

DEVELOPMENT OF A CORRELATION TO ESTIMATE THE FATIGUE STRENGTH FOR STEELS BASED ON LOW-COST TESTS

Alexander Martínez^{1*}, Alban Jaimes², Aníbal Serna¹ and Iván Uribe²

¹ Ecopetrol S. A. – Instituto Colombiano del Petróleo (ICP), Bucaramanga, Santander, Colombia

² Universidad Industrial de Santander, Bucaramanga, Santander, Colombia

e-mail: alexander.martinez@ecopetrol.com.co alban.jaimes@ecopetrol.com.co

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ABSTRACT

Fatigue cracking in metallic materials occurs mainly due to the effect of cyclic stresses and their variation of magnitude over time. To evaluate the fatigue strength based on S-N curves, many tests are needed, which require a lot of time and incur high costs. For this research, several tests were conducted on samples of high-strength steels to determine their mechanical properties, chemical composition and fatigue. It was found that impact toughness Charpy V Notch, the percentage of alloying elements and the mechanical properties show a positive lineal effect in relation to the fatigue strength of the materials evaluated. Considering this behavior, a correlation to predict the fatigue strength of the steel was developed based on the Charpy impact energy, the yield strength, the ultimate strength, and the hardness of the material; this correlation shows a very good fit with the experimental fatigue data. The main advantage of this correlation is that the estimation of fatigue strength is based on very low cost tests.

Keywords: fatigue prediction, fatigue strength, fatigue test, impact resistance, tensile strength, toughness.

* To whom correspondence may be addressed

RESUMEN

El agrietamiento por fatiga en materiales metálicos ocurre principalmente debido al efecto de los esfuerzos cíclicos y la variación de su magnitud en el tiempo. Para evaluar la resistencia a la fatiga basada en las curvas esfuerzo vs. ciclos, se deben correr muchos ensayos, los cuales requieren una gran cantidad de tiempo y altos costos. En esta investigación, se realizaron ensayos en muestras de acero de alta resistencia para determinar sus propiedades mecánicas, composición química y resistencia a la fatiga. Se encontró que la tenacidad al impacto medida en el ensayo Charpy V Notch (CVN), el porcentaje de elementos de aleación y las propiedades mecánicas mostraron un efecto lineal positivo en relación con la resistencia a la fatiga de los materiales evaluados. Considerando este comportamiento, una correlación para predecir la resistencia a la fatiga fue desarrollada basada en la energía absorbida por impacto, la relación entre el esfuerzo de fluencia y el esfuerzo último y la dureza del material; esta correlación presenta un muy buen ajuste con los datos de fatiga experimentales.

Palabras clave: *predicción de fatiga, resistencia a la fatiga, ensayo de fatiga, resistencia al impacto, resistencia a la tracción, tenacidad.*

1. INTRODUCTION

In the oil industry, the use of steel for high-resistance machines is extensive; these steels are subject to high cyclic load conditions that induce damage to the material because of the failure mechanism of fatigue cracking. The selection of these materials is based on fatigue resistance tests carried out in the laboratory, or the performance of the materials in operational conditions, or existing recommendations in the literature. In order to carry out the laboratory tests, a representative number of trials are required, which obviously increases costs. Field tests require an impractical amount of time; therefore, the common rule is to use the general recommendations in the current literature. The present investigation sought to develop a methodology of evaluation that would allow calculating the behavior that a material may show under fatigue conditions, through the implementation of short duration and low-cost tests.

The present research was carried out to determine a correlation between impact toughness and fatigue behavior of the fatigue-resistant steels most commonly used in the production of hydrocarbons. This is based on the fact that an increase in toughness tends to decrease the possibility of the initiation and the propagation rate of fatigue cracks; once a fatigue crack starts to develop, a deformation area encloses the crack tip increasing the number of cycles needed for the beginning and propagation, therefore the fatigue strength of the material is increased. Initially, tests were performed to determine chemical composition, microstructure, presence of impurities, and the mechanical strength of the materials to be evaluated; also impact energy tests were performed by means of the Charpy test to determine toughness and resistance to fatigue.

