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Stiffness and vibration damping capacity of high strength cast irons

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TUPY/UDESC

Abstract

The trend to lightweight design of automotive engines has led to the development of new cast iron grades for cylinder blocks, with very high fatigue properties, resulting in engines in some cases even lighter than engines with cylinder blocks of aluminum. On the other hand, the selection of cast irons grades with high values of mechanical strength and high elastic modulus, for projects of thin-wall engine blocks, may result in decrease in vibration damping capacity, even still far superior to aluminum cylinder blocks. This paper deals with damping capacity and elastic modulus of high strength cast irons, considering how the microstructure affects these properties and how to optimize them.

Introduction

The automotive industry has made continuous improvements aimed at reducing the consumption of fuel, with results as shown in Figure 1, for passenger cars and light trucks in USA. The fuel consumption was reduced by about 50 % for passenger cars between 1980 and 2014. For light trucks the reduction was smaller, about 30 %, but it is still worthy of emphasis.

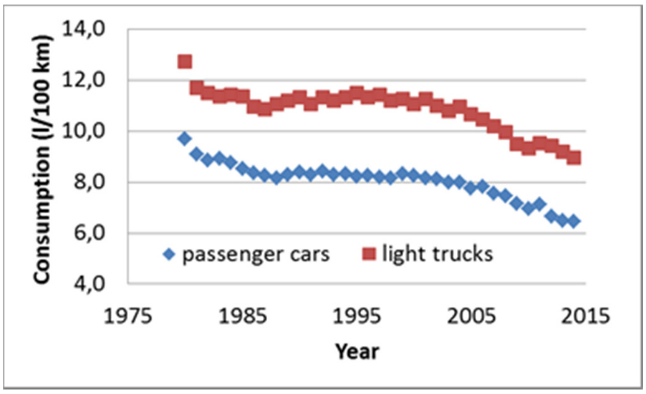


Figure 1 – Fuel economy performance of passenger cars and light trucks in USA. NHTSA (1).

Among the various technologies which allow this result, a decrease in vehicle weight was an important factor. In particular, the use of higher strength materials had significant contribution to various vehicle components. In the engine, the use of high strength cast iron grades, such as gray iron grade 300 (UTS min = 300 MPa) and compacted graphite iron grade 450 (UTS min = 450 MPa), has been a very important tool for engine designs of lower weight and higher specific output (2).
Apart from the fatigue strength, a very important property for engine blocks is the elastic modulus. This property measures the stiffness of the material, which will maintain the shape of the cylinders during engine operation (3). Thus, oil consumption and emissions are affected by elastic modulus of the material used for the construction of engine blocks. Lower bore distortion allows for reduced ring tension and thus reduced friction losses (4). On the other hand, increasing the elastic modulus normally results in decreasing damping capacity, another very important parameter for automotive parts. So, in the present study both properties, elastic modulus and damping capacity are measured, in cast irons with different microstructures.

Experimental procedures

The tests were conducted with two ductile irons (grades 450 and 700), two compacted graphite irons (grades 450 and 500) and seven gray irons (grades 250 and 300), as shown in Table 1. Samples of ductile iron and CGI were casted into 25 mm Y block and gray irons were molded into standard bar of 30 mm diameter. For measuring the physical properties, it was used resonant frequency test. Hence, CGI resonance bars were machined with square section of 20 mm, 120 mm length, whereas gray and ductile iron specimens were machined in bars with 25 mm diameter, 120 mm length.
Different combinations of alloying elements and inoculation were used for the gray iron samples. For the CGI, in order to evaluate the effect of the cooling rate, the samples were machined from two positions of the Y block, the usual bottom position (5 mm from the bottom as cast surface) and at an upper position (50 mm from the bottom).

Table 1 – Cast irons tested on the present work.

Cast Iron	Grade	Alloying elements
Ductile Iron	DI 450	-
	DI 800	0,6Cu
Compacted Graphite Iron	CGI 450	1,0Cu - 0,09Sn
	CGI 500	1,0Cu - 0,3Mo
Gray Iron	GI 250	0,9Cu-0,7Sn-0,27Cr
	GI 300-1	0,7Cu-0,06Sn-0,24Mo
	GI 300-2	1Cu–0,09Sn-0,29Cr
	GI 300-3	0,6Cu-0,06Sn-0,24Cr (*)
	GI 300-4	0,9Cu-0,09Sn-0,3Mo (*)
	GI-300-5	0,6Cu-0,06Sn-0,2Cr-1,5Ni
	GI 300-6	0,7Cu-0,04Sn-0,2Cr-0,27Mo

(*) – Special inoculation to refine graphite.

