be seen in Figures 3(b) and 3(c), together with the sensor and microcontroller connection scheme, in Figure 3(a).

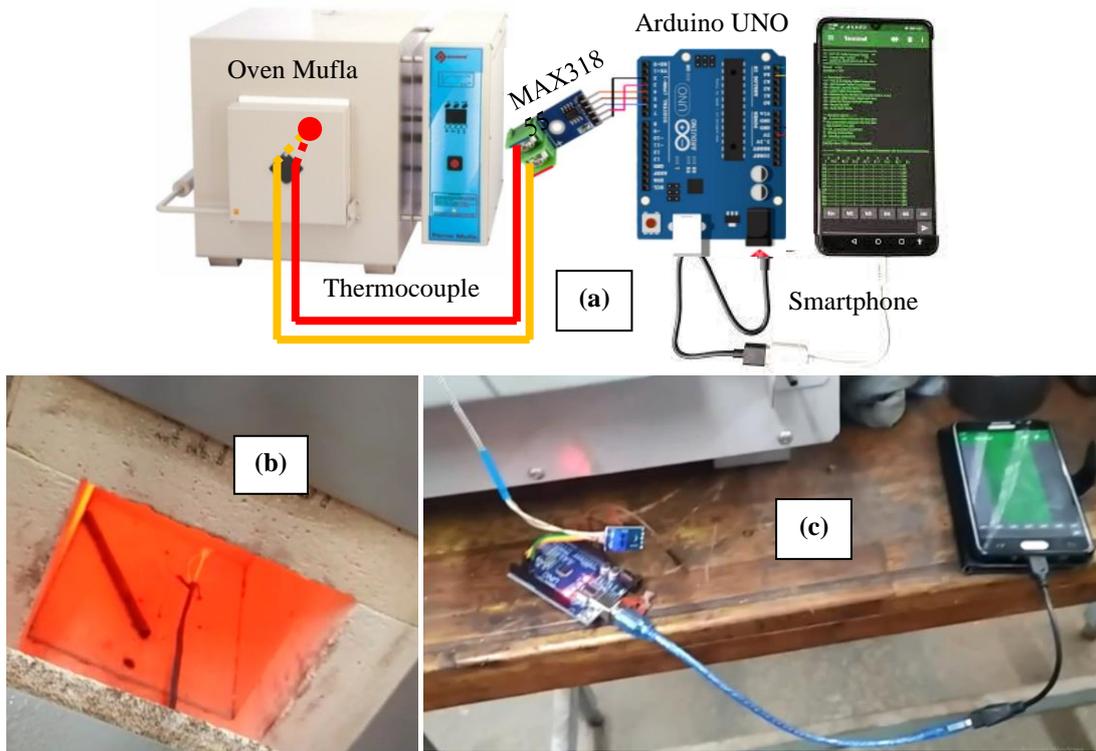


Figure 3. Schematization (a) and photos (b and c) of temperature measurement and acquisition system based on Arduino UNO connected to smartphone, with MAX31855 module and thermocouple measuring temperature in muffle furnace. (b) represents only one thermocouple terminal next to one pin, but during the tests several pins were simultaneously quenched.

The temperature curves of the tests can be seen in Figure 4. Only two quenching operations were carried out in the furnace: the first one with all the samples from conditions A and D (800 °C) and the second with all the samples from conditions E to F (900 °C). It is even possible to observe in the temperature graph the moments in which the samples are removed from the furnace, as there are significant drops in the temperature of the thermocouple when opening the door of the muffle furnace. To facilitate handling, each group of quick-stop pins of the same quenching condition was tied with wire, forming a bunch. Right after heating, the cluster of samples was collected with a long hook and quickly immersed in the cooling media, allowing the samples to rest for a few minutes until they cooled completely. Tap water and engine oil (used) were used for quenching.

