Ageing characterization of exhaust flexible couplings

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AGEING CHARACERIZATION OF EXHAUST FLEXIBLE COUPLINGS

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ABSTRACT

The aim of this work is to investigate the mechanical strength of automotive exhaust flexible couplings subjected to thermo-mechanical fatigue and corrosion. Five different types of flexible coupling have been considered, realised by four different king of materials: three stainless steels (AISI 309, AISI 321, AISI 321 Ti) and a nickel alloy (Incoloy 825). These components have been tested by a dedicated procedure consisting of different cycles of fatigue, heating and corrosion. Performances of the components have been compared by means of the CTQs approach.

Keywords: Mechanical characterization, nickel based superalloy, flexible coupling, ageing

INTRODUCTION

Flexible exhaust coupling is a component joining the exhaust collector with the rest of the exhaust system and also decoupling the engine from the exhaust system. Working conditions of this component are very severe: it is subjected to vibrations, high temperatures, aggressive environment caused by hot exhaust and external conditions (as an example the winter salt deposed on the roads), and mechanical fatigue (Crum et al., 1999).

Exhaust passes through the exhaust flexible coupling, so it is very important the flexible to be well designed in order to avoid cracks and failures causing leak of dangerous and pollutant gases (Curà et al., 2008).

Because of the complex geometry and load conditions of this component, it is important to study not only the characteristics of materials, but also to study the behavior of the whole component. In literature some works are available about thermo-mechanical, ageing and corrosion characterization of materials used for automotive exhaust systems (Curà et al., 2012), but the investigation on the whole component is lacking.

Crum et al., 1999 studied the effect of hot salt attack, stress corrosion cracking and high temperature embrittlement on materials used for automotive exhaust flexibles; the ageing procedure consists in thermal and chemical attack without applying any mechanical stress.

Others works found in literature involve experimental activities related to the mechanical characterisation of metals, but no emphasis has been done to the combined ageing effects found in components of exhaust systems. As some examples: Choi at al. 2008 evaluated the corrosion damage over five years period of coated steels in automotive chassis parts.

Pan et al., 2001 studied the effect of strain rate and aging on the mechanical properties of sheet steels.

Guan et al., 2005 studied the effect of ageing at 700 °C on both AISI 321 and AISI 347 austenitic stainless steels weld pointing out how ductility and toughness may change drastically after long ageing times.

Padilha et al., 2005 studied both microstructures and mechanical properties of Fe15Cr15Ni austenitic stainless steels. In that paper the microstructures and the mechanical properties of cast, hot forged, solution annealed and aged samples are evaluated and compared. The mechanical properties of the hot forged, solution-annealed and aged (700°C) specimens point out improvements in yield strength, tensile strength and hardness, but a significant deterioration in ductility (total elongation).

Llanes et al., 1996 investigated the aging effects on the cyclic deformation mechanisms of a duplex stainless steel, the AISI 329. Aging at 475°C of duplex stainless steels induces several microstructural modifications on mechanical properties as a strong increase of the yield strength and ultimate tensile strength as well as the decrease fracture ductility.

Shanker et al., 2001 investigated the microstructural and mechanical properties of Inconel 625 superalloy; after 60000 hours of service at approximately 873 K and higher than service temperatures for different durations. That paper correlates the mechanical behaviour with the microstructural changes occurring with various heat treatments. It has been observed a decrease in the yielding stress value of the service-exposed material on aging for 1 hour at 1123K. Ageing of re-solution annealed alloy at 923K caused improvement in yielding stress and reduction in ductility with aging time.

Girone et al., 2005 investigated the influence of artificial seawater on the low cycle fatigue behaviour of a superduplex stainless steels in air and in artificial seawater. The results showed a remarkable reduction in fatigue life in the presence of the aqueous solutions especially for high strain amplitudes.

More recently Zhang et al., 2009 and Kuo et al., 2009, made ageing tests respectively on alumina forming austenitic stainless steels, 2101 stainless steel and the nickel alloy Inconel 718.

