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# A DISCUSSION ABOUT THE EFFECTIVENESS OF THE SHOT PEENING OVER THE FATIGUE BEHAVIOR OF METALLIC MATERIALS

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*Abstract. The fatigue failure is responsible for the majority of products failures. Therefore, this work gathered many published papers to promote a discussion and an analysis about the effectiveness of the use of the shot peening over the fatigue resistance enhancement of the material. Thus, it was analyzed the effects of the process over the materials conditions changings. The process was evaluated by the Almen intensity parameter and the materials condition by their mechanical properties and residual stresses. It was concluded that the effectiveness of the process depends more on the material state than the process parameters. In addition, such observations were obtained from papers that tested metallic materials, however it is possible to expand them to others kind of materials since these materials behave similar to metallic materials.*

## 1. INTRODUCTION

The number of available materials for using on a product is huge today, so it's necessary to know the product operation requirements and the materials specifics properties for each kind of application, whether it be mechanical, electrical, thermal or other one. There are also techniques that may modify the materials properties as, for an example, the heat treatments and the superficial treatments that usually are utilized to modify the materials mechanical properties. Therefore, an engineer must identify the best solutions to the project and analyze the most viable one.

Within this context, it's identified one kind of materials failure which is called fatigue. A fatigue failure is characterized by cyclic loadings and usually happens under stresses lesser than the material yield stress. This kind of failure can be seen on many mechanical elements, airplanes and bridges and it represents the main cause of the materials failures, which is estimated in 90 % of all failures. Moreover, this kind of failure suddenly occurs without any previous signal and may cause serious damages to the machines and even the loss of human lives. Consequently, the dimensioning of mechanical elements is generally determined by some fatigue criteria. Thereby, techniques that contributes to an enhanced fatigue resistance of the materials are essential (Callister, Rethwisch, 2012; Norton, 2004).

The fatigue failure mechanism is divided into three stages: the crack initiation, the crack growth and the final failure. The first stage is characterized by the nucleation of a tiny crack in some determined region of stress concentration of the material or by the already presence of this crack due to some reason as its manufacturing process. Normally, the cracks nucleate themselves on the material surface because the majority of the stress concentrations are there. These can happen owing to a surface scratch, a discontinuity, a keyway, a keyseat or others factors. So that is why even if the nominal stress is small in the normal section, it may occur higher stresses than the material yield limit. The second stage represents the crack growth due to the cyclic loading that the material is subjected to. In a such case, where is admitted that the cycle is a compression-tensile one, the cracks behavior is to close and to open themselves respectively. Thus, the propagation of the crack is caused by the crack opening tendency (tensile stresses). The last stage is characterized by the material final failure due to the instable crack growth. This occurs once that the crack stress intensity factor K becomes in the same level as the critical stress intensity factor $K_{1c}$ (Callister, Rethwisch, 2012; Norton, 2004).

One alternative to increase the material fatigue resistance is the introduction of compressive residual stresses, once that these will decrease the tensile stresses. Residual stresses are found in the material even if it has no loading and this happens due to a plastic deformation (Norton, 2004). There is a big variety of techniques that may induce residual stresses on a material and one of the most traditional processes is the shot peening because it has low environment

impact and low cost when it's compared with others process. The process is based on the impacts of spheres on an element. These impacts cause localized plastic deformations that enlarge the superficial area of the element. Consequently, the material will constrict in a lower layer to balance the superficial expansion and this behavior creates a compressive residual stress state (Trsko et al., 2014a).

## 2. MECHANICAL BEHAVIOUR OF METALS

In this work, it was studied the metallic materials because there are more studies about the theme, however, with some care, the proposal can be expanded to others kinds of materials as polymers and composites.

The material behavior is the way that it answers to a stimulus. So, the mechanical behavior is its answer to a loading. Generally, the main mechanical properties are stiffness, resistance, hardness, ductility and toughness. Besides that, this behavior can be verified by standard tests in laboratories that seek to reproduce the kinds of loadings of the materials (Callister, Rethwisch, 2012).