The microstructures of the cast irons evaluated on this work can be seen on figure 2.

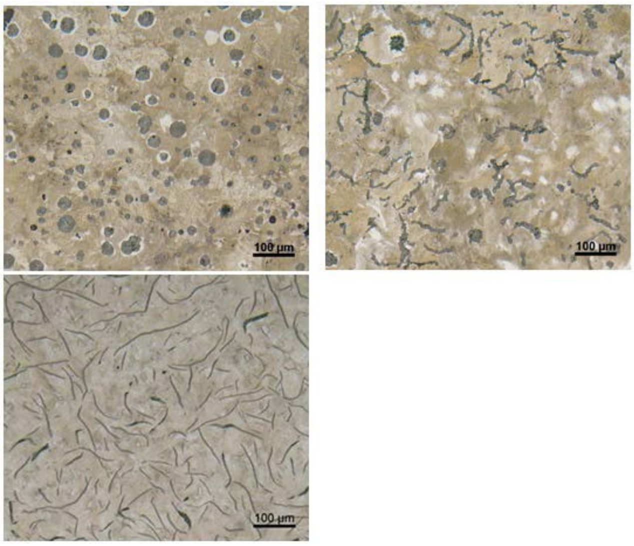


Figure 2– Typical microstructures of ductile iron (grade 800), CGI (grade 450) and gray iron (grade 300), with Nital etching.

The resonance frequency test was carried out using the impulse excitation method (5). The method, illustrated in Figure 3, uses the software Sonelastic ® (6). This consists of an analyzer of transient vibrations, which obtain the resonant frequency for calculating the elastic modulus, and the respective decay rates for the evaluation of damping capacity (7). The damping is calculated by logarithmic decrement technique, which considers the ratio of two successive amplitude signals (8).

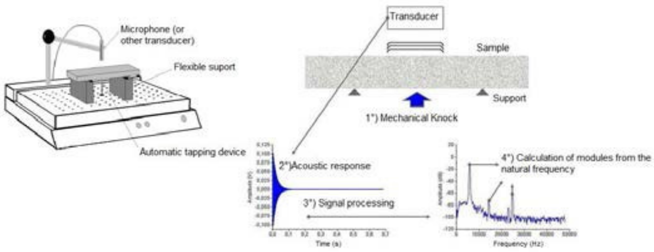
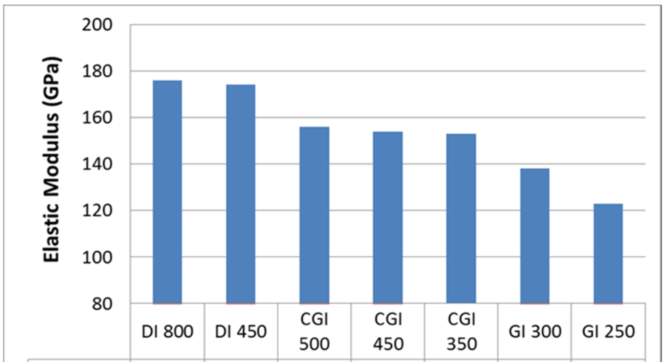


Figure 3 - Scheme of the experimental apparatus used in the resonance frequency test. [7], [8]

Results and Discussion

Figure 4 shows results of elastic modulus and damping capacity, evaluated by vibration tests. It is confirmed that ductile irons have the highest modulus and the lowest values of damping capacity, while gray irons show high levels of damping capacity and the lowest elastic modulus values. Compacted graphite irons are among the ductile and gray irons. In each cast iron family (nodular, compacted, gray), the elastic modulus values are affected by the grade, especially for gray iron. In this case, the change from grade 250 to 300 is obtained by using alloying elements and particularly by reducing the quantity and refining of graphite. This graphite size change affects the propagation of the elastic wave in the material, thus influencing both the elastic modulus values as the damping.



	DI 800	DI 450	CGI 500	CGI 450	CGI 350	GI 300	GI 250
E (GPa)	176	174	156	154	153	138	123
damping	0,16	0,23	0,42	0,38		0,41	0,55

Figure 4 – Elastic modulus and damping capacity of cast irons.