Aim of this paper is to evaluate the effect of thermo-mechanical fatigue and corrosion on the mechanical strength of flexible exhaust coupling made of different materials.

For this reason, an ageing procedure has been developed in order to simulate both mechanical and thermal stresses and chemical attacks subjecting the flexible joints during its life.

This procedure has been tested on five different types of components made by four different materials, three austenitic stainless steels and a nickel alloy.

The comparison between the above quoted components, in terms of variation of both mechanical strength and effect of corrosion, has been carried on by using the Critical to Quality approach CTQs (Zonfrillo et al, 2008).

MATERIAL AND METHODS

The flexible exhaust coupling, represented in Figure 1, is composed of two metal layers. All components tested in this work have the same shape geometry and dimensions, but they are made using different materials: three stainless steels (AISI 309, AISI 321, AISI 316 Ti) and a nickel alloy (Incoloy 825). In this work five kinds of flexible exhaust couplings have been tested, four made of a single material, respectively AISI 309, AISI 321, AISI 316 Ti and Incoloy 825, and one made of two materials Incoloy 825 and AISI 321.

Fig.1 Flexible exhaust coupling

In order to investigate the mechanical strength of these components when subjected to thermo-mechanical fatigue and corrosion, a dedicated testing procedure has been developed.

The ageing procedure consists in three phases:

1. specimens are mounted on a dedicated thermo-mechanical fatigue test rig that and subjected to a fatigue ageing with 350Mpa stress at 600°C being sprayed with a saline solution. The solution is composed by NaCl, MgCl and CaCl2 (30% solution in water: 40 parts in weight of NaCl, 1 part in weight of CaCl2, and 1 part in weight of MgCl2), in order to simulate the chemical mix used on the roads to prevent the formation of ice. This phase consist in 288000 cycles (10 hours at 8Hz);
2. specimens are subjected to a salt spray rest according to the German Standard DIN 50021. The saline solution used in this phase is the same used in phase 1;
3. phase 1 is repeated

At the end of the ageing procedure all components have been analysed by considering mechanical failures and corrosion phenomena by means of an optical microscope.

The comparison between the component has been done from mechanical corrosion and cost point of view by using the CTQs approach (Zonfrillo et al, 2008), in order to compare the materials performance: this approach consists in calculating an index value for each characteristic. In this work five characteristics have been considered and the corresponding index calculated:

- tensile strength index I_{Rm};
- yield strength index I_{Rp02};
- low cycle fatigue index I_{LCF}
- corrosion index I_C;
- cost index I_{cost}

Tensile strength index I_{Rm} has been calculated by the following expression:

$$I_{Rm} = (R_{mTe} - \sigma_{ref}) + (R_{m500} - \sigma_{ref}) \quad (1)$$

where: R_{mTe} is the ultimate tensile stress of the material at room temperature, R_{m500} is the ultimate tensile stress at 500°C temperature, and σ_{ref} is the stress applied at the component during the ageing procedure.

Yield strength index I_{Rp02} has been calculated by the following expression:

$$I_{Rp02} = \frac{R_{p02Te} + 2 \cdot R_{p02500}}{3} \tag{2}$$

where: R_{p02Te} is the yield strength of the material at room temperature, R_{p02500} is the yield strength at 500°C temperature.

The low cycle fatigue index I_{LCF} has been calculated by the following expression:

$$I_{LCF} = 3.5\left(\frac{R_{mTe}}{E}\right)N^{-0.12} + \Delta Z \cdot N^{-0.6} \tag{3}$$

where E is the young's modulus of the material, ΔZ is the necking deformation of the material and N is the number of cycle when the component presents any mechanical failure.

The corrosion index I_C has been obtained considering four kinds of corrosion phenomena: general corrosion, intergranular corrosion, pitting corrosion and hot salt corrosion. For each corrosion phenomena, two penalties have been assigned: one representing the level of danger related to the corrosion and the other concerning the entity of the corrosion attack, according to Table 2.