Based on the data obtained, several multivariable functions were defined that relate the fatigue limit of these steels to their mechanical properties and to the value of the impact energy found in the Charpy test. The correlations obtained allow one to predict fatigue behavior based on the results of the tension test and Charpy impact test; these tests are very low-cost and of rapid implementation, thus facilitating the selection processes for these materials, it should be emphasized that this approach is a novel one in the industry. This correlation only applies to steels with high mechanical resistance.

2. THEORICAL FRAMEWORK

Generally, fatigue failures start on a stress concentrator, which is a microscopic or macroscopic discontinuity, causing an increase in local stress on the material when it is submitted to a load. These may be caused by sudden changes in geometry, superficial defects caused by corrosion, cracks, manufacturing defects, or wear, or any combination of the foregoing. Figure 1 shows a fatigue failure which occurred on a sucker rod, this element is used in beam pumping systems for artificial lift of crude oil; the origin of the fracture was seen to be on a surface defect due to pitting, which was caused by corrosion.

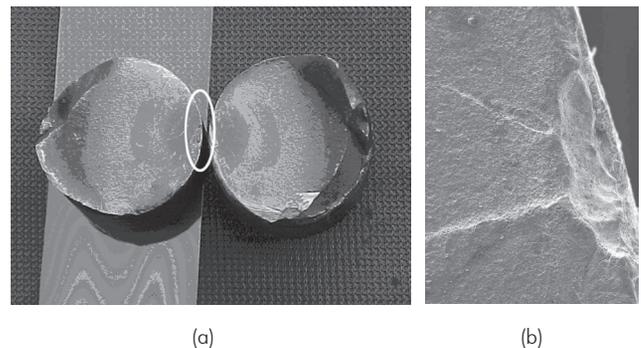


Figure 1 (a) Visual examination of the fracture's surface reveals a rupture of the component caused by a fatigue crack (b) The origin of the fatigue crack is due to the presence of pitting caused by sweet corrosion (CO_2).

In the presence of cyclic loads, at any superficial or metallurgic discontinuity a phenomenon of elastic-plastic deformation is produced from which a fatigue crack could be originated. The surface condition and the nature of the medium plays an important role in fatigue resistance, which means the number of cycles required for the crack to appear. According to Vormwald and Seeger (1987), the time needed to start a fatigue crack of a certain size is determined by the growth of micro-cracks; therefore during the research carried out by the authors, major efforts were made to quantify the initiation stage of cracks by means of the mechanics of the fracture for short or micro-cracks.

Factors affecting fatigue life

The fatigue limit in a material can be obtained experimentally or through the traditional approach of 50% of the tensile strength; for design purposes and in service,

this value is recalculated as the effective or admissible fatigue limit, taking into account the effect of variables such as: average stress, surface finish, environment, stress concentrators, reliability, component size, grain size, heat treatment conditions, chemical composition, and level of inclusions. Listed below are the effects on fatigue performance that various factors cause.

Effect of average stress on fatigue. The contrast between the minimum and maximum load applied to the material has a key effect on the resistance to fatigue cracking; if the ratio is higher, ($R = +1,0$), fatigue endurance limit decreases, where R is the relationship between the minimum and maximum stress.

Effect of stress concentrators. The resistance to fatigue cracking is severely reduced through the generation of specific stress concentrators caused by the presence of surface defects in the material, such as holes, pores, notches, nicks, abrupt changes in geometry. In a study conducted by Smith, Newman, & Piascik (2003), uniaxial fatigue tests were conducted to compare the fatigue life of nicks produced in the laboratory to Electrical Discharge Machining (EDM) defects. Defects made with EDM are used to simulate the effect of corrosion caused by pitting. For AA 7050 aluminum alloy, the notch produced by EDM resulted in a fatigue life similar to that obtained in the tests of samples containing "pitting" of similar size.