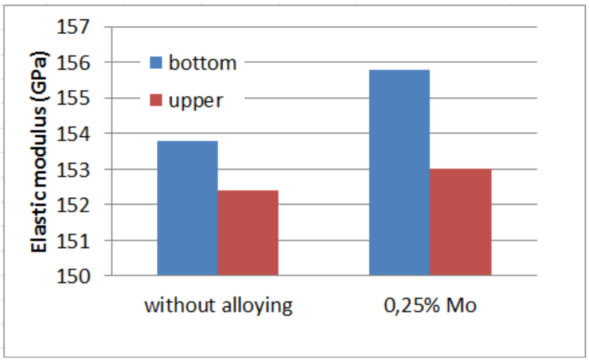
Considering the difference in damping capacity and elastic modulus between the grades GI 250 and GI 300, and between gray and compacted graphite irons, complementary experiments were conducted. It was investigated in detail the effect of microstructure on the damping capacity in the grade GI 300, using 7 different gray irons. It was also evaluated the elastic properties of two types of CGI. Special attention on these families of cast irons (gray and CGI) is driven by its increasing use in modern engines cylinder blocks and heads.

The metallographic and mechanical characteristics of CGI samples are shown in table II. It can be seen that the addition of Mo increases the mechanical strength of CGI and that in the lower position of the Y block the mechanical properties are higher compared to the top position. This is a result of cooling speed differences, which also translate in the metallographic characteristics of pearlite and graphite. Mo also resulted in refining of pearlite.

In figure 5 we can observe the results of elastic modulus and damping capacity, for the CGI samples. The elastic modulus increases with increasing cooling rate (bottom position) and with addition of Mo. This is the result of increased nodularity, refining of compacted graphite (eutectic cells count and graphite particles count) and refining the pearlite. The damping capacity also increases with increasing cooling rate (bottom position), probably due to the refine of the graphite particles and perlite; the effect of Mo it is not clear in this case. As a general observation, for CGI both elastic modulus and damping capacity increase when the microstructure is refined (pearlite and graphite).

Table II- Tensile test results and metallographic analysis of CGI samples. 100 % pearlite. Graphite shape III and VI.

Sample	CGI bottom	CGI upper	CGI Mo - bottom	CGI Mo - upper
UTS (MPa)	458	450	530	514
YS (MPa)	361	353	412	413
Nodulization (%)	6	5	7	6
Eutectic cell count/cm2	677	575	531	518
Graphite particules count/mm2	508	490	502	489
Pearlite interlamelar spacing (µm)	0,32	0,35	0,25	0,29



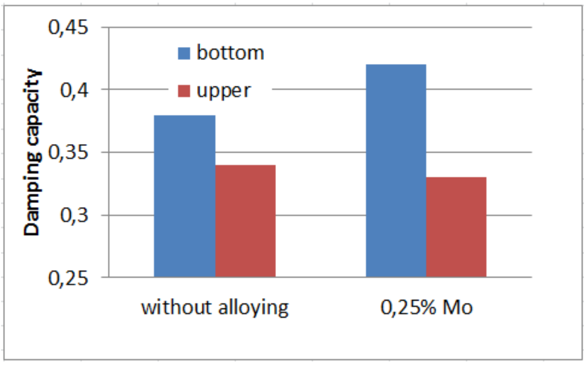


Figure 5 - Results of elastic modulus and damping capacity of CGI samples, in bottom and upper position of the Y block.

Figure 6 shows, for gray irons grades GI 250 and GI 300, the relationship between certain parameters of the microstructure, in particular some aspects of graphite. The number of eutectic cells reflects the conditions of nucleation during solidification, while the number of graphite particles (measured on a metallographic section) is the result primarily of graphite growth conditions. Both parameters relates to the undercooling during solidification, and therefore present a high correlation with each other. The amount of graphite, for cast iron of the same carbon equivalent content, is also influenced by the solidification undercooling, decreasing with the increase of this parameter. In this case, as the geometry of the specimens was always the same (30 mm diameter bars), the variation of the undercooling was a result of different inoculations and alloying elements. We can see that the amount of graphite decreases with increasing number of graphite particles and eutectic cells.

Figures 7 and 8 illustrate the effects of graphite on tensile strength and Elastic Modulus in gray irons. It can be seen that both Elastic Modulus and UTS increase with increasing number of eutectic cells and with the number of graphite particles and decrease with increasing graphite amount. It thus appears that the microstructural factors related to graphite affect likewise the material stiffness (Elastic Modulus) and its fracture strength (UTS). In this case, during the process of fracture of the material, increasing the number of eutectic cells and refining the graphite particles imposes difficulty in the progress of cracks, while increasing the amount of graphite facilitate crack growth.