Table 2: Penalty assigned to the corrosion phenomena

Danger	**Penalty**
Not dangerous	1
Dangerous	2
Very dangerous	3
Entity of the corrosion	**Penalty**
Not present	0
Small traces	0.5
In much of the area	1
Large areas	1.5
Widespread	2

The cost index I_{cost} has been obtained considering the material costs and normalising by the maximum cost value.

The ranking of analysed materials is obtained by means of the target function OF. The OF function is calculated by multiplying the normalized values of the indexes $CTQs_i$ with the associated weight C_i:

$$OF = \sum_i C_i \cdot CTQs_i \tag{4}$$

Weights considered in this work are: $C_{Rp02} = 1$; $C_{Rm} = 1$; $C_{LCF} = 2$; $C_C = 3$; $C_{cost} = 3$.

RESULTS AND DISCUSSION

In this work totally 39 components have been tested. During the aging tests many mechanical failures occurred on the components, as an example Figure 2 shows a fatigue crack occurred on an AISI 309 component.

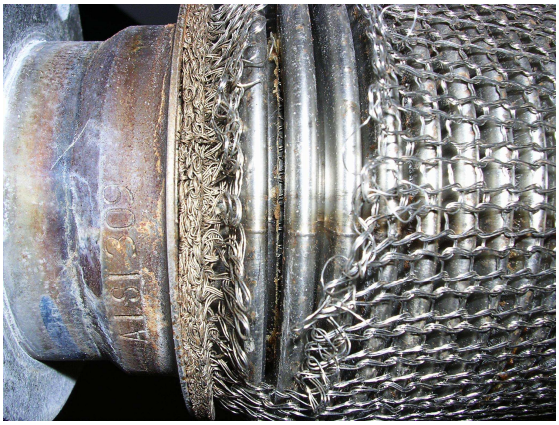

Fig.2 Fatigue crack on a AISI 309 component

Figure 3 shows a detail (400X magnification) of a crack growth of an AISI321 component.

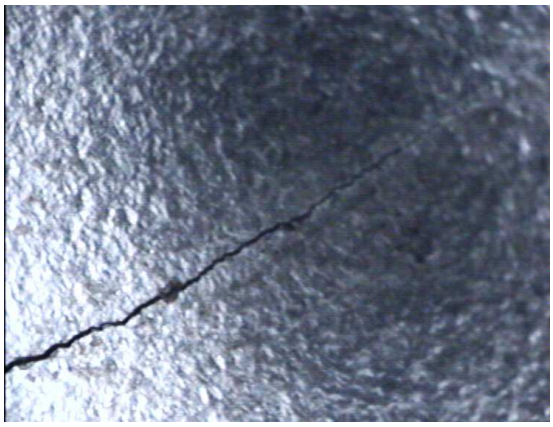

Fig.3 Fatigue crack propagation on a AISI 321 component (400X magnification)

The most important corrosion phenomena occurred on the tested components are: general corrosion, intergranular corrosion, pitting corrosion and hot salt corrosion.
As an example, Figure 4 shows a particular of general corrosion on an AISI 309 component, and Figure 5 shows pitting corrosion phenomena on AISI 321 component.

Fig.4 General corrosion on a AISI 309 component (800X magnification)

Fig.5 Pitting on a AISI 316Ti component (800X magnification)

The results in terms of fatigue and corrosion resistance have been analysed by means of the CTQs approach, giving penalty factors and weight to each damaging parameter showed in the precedent paragraph. Also the costs of materials have been considered into the CTQs analysis.

Figures 6 to 10 show respectively the tensile strength, the yield strength, low cycle fatigue, corrosion, and cost normalised indexes.