Within the available tests, one of the most common and important tests is the tension tests because it may be accomplished to characterize many important properties of the materials. It's based on the deformation of a specimen with a tensile loading. A standard for this test is the ASTM E8/E8M-16a (2016) and the Fig. 1 presents one kind of test specimen, where G is the initial length of the test section, $A_r$ is the length of the reduced section, D is the initial diameter of this same section and R is the relief radius. The test result is acquired generally by a computer and its answer is a stress-strain diagram of the specimen. The stress is calculated by Eq. 1 and it is obtained by the ratio of the instantaneous applied load and the initial cross-sectional area of the test specimen. The strain is calculated by Eq. 2 and it is obtained by the ratio of the material elongation and its initial length of the test section (Callister, Rethwisch, 2012; Hibbeler, 2010).
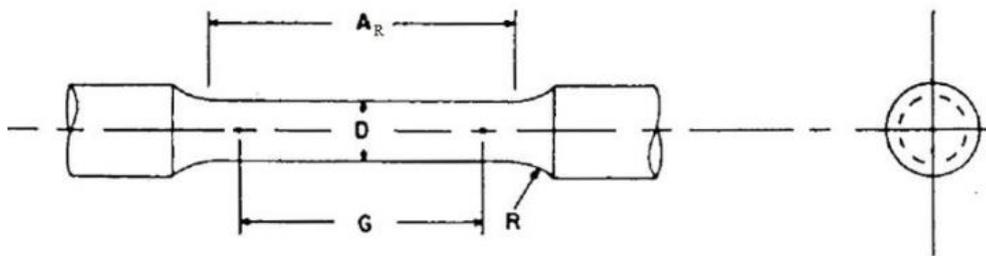


Figure 1. Generic test specimen of a tension test.

$$S = \frac{F}{A_0}$$  (1)

Where S is the stress [Pa], F is the applied load [N] and $A_0$ is the initial cross-section area of the test specimen [m²], given by the diameter D.

$$e = \frac{\Delta l}{l_0} = \frac{l_i - l_0}{l_0}$$  (2)

Where $e$ is the strain [m/m or mm/mm], $\Delta l$ is the elongation [mm], $l_0$ is the initial length and $l_i$ is the instantaneous length.

Figure 2 presents a typical out of scale stress-strain diagram of a steel and it may be observed its standard behavior under a tension test. There is a region where the strain answer is proportional to an applied stress and that, if the load is removed from the material, it will return to its initial conditions with no deformations. This is the elastic region of the material and it's equated by the Hooke's law, which is presented by Eq. 3. This behavior occurs until the proportional limit, where the material still can answer elastically, however, the diagram curve trend is to flatten itself. This process happens until the elastic limit, where the material will not answer elastically anymore. From this stress, the material starts to collapse and to deform permanently. Usually, but there are variations, the region between the proportionality limit and the yield stress is so small that they are not distinguished. Increasing the load, the material will deform more plastically and the curve raises until a determined maximum level that is called ultimate tensile stress. Furthermore, the test specimen is uniformly deformed in its reference length. This behavior is called strain hardening and it's represented by the third region of the Fig. 2. By last, after the ultimate tensile stress, the specimen starts to deform locally in a determined section instead of in its all reference length, which characterize a necking, and continues to deform until its rupture when it reaches its rupture strength (Hibbeler, 2010).