Effect of the level of inclusions. In a study conducted by Atkinson and Anderson (2003), a correlation was developed of the maximum inclusion size in clean steels and the relationship to the mechanical properties; among the important contributions of this research is the development of a new approach for the design for fatigue using the generalized Pareto distribution to predict the form of the size distribution of the biggest inclusions and the accumulative volumetric fraction of the component in which the local fatigue stress exceed a particular stress level. The new design method developed in this research allows one to analyze the effect of changes on the design stresses or the cleanliness of the steel on the likelihood of failure. Yang and Zhang (2004) investigated the behavior of the inclusions on fatigue behavior in the super-long-life regime in 42 *CrMo* steels. The analysis by electron scanning microscope showed that fatigue cracks start mainly from non-metallic inclusions, so the high cycle fatigue

behavior is presented in steels with very low content of inclusions (almost zero inclusions).

The size of inclusions can affect the initiation of fatigue cracks, according to the research conducted by Juvonen (2004), in which it was evaluated the effect of the level of inclusions on the fatigue behavior of different carburization conditions in AISI SAE 8620 steel. The relevant conclusion was that the average size of inclusion for the start of fatigue cracks had an effect on the relationship between the fatigue limit and the mechanical resistance when the size of the inclusions ranged between 70 - 90 microns.

Effect of grain size and grain direction. Materials with fine grain size exhibited higher fatigue properties than materials with coarse grain size. The direction of flow of aligned grains in wrought or laminate sheets relative to the direction of the load has a significant effect on fatigue resistance, with cyclic loads across the direction of the grain generating fatigue properties that are inferior to the cyclic loads along the direction of the grain (longitudinal). Research carried out by Di Schino and Kenny (2003) on type 304 stainless steels studied the effect of the grain size of austenite (1 - 47 microns) on behavior in a test of tensile stress and fatigue. The relevant results of this investigation showed an increase in tensile stress and fatigue properties through refining the grain size. In research carried out by Subramanya, Padmanabhan, & Jaeger (2000), the speed of crack growth caused by fatigue was evaluated under the Paris regime for two microalloyed steels with ferrite and pearlite microstructures; the results obtained from testing crack growth rate showed no differences in the response in the region of fatigue crack propagation in two materials evaluated, considering that these materials showed differences with respect to the yield stress on the order of 170 MPa and in the size of pearlite colonies of 7 microns. The previous austenite grain size is directly related to the refining elements of the grain size.

Effect of the microstructure. The microstructure of tempered martensite obtained from a heat treatment of quenching and tempering exhibits fatigue behavior superior to that of any other microstructure. Tempered martensite in steels increases the fatigue limit because it is a structure in which the mobility of dislocations is minimal, resulting in an increased load level necessary to be applied in order to displace the dislocations (Lampman, Davidson, & Reidenbach, 1996).

Initiation of microcracks. In presence of cyclic loads, at the tip of a geometric or a metallurgic discontinuity, a phenomenon of cyclic elasto-plastic deformation occurs, on which the initiation of the fissure takes place. The surface condition and the nature of the medium play an important role in the fatigue strength; this determines the number of cycles required for the crack to appear (Dowling, 1998).

According to Takuhiro (2007) there is a correlation between the speed of crack propagation and the tensile strength in pre-deformed materials. Under conditions of large deformation there is a defined correlation between the two variables; when they have low deformations, the correlation is not strong compared to conditions of high deformation. In the literature, no studies were found that focus on the analysis and assessment of the fatigue limit in terms of impact toughness, nor in factors related to the chemical composition of the material. To our knowledge, we would said that the approach to estimate the fatigue strength used in this research is a novel process one.