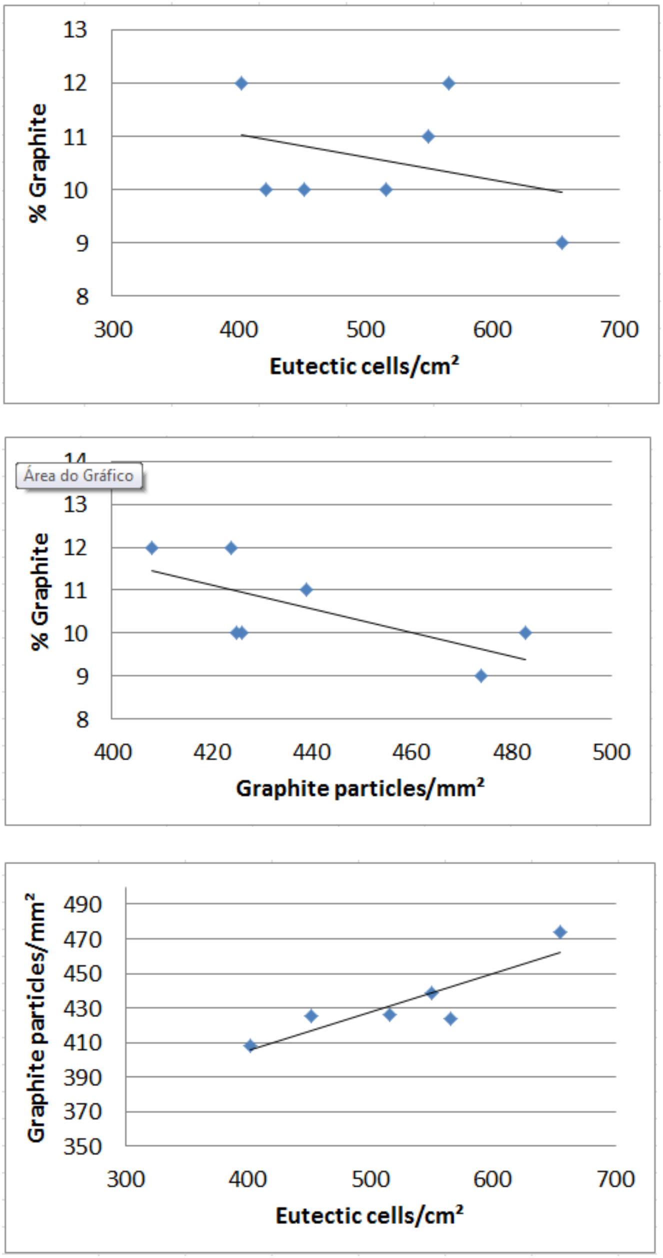


Figure 6 – Relationship between graphite microscopic characteristics in gray irons. Bars with 30 mm diameter, with CE = 4,0-4,1. The amount of graphite decreases with increasing number of graphite particles and eutectic cells.