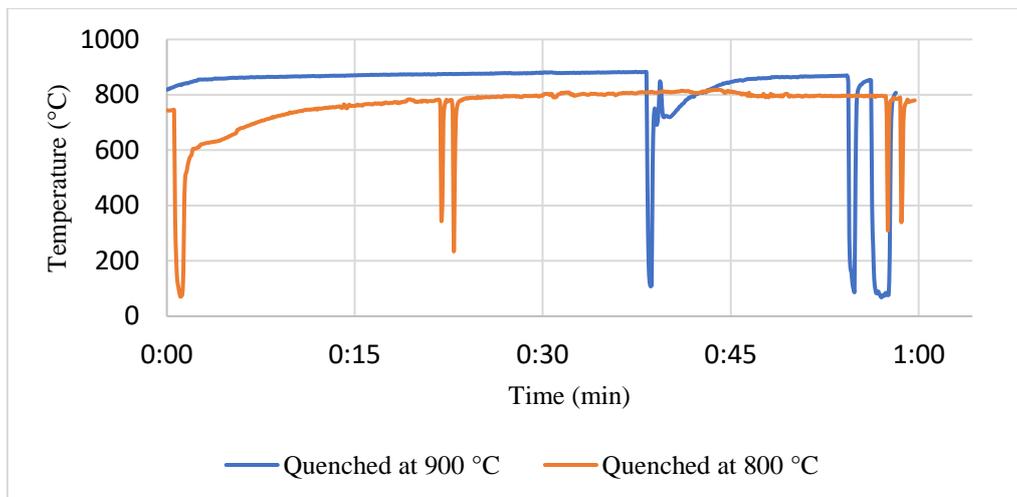


Figure 4. Furnace temperature curves during austenitization of 1045 steel pins.

The impact tests were carried out following the general recommendations of the ASTM E23 (2018) standard, for Izod-type tests, with the sample in a vertical position, set at the bottom. It is noteworthy that the dimensions of the specimen adopted are different from those recommended by the standard, which does not prevent the tests from being carried out, since the standard allows modification according to the characteristics of the material to be tested (item 8.1.2). In this case, the recesses of the pins were used as a stress concentrator, simulating the condition that the piece will be submitted to at the moment of impact applied by the pneumatic propelled quick-stop.

The equipment used can be seen in Figure 5 and has a system for measuring the maximum angle reached by the pendulum after impacting the sample, with a resolution of 0.5°. In this way, the resistance of the sample to impact is given by the energy removed from the pendulum after the impact, which can be measured by applying the principle of conservation of mechanical energy to verify the difference in the height reached by the pendulum. Thus, the calculation of the absorbed energy E (J) is done by the difference in potential energy of the pendulum, according to Eq. (1), in which M is the total mass of the pendulum (kg), g is gravity (m/s^2), and h is the difference between the maximum height of the pendulum (releasing the pendulum free, without a sample in the equipment) and the height reached after impact on each sample (m). The value of h is calculated according to the angle indicated by the equipment, based on the geometric relationship in Eq. (2).

$$\mathbf{m \cdot g \cdot h = E}, \quad (1)$$

where \mathbf{m} , \mathbf{g} , \mathbf{h} and \mathbf{E} are the mass (kg), gravity (m/s^2), height (m) and Energy (J), respectively.

$$\mathbf{L \cdot \sin \theta = h}, \quad (1)$$

where \mathbf{L} , $\mathbf{\theta}$ and \mathbf{h} are the length (m), angle (°) and height (m), respectively.