$$\sigma = E\varepsilon \tag{3}$$

Where $\sigma$ is the stress [Pa], $E$ is the elastic modulus [Pa] and $\varepsilon$ is the strain [m/m].
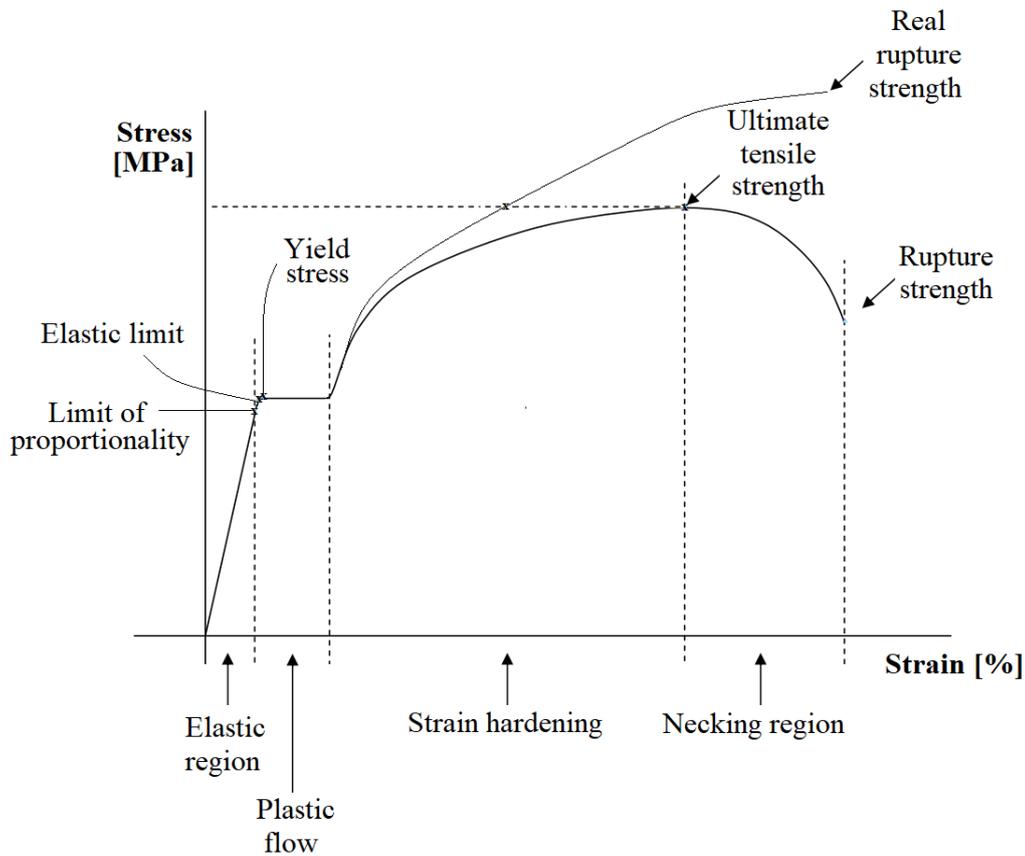


Figure 2. Engineering and real stress-strain curves of an steel.

When it's utilized the initial cross-sectional area and the initial length, the stress and the strain are called engineering stress and engineering strain, however it's possible to utilize the instantaneous cross-sectional area and the instantaneous length of the test specimen in the same moment of the applied load to obtain the real stress and the real strain. In the Figure 2, it may be observed a higher curve with this behavior. It's also noted that the difference between the curves starts to be considerable after the yield stress. Particularly, this difference is bigger from the ultimate tensile stress, since that the cross-sectional area decrease quickly until the rupture (Hibbeler, 2010).

The real stress and the real strain are calculated by the Eq. 4 and 5 respectively. If there is no change in the volume, what is true in the strain hardening region until the ultimate tensile stress, the real stresses and the real strains are related to the engineering stress and strains through the Eq. 6 and 7 respectively (Callister, Rethwisch, 2012).

$$\sigma = \frac{F}{A_i} \tag{4}$$

$$\varepsilon = \ln(\frac{l_i}{l_0}) \tag{5}$$

$$\sigma = \sigma(1+e) \tag{6}$$

$$\varepsilon = \ln(1+e) \tag{7}$$

The region of the real stress-strain curve between the plastic deformation and the ultimate tensile stress may be calculated by the Hollomon equation (Eq. 8) for some metals and alloys (Callister, Rethwisch, 2012):

$$\sigma = K\varepsilon^n \tag{8}$$

Where $K$ is the resistance coefficient [Pa] and $n$ is the strain hardening exponent, which goes from zero to the unity.

These coefficients vary for each material and for each kind of manufacturing process. Specifically, the strain hardening exponent will inform how much strain hardened the material can become (Callister, Rethwisch, 2012). So, when this exponent is zero, the material will deform plastically all the time with constant stress, while the material will deform proportionally to the stress when the exponent is equal to one. The Figure 3 represents these two cases.
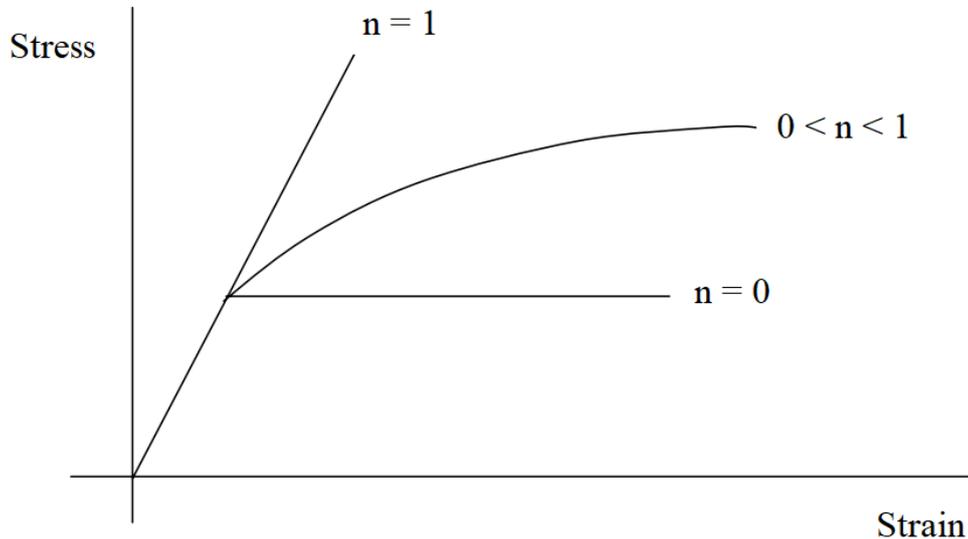