3. EXPERIMENTAL PROCEDURE

For this investigation five steels with high mechanical resistance were assessed. Evaluation tests were carried out for chemical composition and metallographic analysis, mechanical properties such as; tension, fatigue, and toughness CVN test. Fatigue tests were carried out

according to the specifications of the ASTM E 739-91, according to this standard, the tests have a confidence level for research and development of components with a replication of 33-50%.

Chemical composition

The samples received were analyzed chemically using the optical emission spectroscopy technique, according to the specifications of the ASTM E 415-08 Standard.

Table 1 shows the chemical composition of the five materials tested. According to the percentage of elements, they were classified following the AISI-SAE designation.

Mechanical properties

Tests of tensile stress, hardness and impact were performed in order to determine the properties of yield strength, ultimate tensile strength, elongation, Brinell hardness, and value of energy absorbed. These tests were conducted under the specifications of ASTM A 370. Tables 2 and 3 shows the results.

Metallurgic analysis

Table 4 shows the results of the analysis of inclusions and microstructure. At this stage of the investigation, the phases present in each of the samples, previous austenite grain size, ferrite grain size by

Table 1 Chemical Composition of the materials evaluated

Element	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
C	0,341	0,318	0,405	0,410	0,404
Mn	0,833	0,848	1,065	1,256	0,861
P	0,013	0,007	0,006	0,000	0,014
S	0,006	0,030	0,008	0,000	0,008
Ni	2,047	1,922	0,067	0,000	0,003
Cr	0,940	0,877	0,594	0,722	0,989
V	0,064	0,097	0,095	0,059	0,002
Mo	0,248	0,236	0,255	0,309	0,165
Al	0,042	0,005	0,003	0,027	0,029
Nb	0,008	0,007	0,006	0,045	0,005
AISI -SAE	4330M	4330M	4138M	4138M	4140

Table 2 Results of tension and hardness tests

Material	Sample	σ_y (MPa)	σ_{UTS} (MPa)	% e (50 mm)	HBN Hardness
M1	M1.1	929,5	1060,7	15,2	336
	M1.2	928,5	1067,7	20,6	
M2	M2.1	820,4	971,2	16,6	312
	M2.2	830,5	980,9	16,8	
M3	M3.1	724,4	918,6	15,2	287
	M3.2	721,1	915,1	14,3	
M4	M4.1	825,9	1015,5	15,2	312
	M4.2	837,3	1022,8	15,0	
M5	M5.1	690,4	798,9	19,8	245
	M5.2	689,5	792,3	23,6	

means of a scanning electron microscope (SEM), and the type of inclusions present were determined. These tests were conducted under the specifications of the ASTM E 3-01 and ASTM E 45-05 Standards. The previous austenite grain sizes for the samples determined according to the ASTM E 112-96 Standard may be seen in Table 5.

Fatigue tests

According to the specifications of the ASTM E 466-07 and ASTM E 468-04 Standards, fatigue curves for the materials tested were assessed. A stress ratio equal to zero and a stress application rate of 60 Hz were defined. Figure 2 shows the fatigue curves for samples M1, M2, M3 and M4.

Table 3 Results of the impact test

Material	Sample	CVN Joules	Average CVN Joules
M1	M1.1	40,0	37
	M1.2	37,3	
	M1.3	33,9	
M2	M2.1	54,9	52,9
	M2.2	52,2	
	M2.3	51,5	
M3	M3.1	29,8	27,3
	M3.2	24,4	
	M3.3	27,8	
M4	M4.1	20,3	23,3
	M4.2	24,4	
	M4.3	25,1	
M5	M5.1	149,1	148,5
	M5.2	153,2	
	M5.3	143,2	

