INFLUENCE OF SHOT PEENING ON CHROMIUM-ELECTROPLATED AISI 4340 STEEL FATIGUE STRENGTH

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Abstract

Chromium electroplated AISI 4340 steel features good wear and corrosion resistance due to chromium coating and it is widely used in aeronautical components. But microcracks in chromium layer deriving from the process are prejudicial to component fatigue strength as these cracks rapidly propagate when under cyclic loads. One way to recover fatigue strength of chromium electroplated AISI 4340 steel is to treat its surface with shot peening, inducing compressive residual stresses on surface layers that act as a barrier to microcracks propagation deriving from the chromium coating. This research objective is to evaluate the influence of shot peening in chromium-electroplated AISI 4340 steel fatigue life and the influence of different shot materials, this is, steel and ceramic shots. It was observed that peened chromium electroplated AISI 4340 steel presented around 100% of recovering in fatigue limit in both peening conditions.

Introduction

In evaluation of components and structures fatigue has become an integral part of the design process in many industries – Pelloux [1]. Therefore, components subjected to constant and variable amplitude loading must have an improved research which main objective is structural security – Perez [2]. In high strength steels under high stress amplitude level, fatigue life is directly related to surface conditions, as the surface has more favourable conditions for nucleation and crack growth than the core, due to geometrical and mechanical conditions - Bodger [3].

AISI 4340 steel is widely used in aircraft industry for fabrication of structural components, in which strength and toughness are important design requirements. It is heat treatable, low alloy steel containing nickel, chromium and molybdenum. It features good performance when under cyclic loads, retaining good fatigue strength while developing high tensile strength in heat treated condition.

Despite of such characteristics, in some aeronautical applications it is interesting to improve wear and corrosion resistance of AISI 4340 steel components. Corrosive gases coming from turbines in high speed and temperature can give cause to a severe corrosion process in some components, leading to its failure. One of the most used techniques to improve corrosion and wear resistance under such conditions is to cover the component with a thin layer of some material resistant to corrosion. Researches have been developed in

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recent years showing that coatings with materials like nickel, chromium, tungsten carbide, Zn-Ni, Zn-Co and Zn-Fe are effective to increase wear and corrosion resistance of aeronautical components [4 – 8].

Between then, chromium plating is the most used electrodeposited coating to obtain high levels of hardness, resistance to wear and corrosion and a low coefficient of friction for applications in aerospace, automotive and petrochemical fields - Bodger [3]. These chromium features are due to its high hardness, about 70 HRc or 800 HB. A superficial covering using hard chromium is applied to improve corrosion resistance and low friction coefficient of AISI 4340 steel.

A significant characteristic of chromium electroplating is the high tensile residual internal stresses originating from the decomposition of chromium hydrides during the electrodeposition process - Jones [10]. These high tensile stresses in electroplated chromium coatings are relieved by local microcracks during electroplating. As the coating thickness increases, tensile stresses get higher until the occurrence of microcracks that relieve the deposition stresses – Nascimento et al [4].

Under fatigue conditions, these microcracks propagate and penetrate through the substrate leading to a decrease of fatigue strength of a component. Due to this fact, the design of hard chromium electroplated components, which are subjected to dynamic loads, may consider this negative influence to guarantee safety during operation. Therefore, the use of effective methods to improve fatigue strength must be considered [4].

One of the known ways to improve fatigue resistance is by using the shot peening process to induce compressive residual stress in the surface layers, making propagation of fatigue cracks originated in chromium coating more difficult – Los Rios et al [11]. The compressive residual stress is obtained due to surface plastic deformation and is responsible for increasing fatigue strength in mechanical components. Usually, fatigue cracks nucleate and propagate from the surface due to surface texture and defects like stretches, but Torres and Voorwald [5] presented some cracks nucleation originated in sub surface layers, under the compressive residual stress field due to shot peening treatment, indicating that such stress acts as a barrier to crack propagation. The compressive residual stress field induced by shot peening is dependent on various parameters like shot intensity, stream energy, shot material and dimensions.

In that case, shot peening is a good technique to recover the fatigue strength decreased by chromium coating on AISI 4340 steel. The objective of this paper is to study such effect of shot peening in specimens chromium electroplated subjected to rotating bending fatigue test evaluating the influence of different shot materials used in shot peening process, this is, steel and ceramic shots.

**Experimental Procedures**

AISI 4340 is a heat treatable, low alloy steel containing nickel, chromium and molybdenum. It is known for its toughness and capability of developing high strength in the heat-treated condition while retaining good fatigue strength. The chemical analysis of the material used in this research indicates accordance with specifications. AISI 4340 chemical composition used was 0.41 C–0.73 Mn–0.8 Cr–1.74 Ni–0.25 Mo–0.25 Si, wt%. The mechanical properties of this alloy are: (49–53) HRC, yield strength of 1511 MPa, ultimate tensile of 1864 MPa, and
fatigue limit of 800 MPa (53% of yield strength). These properties were obtained by means of quenching from 830 °C followed by double tempering in the range (230 ±5)°C for 4 hours.

![AISI 4340 Heat treatment](image)

**FIGURE 1. AISI 4340 Heat treatment**

**Fatigue test**

Rotating bending fatigue tests according to AMS6414 were conducted using a sinusoidal load of frequency 50 Hz and load ratio R = -1, at room temperature, considering, as fatigue strength, the complete specimens fracture or $10^7$ load cycles. Six groups of fatigue specimens were prepared to obtain S –N curves for bending fatigue tests:

- specimens of base material,
- specimens of base material with conventional hard chromium electroplating, 160 µm thick,
- specimens of base material peened with steel shots,
- specimens of base material peened with ceramic shots,
- specimens of base material peened with steel shots and chromium electroplated,
- specimens of base material peened with ceramic shots and chromium electroplated.