Figure 3. Effect of the strain hardening exponent on the plastic region of the stress-strain curve.

## 3. OBJECTIVES

The main objective of this work is to discuss and to analyze the capacity of manufacturing process to induce compressive residual stresses on a material and to relate this capacity to the strain hardening exponent of the material. Consequently, it was also evaluated the capacity to enhance the fatigue resistance of the material. The purpose was also to increase and to promote discussions about enhanced fatigue resistance of materials due to finishing process.

In this work, it was studied the shot peening process because its relatively easy to find works about it and it is a common process. Moreover, it was studied the strain hardening exponent with the attempt of excluding the influence of different kinds of materials.

## 4. LITERATURE REVIEW

There are many studies about increasing the fatigue resistance of a material due to some treatments and processes. Particularly, there are many studies about the shot peening influence over that property, however these studies focus on specific materials, so they cover a big variety of materials and they don't have correlation among each other. Nevertheless, they support and prove the thesis that the shot peening increases the fatigue resistance due to the induction of compressive residual stresses.

Recently, Antonialli et al. (2017) studied the surface condition influence over the fatigue resistance of carbon steels (AISI 1045 and AISI 1020) under specifics conditions and achieved an enhance of 58 % in the fatigue resistance for the first material, however no increase was identified for the second material. This difference was explained through the different conditions of the materials, while the first was annealed, the second was hardened. Also with a medium carbon stell, Sakamoto et al. (2015) studied the crack initiation and the fatigue resistance of this material and observed an enhance of 25 % in this last parameter.

Vielma et al. (2014) optimized the shot peening process for a higher increase in the fatigue resistance for an AISI 4340 steel and reached an increase of 100 % on the number of cycles to failure of this material. For low alloy steels, Trsko et al. (2014a) studied the influence of shot peening over the fatigue resistance of an 50CrMo4 steel and achieved an increase of 22 % on this resistance. Zavodská et al. (2016) studied the same influence on a 40NiCrMo7 steel and achieved an increase of 19 % on the same resistance.

Miková et al. (2013) utilized the shot peening to study the fatigue resistance of an microalloyed X70 steel and observed an enhance of 13 % in that property. Gerin et al. (2017) studied the superficial integrity influence over the fatigue resistance of an C70 steel and, after two different levels of the shot peening parameters, they achieved increases of 35 % and 40 % on the resistance.

Lindemann et al. (2016) studied the fatigue behavior of a titanium aluminide alloy with two different microstructural after been shot peened and verified an increase of 23 % and 57 % on the fatigue resistance.

There are many other studies about the effect of the shot peening over the fatigue resistance of the materials, as it may be seen in Tekeli (2002) and Trsko et al. (2014b), and they also verify an enhancing in this resistance. However, no more studies are mentioned here because they lack the mechanical properties of the materials, which are needed to help the further discussions of this work.

## 5. ANALYSIS METHODOLOGY

The calculus of the strain hardening exponent and of the resistance coefficient is done by admitting that the strain hardening region of the material obeys the Eq. 8. Applying the logarithm on both sides of this equation, it's obtained the Eq. 9 and it's observed that the strain hardening exponent is the angular coefficient of the line and Log(K) is the linear coefficient of this same line (ASTM E646-16, 2016).

$$\log \sigma = \log K + n \log \varepsilon \tag{9}$$

Besides that, it's utilized an analysis of the yield stress, proof stress, which is the necessary level of stress to get an 0,2 % of deformation of the material, and the ultimate tensile stress of the materials when the necessary data to the calculus of the strain hardening exponent is not informed. Moreover, it's done a comparation among the shot peening parameters, the compressive residual stresses and the increase in the fatigue resistance of the material.