Table 4 Results of the analysis of inclusions and microstructure

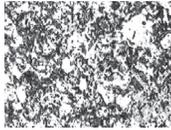
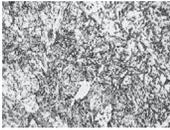
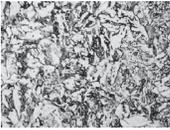
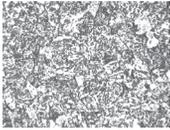
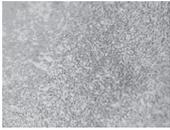
Sample	1	2	3	4	5
Analysis of Inclusions	Displays thick globular oxide inclusions type 1½, thin globular oxides type 1, and thin sulphides type ½.	Inclusions of thin globular oxides type 1, thin sulphides type 1 and 2.	Inclusions of thick globular oxides type 1, thin globular oxides type 1 and 1½, thin sulphides type 1½ and 2.	Inclusions of thick globular oxides type 1, thin globular oxides type 1 and 1½, thin sulphides 1½.	Non-metallic inclusions of globular oxides, thick and thin series, severity level 1 and 1½.
Microstructure	Ferrite - pearlite 	Ferrite - pearlite 	Ferrite - pearlite 	Ferrite - pearlite 	Tempered martensite 

Table 5 Previous austenitic grain size

Sample	Austenitic grain size (ASTM number)
Sample 1	8
Sample 2	4 - 6
Sample 3	4 - 6

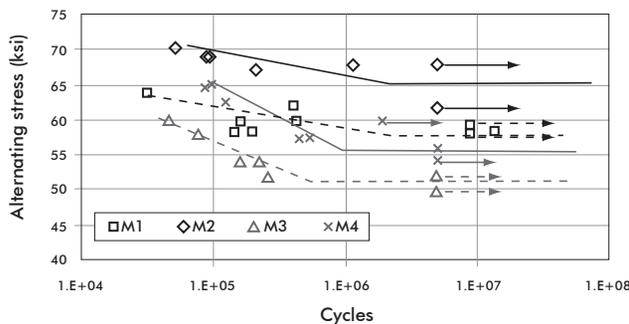


Figure 2 Fatigue curves in a supplied condition free of defects. The arrows indicate alternating stress values where failure of the material was not seen for 5 million cycles

Heat Treatment

The samples of materials M3 and M4 were modified with a heat treatment of tempering and quenching, in order to assess the effect of the microstructure on resistance to fatigue. The tempering was done in oil from a temperature of 860°C with subsequent tempering at a temperature of 650°C with a sustaining time of 1 hour. Under these conditions, the heat-treated materials showed

a microstructure composed of tempered martensite. The yield strength, tensile strength, notch tensile strength, impact toughness CVN and their behavior under fatigue were measured. Table 6 shows the fatigue limit values obtained from Samples M1, M2, M3, M4 and M5, as well as fatigue resistance in samples M3 and M4, heat-treated with quenching and tempering treatment.

4. ANALYSIS OF RESULTS

Effect of chemical composition

The steels tested belong to the families of steels AISI-SAE 4330M (chromium - nickel - molybdenum), 4138M (chromium - molybdenum steel), and 4140 (chromium molybdenum steel). Steels Sample 1 and Sample 2 (4330M) showed the highest values of fatigue limit in the normalized and tempered condition. The combination of chromium, nickel, and molybdenum tends to increase the degree of hardening, raising levels of yield and tensile strength.

Effect of mechanical properties

A wide variation in the toughness of the materials evaluated is observed. The sample 5 showed the highest toughness. It can be seen that the greater the levels of mechanical properties such as; yield strength, tensile strength, and notch tensile strength; the higher the value of fatigue limit.