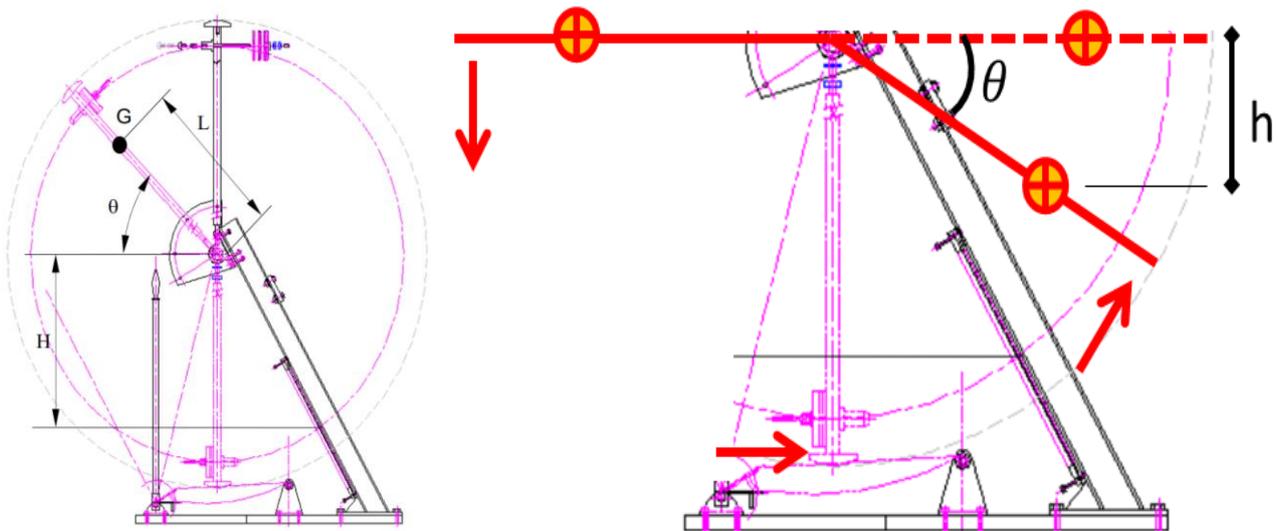


Figure 5. Schematic drawing of the impact testing machine with the pendulum center of gravity G , at a distance L from the center of rotation, in different initial release positions. After impact, the pendulum will rise to less than its initial release height, due to the energy absorbed by the sample fracture. Adapted from Tsuruta (2015).

As indicated by the standard, E corresponds to the energy consumed in breaking the sample and in its acceleration. In this way, graph paper was used together with a smartphone slow motion camera to measure the speed with which the fractured piece of the sample is thrown forward. Thus, the corrected absorbed energy E_c was calculated, which in turn is used to calculate the impact energy E_I by dividing the value by the cross-sectional area of the sample of radius R at the fracture point, as indicated in Eq. (3), finally obtaining the value in J/mm^2 .

$$\mathbf{E_c / (\pi \cdot R^2) = E_I}, \quad (3)$$

where $\mathbf{E_c}$, \mathbf{R} and $\mathbf{E_I}$ are the corrected energy (J), radius (mm) and Impact Energy (J/mm^2), respectively.

The values obtained for E_I were submitted to analysis of variance to verify the effects of the variable's temperature, time and cooling method on the brittleness of the bars used as a quick-stop fuseable pins. The Statistica 12 Software was used to calculate the significance level and Pareto chart with 95% of reliability index.

3. RESULTS AND ANALYSIS

The images of the samples impacted by the pendulum in the Izod test can be seen in Figure 6, where the quenching conditions A, C and E, all cooled in oil, did not brittle the sample enough for it to break. In these cases, the part absorbed all the energy of the pendulum without breaking, which is equivalent to approximately 24.28 J, considering that the pendulum has $M = 5.81$ Kg and $L = 0.471$ m. In the other conditions, however, all the tested samples ruptured (including condition G, the only one cooled by oil that ruptured), with fractures that have a brittle behavior, as can be seen by the shiny appearance of the fracture surface, contrary to the dull appearance typical of ductile fractures (Callister, 2008).

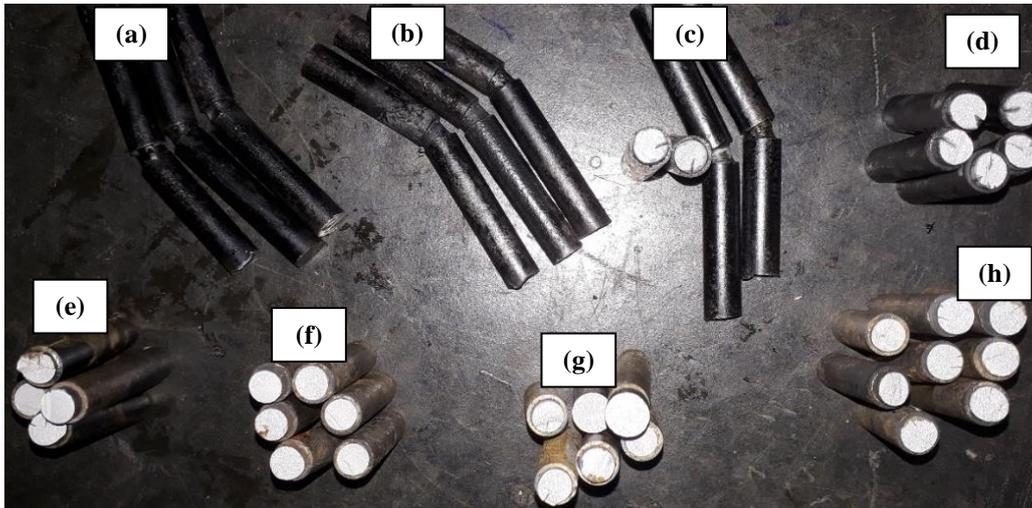


Figure 6. Aspect of the fracture for the tested samples.