## 6. ANALYSIS AND DISCUSSIONS

As it was said before, the induction of compressive residual stresses increases the fatigue resistance of the materials, once that the fatigue occurs due to tensile stresses. So, the induction of those stresses should be done depending on the kind of loading on the material. A great variety of applications of the materials is subject to cyclic loadings that cause tensile and compressive stresses and, usually, these stresses are higher on the surface of the material due to stress concentration factors or due to the kind of loading. Therefore, as the stresses are higher on the surface, the induction of compressive residual stresses are only needed on the surface of the material and that is why the shot peening is an important process to the increasing of the fatigue resistance.

Shot peening is a process that is characterized by the Almen intensity and by the coverage. The first parameter indicates the kinetic energy of the process and the second parameter indicates how much of the area has been processed.

The Table 1 presents the data withdraw from the references. Besides this, it was only possible to calculate the strain hardening exponent from the Antonialli's et al. (2107) study because the authors informed the data of their stress-strain curves. So, for the others works, it was identified others kinds of relations.

Table 1. References' mechanical properties, shot peening parameters and obtained results.

| Authors | Material condition | $\sigma_y$ [MPa] | $\sigma_{pr}$ [MPa] | $\sigma_{ut}$ [MPa] | Almen intensity | Coverage [%] | $\sigma_{rs}$ [MPa] | $\Delta$FL [%] |
|---|---|---|---|---|---|---|---|---|
| Antonialli et al. (2017) | Strain hardened | 546 | - | 620 | - | - | - | 0 |
| Antonialli et al. (2017) | Annealed | 375 | - | 705 | - | - | - | 58 |
| Sakamoto et al. (2015) | Annealed | - | - | - | 17 A | 500 | -300 | 25 |
| Vielma et al. (2014) | Quenched and tempered | 914 | - | 1197 | 10 A | 100 | -634 | 100 |
| Trsko et al. (2014) | Quenched and tempered | - | 702 | 929 | 15,6 A | 1000 | -500 | 22 |
| Zavodská et al. (2016) | Quenched and tempered | 1170 | - | 1292 | 12 A | 100 | -700 | 10 |
| Miková et al. (2013) | - | 495 | - | 605 | 16 A | 1000 | -430 | 13 |
| Gerin et al. (2017) | Annealed | 598 | - | 1020 | 3060 A | 200 | -500 | 40 |
| Gerin et al. (2017) | Annealed | 598 | - | 1020 | 2060 A | 200 | -500 | 35 |
| Lindemann et al. (2006) | - | - | 447 | 597 | 15,7 N | 100 | -610 | 57 |
| Lindemann et al. (2006) | - | - | 834 | 967 | 15,7 N | 100 | -820 | 23 |

Where $\sigma_y$ is the yield stress, $\sigma_{pr}$ is the proof stress, $\sigma_{ut}$ is the ultimate tensile stress, $\sigma_{rs}$ is the maximum residual stress and $\Delta$FL is the variation of the fatigue resistance.

With the Eq. 6, 7 and 8 and with the obtained data from Antonialli et al. (2017), it was possible to calculate the resistance coefficients and the strain hardening exponents of each material. These data are exposed in Tab. 2. It's observed that it was not informed the residual stresses, the Almen intensity neither the coverage in that work, however it's said that it was utilized the same shot peening parameters, so it's possible to infer that the capacity of the shot peening is related to the material condition, in others words, it was not observed an influence of the shot peening over the fatigue resistance for the hardened material, but, for the annealed material, which had no initial strain, it was observed an increase of 58 % in the fatigue limit. This difference between the conditions may be also verified by the difference between the ultimate tensile stress and the yield stress.