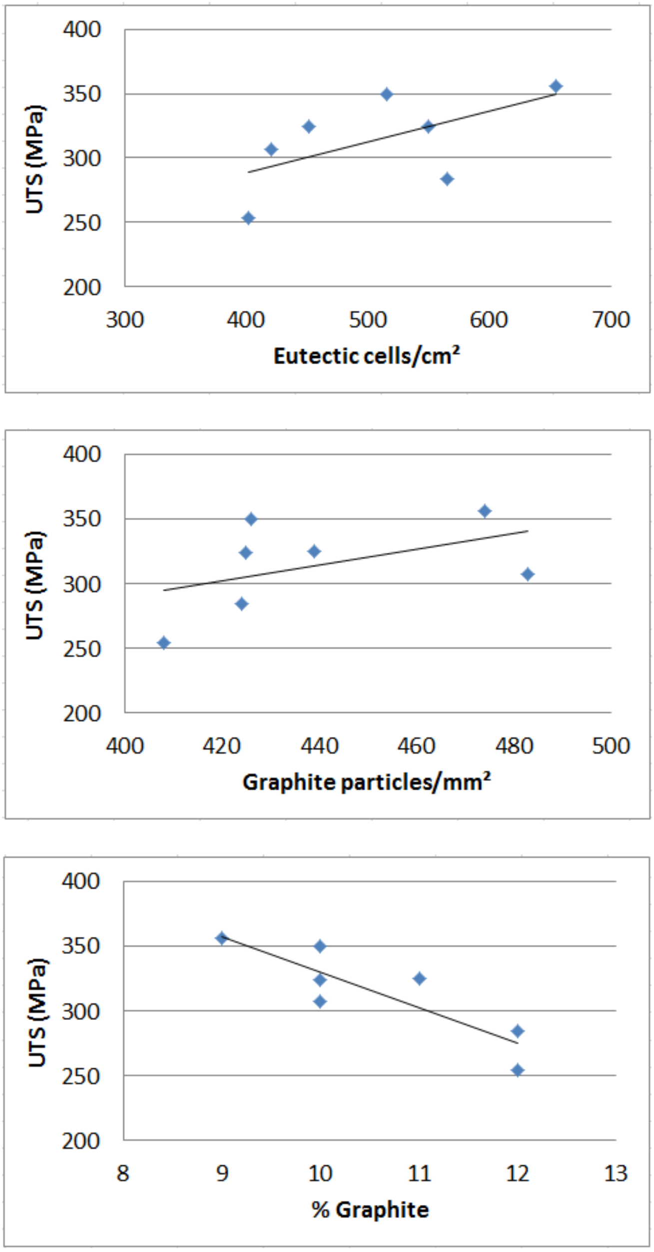


Figure 7 – Relationship between graphite microscopic characteristics and tensile strength in gray irons. Bars with 30 mm diameter. UTS increases with higher eutectic cell number, refined graphite and lower amount of graphite.

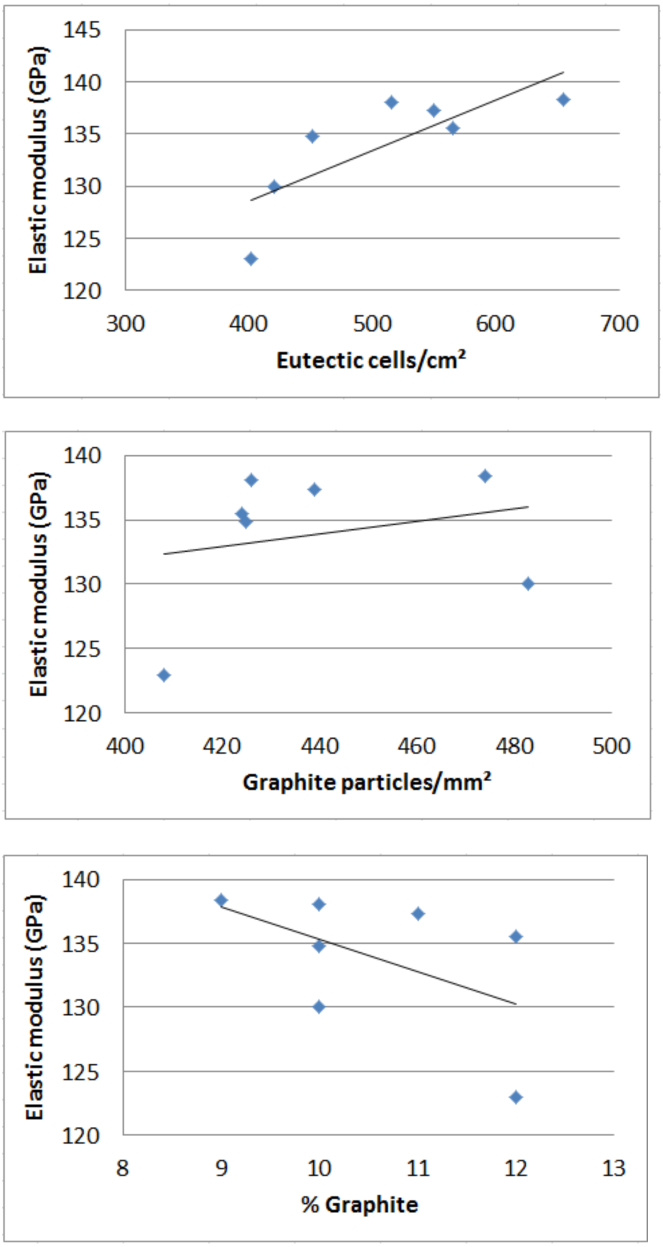


Figure 8 – Relationship between graphite microscopic characteristics and elastic modulus in gray irons. Bars with 30 mm diameter. Elastic modulus increases with higher eutectic cell number, refined graphite and lower amount of graphite, the same trend for UTS.