The analysis of the graph in Figure 7 corroborates the observation that quenching in oil, although common for steel parts (Chiaverini, 2003), is not suitable for quick-stop pins, as in this condition the quenching is not severe enough to allow the brittle fracture of the piece when impacted by the quick-stop propeller. It is also observed that conditions D, E and F have a high standard deviation, which indicates a large variation in the properties of the materials tested. It is possible that this effect is caused by a large variability in the metallurgical conditions of the material before quenching. The pins with 135 mm of length were cut from 12 m long bars, and it is likely that both the content of alloying elements (such as Si, Mn and C) and the average grain size may vary between bars, explaining such behavior.

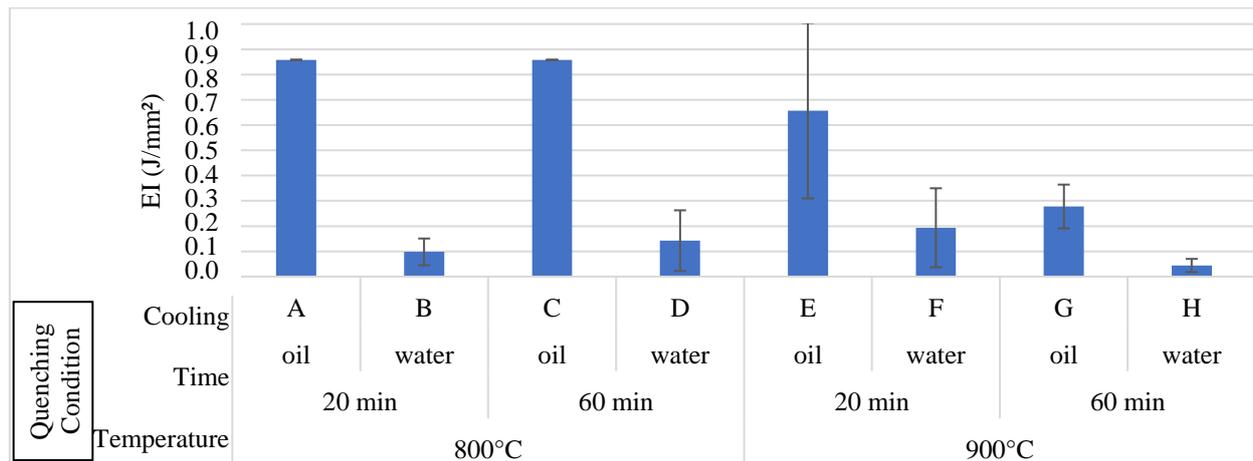


Figure 7. Impact energy (EI) absorbed by the samples in the Izod tests, according to the quenching condition. Error bars represent the standard deviations observed in the tests.

The result of the analysis of variance can be seen in Figure 8, which shows the significance level for the three evaluated variables and their combined effects. Along with the Pareto chart in Figure 9, these data indicate that the most important factor for quenching was the cooling method (3), followed by the heating temperature (1) and the combined effects between (1) and (3), and (1) and (2), while quenching time (2) and the combined effect of (2) with (3) were the only non-statistically significant factors for a 95% confidence level, as they presented p-value greater than 0.05.

ANOVA; Var.:EI (J/mm²); R-sqr=.8744; Adj.:.83007 (data 2**(3-0) design; MS Residual=.0208658
DV: EI (J/mm²)

Factor	SS	df	MS	F	p
(1) Temperature	0,230814	1	0,230814	11,06185	0,004000
(2) Time	0,088143	1	0,088143	4,22427	0,055547
(3) Cooling	1,771630	1	1,771630	84,90602	0,000000
1 by 2	0,123423	1	0,123423	5,91507	0,026355
1 by 3	0,227092	1	0,227092	10,88347	0,004239
2 by 3	0,028367	1	0,028367	1,35949	0,259724
Error	0,354718	17	0,020866		
Total SS	2,824186	23			

Figure 8. Analysis of variance with significance level for the effect on the EI of quenching variables and their combinations.