Table 6 Fatigue values, obtained for the materials evaluated

Sample	Heat treatment	Cp %C+Mn+ Ni+Cr+Mo+ V+Ti+Nb	Brinell Hardness HBN	σ_{NTS} (Mpa)	σ_y (MPa)	σ_{UTS} (Mpa)	σ_y/σ_{UTS}	% E	CVN (J)	σ_e (Mpa)
Sample 1	Normalized and tempered	4,48	336	1590	929	1064	0,87	17,9	37	441
Sample 2	Normalized and tempered	4,31	312	1571	826	976	0,85	16,7	53	403
Sample 3	Normalized and tempered	2,49	287	1364	723	917	0,79	14,7	27	352
Sample 4	Normalized and tempered	2,81	312	1420	832	1019	0,82	15,1	23	383
Sample 5	Tempered and quenched	2,43	245	No info	690	796	0,87	21,7	149	310
Sample 4	Tempered and quenched	2,81	328	1630	1013	1082	0,94	12,8	79	431
Sample 3	Tempered and quenched	2,49	308	1498	880	983	0,89	15,2	95	442

Cp= Chemical composition
 σ_{NTS} = Notch tensile strength of the material (MPa)
 σ_y = Yield strength of the material (MPa)
 σ_{UTS} = Ultimate tensile strength of the material (MPa)
 %E= Percentage of elongation
 CVN = Impact Charpy test (Joules)
 σ_e = Endurance fatigue limit (MPa)

Fatigue limit

From the standpoint of fatigue behavior, there is a direct relationship between the mechanical properties and the value of the fatigue limit. Sample 1 showed the highest fatigue limit of the materials tested (condition normalized and tempered); this value is linked to the ratio between the yield and ultimate tensile strength. For Sample 1 the ratio was 0,87; for Sample 2 there was a ratio of 0,85; Sample 3 showed a value of 0,79, and for Sample 4 it was 0,82.

Effect of heat treatment

The heat treatment of quenching and tempering performed on samples 3 and 4 reveals the following aspects:

- The mechanical properties remained at levels similar to those found in these materials in the supply condition (standardized and quenched heat treatment during manufacturing).
- The level of impact toughness showed an increase at a (3:1) ratio compared to the value evaluated in the supply condition.
- The fatigue limit evaluated in the heat-treated samples showed an increase of more than 45 MPa.
- The evaluated martensite tempered microstructure shows better performance under fatigue than the ferrite-pearlite microstructure. The last is the typical microstructure of the steels used for suckers

rods provided in normalized and tempered supply condition.

- This indicates that an additional parameter had a positive effect on this outcome, and it was impact toughness level.

Formulation of the correlation model

Based on carrying out inexpensive and rapid tests such as; the Charpy impact toughness, the tensile tests, Brinell hardness, and the chemical composition of the material; a correlation to predict the fatigue endurance limit was developed. Using Matlab mathematical software, correlations with three variables were generated, using linear functions for data adjustments. The results in Table 6 were used as the input data for model generation.

Here, see *Equations 1, 2 and 3* below as the correlations found, which show a difference of ± 2% compared to the value obtained in the long-term fatigue tests. From these equations it can be seen that positive effects were found in the value of impact toughness, hardness of the material, and in the sum of the percentage of alloying elements ($C+Mn+Ni+Cr+Mo+V+Nb$) in steel, which tend to increase the mechanical properties and fatigue performance, favoring, in addition, an increase in the value of impact toughness.

Dependent correlation of toughness, hardness, and tensile strength

The following expression relates the mechanical variables of toughness, hardness and strength on the fatigue limit, and combines the toughness field that tends to oppose the resistance to the spread of fatigue cracking.

$$\sigma_e = 0,17CVN + 2,59HBN - 0,41\sigma_{UTS} \tag{1}$$

Dependent correlation of toughness, chemical composition and tensile strength

The following expression relates the mechanical variables of toughness, chemical composition and ultimate tensile strength.

$$\sigma_e = 0,13CVN + 7,49Cp + 0,37\sigma_{UTS} \tag{2}$$

Dependent correlation of the toughness, relationship of strength and hardness

The following expression relates the mechanical variables of tenacity, strength ratio and hardness.

$$\sigma_e = 1,35CVN - 791,03 \frac{\sigma_y}{\sigma_{UTS}} + 3,27HBN \tag{3}$$

Table 7 presents the results obtained considering the three correlations evaluated. It is shown that the correlation that best fits the experimental data of resistance to fatigue is represented by *Equation 2*. However, correlations 1 and 3 show very close fits, comparing the values obtained based on the models and those obtained through experiment. (See Figure 3).