Figure 9 also shows the inverse relationship between elastic modulus and damping capacity for the samples of gray irons under examination, so that high values of elastic modulus are associated with low values of damping capacity. The microstructure characteristics that most influence the damping capacity are the number of eutectic cells and the amount of graphite (Figure 10). There was no observed relationship between the refining of graphite and damping capacity. Thus, to maximize the damping capacity should be selected gray irons with large amounts of graphite and large eutectic cells.

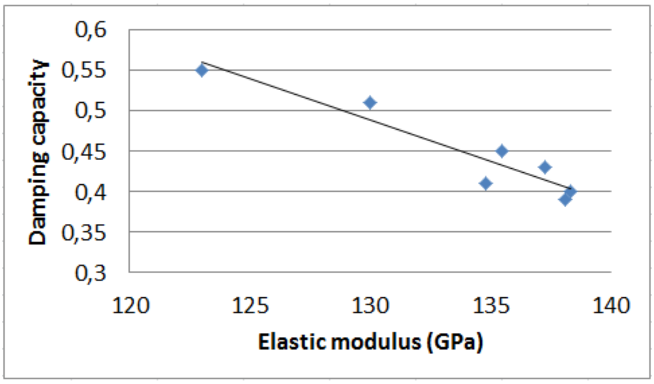
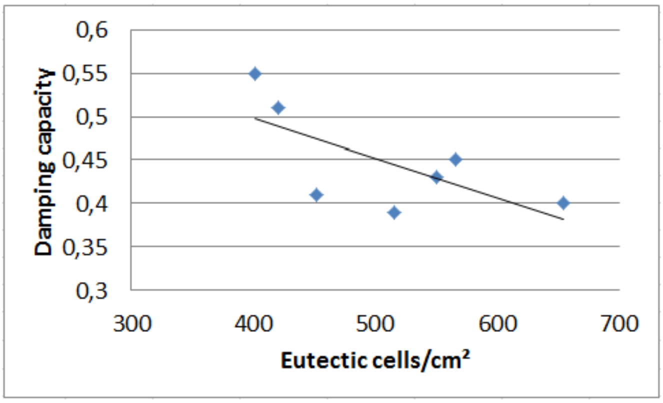


Figure 9 – Relationship between elastic modulus and damping capacity. Inverse relationship.



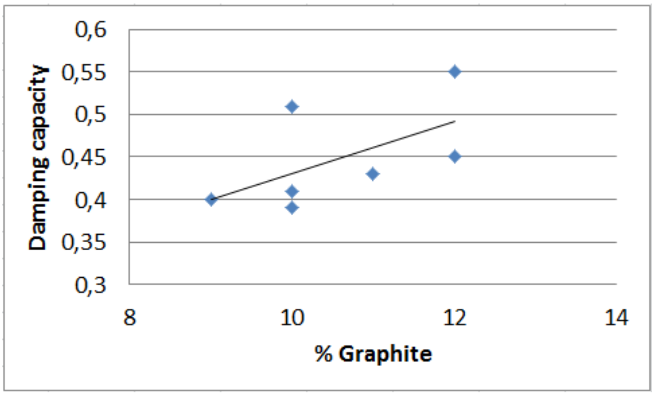


Figure 10 – Relationship between graphite microscopic characteristics and damping capacity in gray irons. Bars with 30 mm diameter. Damping capacity increases with lower eutectic cell number and higher amount of graphite, the opposite trend for elastic modulus and UTS.

Conclusions

It was found that the elastic modulus of cast irons correlates with the strength of these materials, and is dependent on graphite shape, presenting high values for ductile irons, low values for gray irons and intermediate values for compacted graphite iron. Inverse relationship is recorded for the damping capacity, with high values for gray irons. This property can still be maximized for gray irons with the design of the microstructure, selecting gray irons with high amounts of graphite and low number of eutectic cells. These factors are contrary to the search for the increased strength and stiffness of gray irons, so the selected microstructure must be a compromise between strength, stiffness and damping capacity.

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Definitions/Abbreviations

SGI	Spheroidal graphite iron
CGI	Compacted graphite iron
GI	Gray iron
USA	United State of America
UTS	Ultimate tensile strength
Cu	Copper
Sn	Tin
Mo	Molybdenum
Cr	Chrome
YS	Yield strength
E	Modulus of elasticity
G	Shear modulus
μ	Poisson coefficient
UDESC	University of State of Santa Catarina