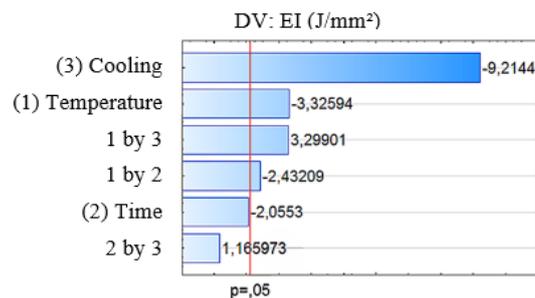


Figure 9. Pareto chart indicating the most important factors for material quenching, considering the sample's impact energy.

As explained by Chiaverini (2003), the most important factor for obtaining the most brittle martensitic structure during quenching is the cooling time in the TTT curve, as can be seen in the graph of Figure 10. Thus, due to the higher convection coefficients and specific heat of water (300-6000 W/m² K, 1 Kcal/g°C) in relation to oil (60-1800 W/m².K, 0.4 Kcal/g°C), water leads to a much faster cooling of the samples, causing the material to remain mostly in the martensitic transformation region of the graph (Dassault Systemes, 2023). Oil, on the other hand, due to slow cooling, shifts the curve to the right and results in a less brittle structure, which has less martensite and more pearlite.

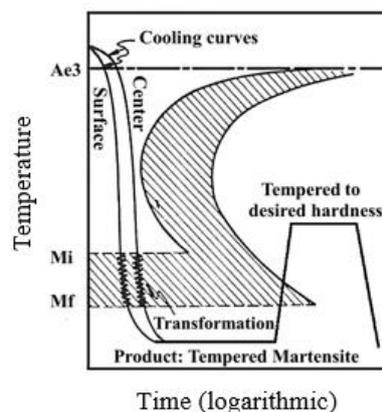


Figure 10. Example of TTT curve for carbon steels. Adapted from Oliveira and Denti (2007).

In the case of temperature, quenching depends on the dissolution of carbon in the crystalline structure, and this phenomenon is facilitated when the material is in the form of austenite, which occurs above approximately 787°C for 1045 steel (Callister, 2008). Thus, at 900 °C carbon diffusion is greater, and provides a greater amount of martensite after quenching, as shown in the graph of averages in Figure 11. Although time is also an important factor for carbon diffusion, with greater brittleness for longer quenching, as seen in Figure 11, this factor was not statistically significant. It is likely that although the longer times favors the formation of martensite, due to the reduced size of the samples, the two conditions (two times) are sufficient to obtain good temperature homogenization in the pins and sufficient carbon diffusion to weaken the pieces. The rapid cooling rate of the water makes this media much more efficient for brittle the pins than oil (Fig. 11).

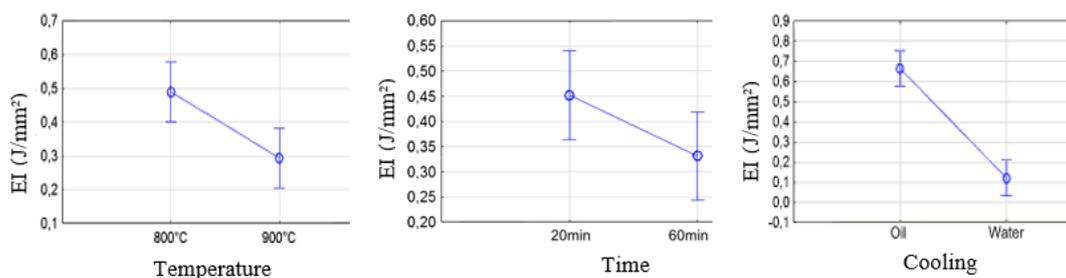


Figure 11. Tendency plots of the average impact energies when changing the quenching variables of the samples.

4. CONCLUSIONS

In this work, the following conclusions were highlighted:

- Cooling method had the most significant effect on the impact energy of the bars. Oil quenching are very low in severity, leading to crystalline structures that do not always fracture under impact and are therefore unsuitable to produce quick-stop pins.
- The oven temperature for austenitization had a significant effect, with higher values favoring the diffusion of carbon in the crystalline structure and producing more brittle pins, being more suitable for use in the quick-stop.
- Longer quenching times caused a greater reduction of impact energy on average, however, not statistically significant, probably because the two levels used produce sufficient diffusion of carbon in the structure for the generation of martensite in rapid cooling.
- The most suitable quenching condition to produce pins was H, with the pieces for 60 min in an oven at 900 °C and cooling in water. In this case, in addition to obtaining the lowest impact energy, there was also a lower standard deviation, generating better uniformity of the fusible pins.

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