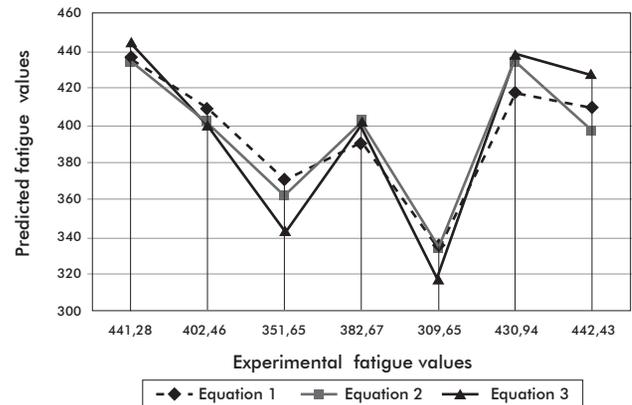


Figure 3 Fatigue values predicted by the models vs. Actual values obtained from fatigue tests

5. CONCLUSIONS

- Several correlations were developed that allow predicting the behavior of the fatigue performance of steels of high mechanical resistance. The parameters of CVN impact toughness, percentage of alloying elements, and mechanical properties show a positive linear effect on the fatigue resistance of the materials evaluated.
- A significant contribution is made to the field of material selection, due to the development of novel correlations that allow one to determine the fatigue limit based on mechanical tests and chemical characteristics of easy and quick implementation.

Table 7 Model output data

Sample	σ_e (Mpa) Experimental	$\sigma_e = f(\text{CVN}, \text{HBN}, \sigma_{\text{UTS}})$	% Error (CVN, HBN, σ_{UTS})	$\sigma_e = f(\text{CVN}, \text{Cp}, \sigma_{\text{UTS}})$	% Error (CVN Cp σ_{UTS})	$\sigma_e = f(\text{CVN}, \sigma_y/\sigma_{\text{UTS}}, \text{HBN})$	% Error (CVN $\sigma_y/\sigma_{\text{UTS}}$ HBN)
Sample 1	441,30	440,2	0,2	432,1	2,1	460,5	-4,3
Sample 2	402,50	416,9	-3,6	400,3	0,6	419,3	-4,2
Sample 3	351,70	372,0	-5,8	361,4	-2,8	350,4	0,4
Sample 4	382,70	394,2	-3,0	401,1	-4,8	403,1	-5,3
Sample 5	309,70	333,6	-7,7	331,9	-7,2	313,4	-1,2
Sample 4	430,90	418,8	2,8	431,6	-0,2	434,8	-0,9
Sample 3	442,40	410,2	7,3	394,8	10,8	431,0	2,6
		Mean Error	-1,4	Mean Error	-0,20	Mean Error	-1,9
Correlation		Equation 1		Equation 2		Equation 3	
σ_e = Endurance fatigue limit (MPa) CVN = Impact Charpy test (Joules) Cp = Chemical composition HBN = Hardness on the Brinell scale σ_y = Yield strength of the material (MPa) σ_{UTS} = Ultimate tensile strength of the material (MPa)							

- The correlation that takes into consideration the parameters of Charpy impact energy, yielding stress, ultimate tensile strength and the hardness of the material showed the best fit to the prediction of the value of resistance to fatigue of the steels tested.
- The correlations found allow the determination of resistance to fatigue of high-strength steels, based on very low-cost tests, compared to the cost required to run a fatigue test.
- AISI SAE 4330M steel is higher in fatigue resistance compared to 4138M. The presence of nickel and the use of modified steel increase the mechanical properties, toughness and resistance to fatigue, due to the refinement of ferrite and austenitic grain size.
- For materials of similar chemical composition, an increase in the mechanical properties has a positive effect the fatigue limit of the material.

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