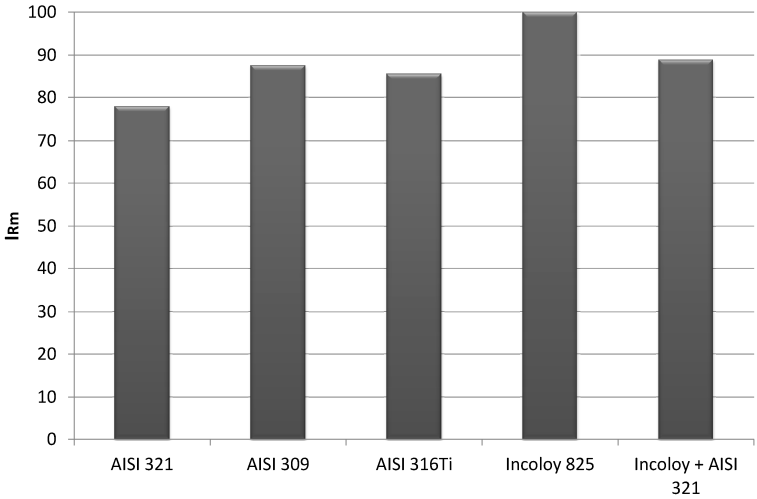

Fig.6 Tensile strength index I_{Rm}

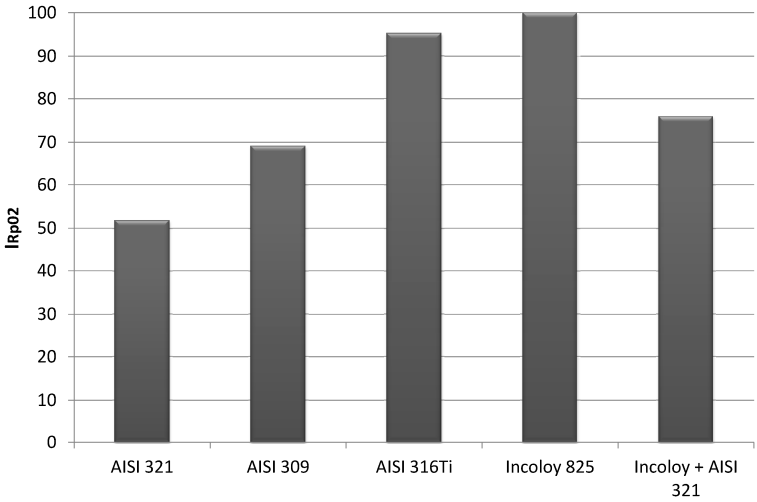

Fig.7 Yield strength index I_{Rp02}

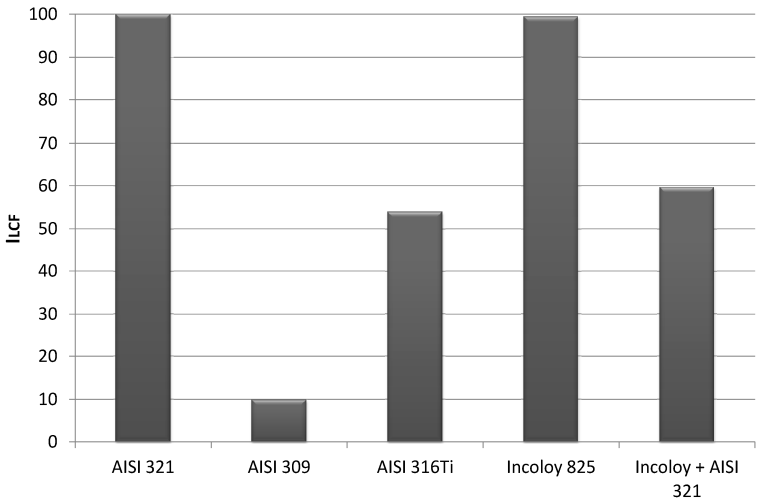

Fig.8 Low cycle fatigue index I_{LCF}

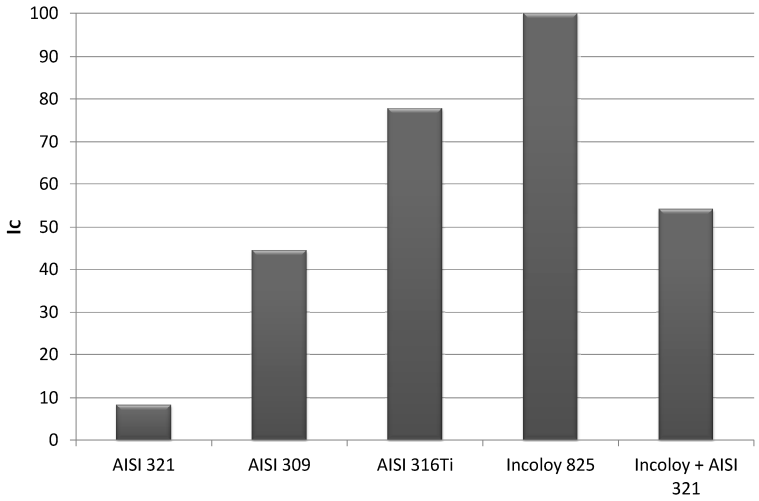

Fig.9 Corrosion index I_C

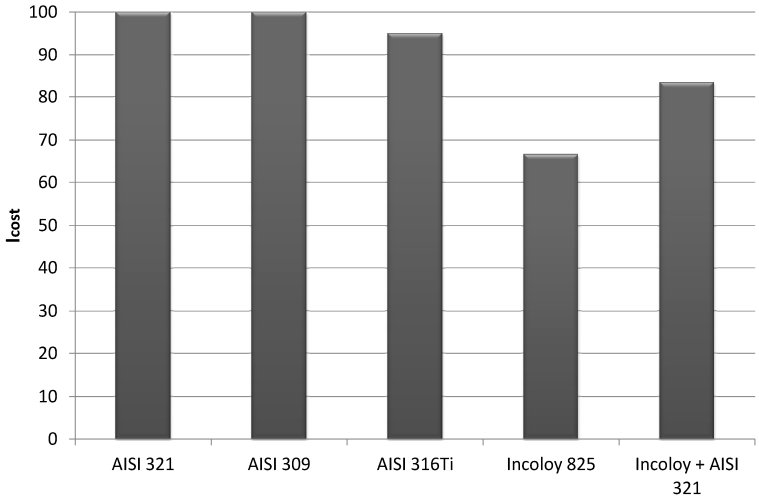

Fig.10 Cost index I_{cost}

Figure 11 shows the final ranking of the analysed components. Components made of Incoloy 825 have the best scores given by CTQs analysis.

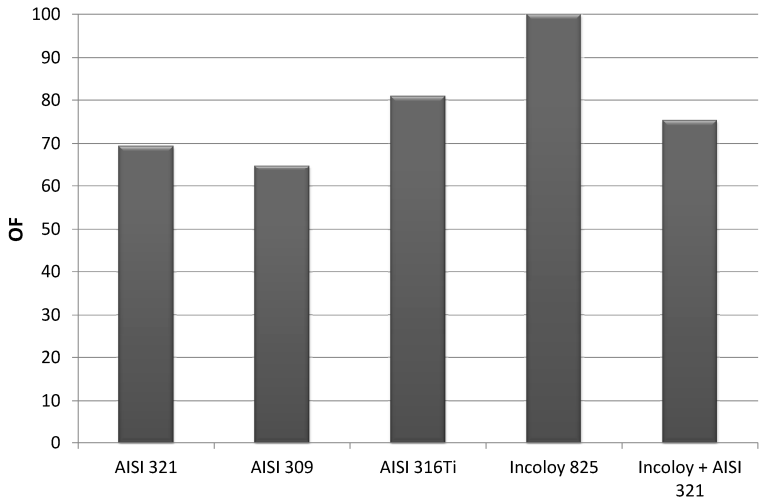

Fig.11 Final ranking of analyzed components

CONCLUSIONS

In this work an investigation about the mechanical strength of exhaust flexible coupling subjected to thermo-mechanical fatigue and corrosion have been performed. Five king of component have been considered, made of different materials. Performances of the components have been compared using the critical to quality (CTQs) approach. Results show that the components made of Incoloy 825 are the best for the application in flexible exhaust joints, referring to the materials considered in this work. Moreover, results show that the fatigue ageing process developed in this work allows a good damage characterization of commercial automotive flexible joints. The CTQs approach results being an useful method to compare the performances of mechanical components.

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