Table 2. Real stresses and real strains, resistance coefficients and strain hardening exponents of the Antonialli's et al. (2017) study.

| Material | $S_1$ [MPa] | $e_1$ [%] | $\sigma_1$ [MPa] | $\varepsilon_1$ [%] | $S_2$ [MPa] | $e_2$ [%] | $\sigma_2$ [MPa] | $\varepsilon_2$ [%] | n | K [MPa] |
|---|---|---|---|---|---|---|---|---|---|---|
| AISI 1045 | 430 | 1,28 | 436 | 1,27 | 621 | 4,29 | 648 | 4,20 | 0,328 | 402 |
| AISI 1020 | 566 | 1,18 | 573 | 1,17 | 605 | 1,84 | 616 | 1,82 | 0,163 | 558 |

Examining the Gerin's et al. (2017) results, it can be seen that the significant relative increase of the Almen intensity (50 %), when compared to the other experiment, did not considerable increase the fatigue resistance of the material. It's also observed that the levels of the induced compressive residual stresses were the same. So, it can be inferred that both the induction of compressive residual stresses and the increase in the fatigue resistance do not depend just on the Almen intensity. It was also discussed that there are not preferred directions for the induction of the residual stresses.

Vielma's et al. (2014) study showed a big increase in the fatigue resistance of the material for a condition in which was applied 50 % of the ultimate tensile strength as the cyclic load. Besides that, it was discussed that the induction of residual stresses didn't depend too much on the Almen intensity. This was concluded by the observation that the higher induced levels of the compressive residual stresses didn't increase with an increase in the Almen intensity, this just caused an induction of the residual stresses in lower layers. So, the amount of induced compressive residual stresses would be limited by characteristics of the material.

Trsko et al. (2014a) and Miková et al. (2013) obtained similar induced compressive residual stresses with similar Almen intensities, however the increase in the fatigue resistance was different, with the second work achieving almost twice times as much increase in the resistance as the first work. By this fact, it may be inferred that the increase in the fatigue resistance will not depend on the higher compressive residual stress level, but it will depend on the variation of the induced residual stresses. The Sakamoto's et al. (2015) and Zavodská's et al (2016) studies don't provide much information when analyzed separately, however, when they are compared with each other, it can be observed that the first work achieved an increase in the fatigue resistance that is twice and a half times than the second work. This also occurred in a lower level of the Almen intensity and with a considerable lower compressive residual stress. These data collaborate with the thesis that the residual stress does not depends just on the Almen intensity and that the increase in the fatigue resistance depends also on the variation of the residual stresses on the material. By last, the Lindemann's et al. (2006) results were different from each other even being obtained with the same shot peening parameters. The authors say that this may have happened because the induction of compressive residual stresses depends more on the material condition than the shot peening parameters.

## 7. CONCLUSIONS

This work reviewed some references that studied the effect of the shot peening over the induction of compressive residual stresses on a material and, consequently, over the fatigue resistance. The main conclusions of this work are:

- The induction of compressive residual stresses by shot peening occurs due to the plastic deformation on the surface that this process provokes. So, if the material is in a condition that has low capability to deform plastically, these compressive residual stresses won't be induced. This capacity can be observed by the strain hardening exponent. The difference between the yield stress and the ultimate tensile stress could also indicate this capacity to deform plastically;

- The limit of the shot peening capacity on inducing compressive residual stresses was related to the capacity of the material to strain harden. Thus, there is no effectiveness on increasing the Almen intensity for a material that can't be more plastically deformed. It was also observed that the increase of the intensity beyond the material limit just induces residual stresses on lower layers, however this was not very helpful because it is the surface compressive residual stresses that increase the fatigue resistance;

- The effectiveness of the shot peening also depends on the yield limit of the material because a determined Almen intensity may cause big plastic deformations on a material with low yield limit, while it will cause just small, or even none, plastic deformations on a material with high yield limit;

- The increase in the fatigue resistance is related to the induction of residual stresses variation and not with the final value of it. So, materials that already have residual stresses may suffer a lower influence of the shot peening when they are compared to materials that do not have residual stresses.

It was not studied others parameters in this work because there are not too many data on the references. These others parameters could be the coverage, the variation of residual stresses and others. Thus, it is identified the need for more studies that cover and study all the parameters mentioned in this work, as their variation, for a more complete comprehension of the shot peening effect or of other process that also induce compressive residual stresses. It is also verified that is possible to stablish a relation among the induction of residual stress, the Almen intensity, the yield stress and the ultimate tensile stress or the strain hardening exponent. So, this possible induction of residual stresses can be related to the enhance in the fatigue resistance, provided that it is evaluated the initial residual stresses of the materials.

## 8. ACKNOWLEDGEMENTS

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