![Rotating bending fatigue testing specimen](image)

**FIGURE 2. Rotating bending fatigue testing specimen.**

**Shot Peening**

Specimens were submitted to shot peening treatment with steel shots in accordance to MPE01-009, hardness range of 55 - 65 HRC, diameter of 1.0 mm and, also using ceramics shots (Z300) supplied by SERP, diameter between 0.3 mm and 0.4 mm. Shot peening intensity used was 0.008 A for ceramics shots and 0.00118 A for steel shots. The process was carried out on an air-blast machine according to standard MIL-S-13165.
**Hard chromium electroplating**

The conventional hard chromium electroplating was carried out from a chromic acid solution with 250 g/l of CrO₃ and 2.5 g/l of H₂SO₄, at 50-55 °C, with a current density from 31 to 46 A/dm², and speed of deposition equal to 25 µm/h. A bath with a single catalyst based on sulphate was used. After coating deposition, the samples were subjected to a hydrogen embrittlement relief treatment at 190 °C for 8 hours.

**Results and discussion**

The S–N curves for the rotating bending fatigue test for the base material and coated specimens are presented in Fig. 3. It is possible to observe the great decrease in fatigue strength due to chromium coating, around 47%. Fatigue limit for base material is 800 Mpa (53% σ<sub>ys</sub>) while fatigue strength for coated material is 420 MPa (28% σ<sub>ys</sub>).

A comparison between S-N curves of base material and for the two peening conditions – steel shots and ceramic shots – is made on Fig. 4. It was observed that shot peening increased fatigue strength of base material. Peening using ceramic shots presented a lower scatter than peening with steel shots, moreover the former presented a higher fatigue limit of 930 MPa (61% σ<sub>ys</sub>) against 900 MPa (59% σ<sub>ys</sub>) of steel shots. It is possible to observe in Fig. 5a the deformation on surface due to shot peening, and in Fig. 5b the crack nucleation under the compressive residual stress field on surface layers.

Surface roughness after shot peening is Rₐ = 1.38 for ceramic shots and Rₐ = 0.95 for steel shots. These results are in accordance to shot diameter, between 0.3mm and 0.4mm for ceramic shots and 1.0mm for steel shots. The roughness was not a determinant factor on fatigue strength as a higher roughness tends do decrease fatigue limit. On the contrary it was
observed that in spite of its higher roughness in comparison to steel shot, ceramic shot fatigue limit is higher. Thus, probably, the determinant factor was peening intensity as the specimens were shot peened with 0.008 A with ceramic shots and 0.00118 A with steel shots.

![Figure 4](image1.png)

**FIGURE 4.** S-N curves for base and peened material.

![Figure 5](image2.png)

**FIGURE 5.** Fatigue fracture surface AISI 4340 peened with ceramic shot

Finally, it is presented in Fig. 6 the effect of peening on fatigue strength of AISI 4340 steel chromium electroplated. The peening treatment, both with steel and ceramic shots, presented good results, increasing the fatigue strength of AISI 4340 steel chromium electroplated up to levels of base material without chromium. In this situation, the compressive residual stress field induced on material surface due to shot peening treatment acted decreasing the harmful effects of microcracks in chromium layer.
FIGURE 6. S-N curves for base material chromium electroplated and shot peened.

In all situations presented, the effect of chromium or shot peening is more significant in high cycle fatigue tests than in low cycle fatigue tests. High stress on low cycle makes crack propagation so fast after crack nucleation, no matter whether the specimen is the base material or electroplated or peened. In specimens without shot peening or chromium it is natural that the crack source comes from the surface, where the maximum tensile stress occurs, induced by the tests characteristics [5]. Chromium layer acts as an artificial surface for the specimens and this surface is full of microcracks that rapidly propagates under high stress. The high applied tensile stresses always surpass the compressive residual stress field induced by shot peening on specimen surface inducing a fast crack propagation, no matter if the crack is deriving from chromium layer or surface defects.

In chromium electroplated specimens under high cycle fatigue tests or lower stresses, it is not necessary a nucleation of a crack from surface as chromium layer provides several microcracks. The nucleation phase of fatigue crack is skipped and the fatigue process go straight to second phase, this is, propagation, reducing the time needed to lead the component to failure. Lower stresses do not surpass the compressive residual stress field on peened specimens allowing shot peening treatment to act as a barrier to crack propagation, delaying the second phase of fatigue process. These mechanisms explain how chromium decreases fatigue life of AISI 4340 steel when chromium electroplated and how shot peening increases its fatigue life.
FIGURE 7. Fatigue fracture surface of chromium electroplated AISI 4340 peened with ceramic shot (112x).

Conclusions

1. Experimental results indicate a significant reduction in AISI 4340 steel fatigue strength when chromium electroplated.

2. S-N curves indicate the importance of the compressive residual stress field induced by shot peening treatment as a barrier to crack propagation.

3. For base material AISI 4340 52 HRC peened, the fatigue limit obtained with ceramic shots 930 MPa (61% $\sigma_{ys}$) was a little higher than with steel shots 900 MPa (59% $\sigma_{ys}$), indicating that the differences between the two processes were not so significant to final results.

4. For base material peened and chromium electroplated it was observed a recovery of fatigue limit up to levels of base material without chromium, with no considerable differences between ceramic shots and steel shots treatments.

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References


