# INFLUENCE OF MECHANICAL CHARACTERISTICS ON THE OPERATING BEHAVIOR OF COMPRESSORS INTAKE AND EXHAUST VALVES MADE OF INCONEL X750 SUPERALLOY

Andrei GRECU[1], George COMAN[1*], Andrei BERBECARU[1], Ecaterina MATEI[1], Ioana GHERGHESCU[1], Andra PREDESCU[1], Sorin CIUCĂ[1], Cristian PREDESCU[1]

*The objective of the research is to establish the causes that led to the shutdown of a recirculation compressor following the failure of several springs in the intake and exhaust valve system. The Inconel X750 superalloy is known as a material with excellent corrosion and mechanical performance in a wide range of temperatures and working environments, being used for highly stressed components in steam turbines, gas turbines, petrochemical equipment or nuclear energy. The choice of Inconel X750 superalloy for the execution of valve springs of compressors is correct, it has mechanical characteristics in a relatively wide band, depending on the applied heat treatment.*

*Structural and chemical analyzes were carried out on damaged springs in order to determine the material quality and also the matrix and precipitates chemical composition by SEM - EDAX. HV50 hardness tests were made and phenomena that determined the springs breaking were evaluated by SEM fractographic analyses.*

**Keywords**: Inconel X750, compressor valve spring, SEM fractographic analysis.

## 1. Introduction

Inconel X750 superalloy is known as a material with excellent performances regarding corrosion and mechanical resistance in a wide range of temperatures and working environments. Highly stressed components for steam turbines, gas turbines, petrochemical or nuclear energy equipment are its typical applications.[1]

Considering the information provided by technical literature, one may estimate that the choice of Inconel X750 superalloy for compressors valve springs execution is a correct one. Although the material is efficient and recommended in such applications, many such springs have failed in operation after shorter periods of time than the compressor lifetime. The research objectives presented in this paper were to find the causes that led to the premature failure in service of these parts.

[1] Faculty of Applied Chemistry and Materials Science, University POLITEHNICA of Bucharest, Romania, *Corresponding author: george.coman@upb.ro

## 2. Macroscopic analysis

### 2.1 Springs visual assessment

29 valve springs made of 0.7 mm wire, with different features, were analyzed. 13 springs, 9 unbroken and 4 broken, are of a darker colour (Fig. 1), while 16 other springs, all broken, are light coloured (Fig. 2), suggesting easier working conditions or shorter working times when compared to the dark colored ones.[2]

Fig. 1. Full spring with 10 coils, dark coloured.

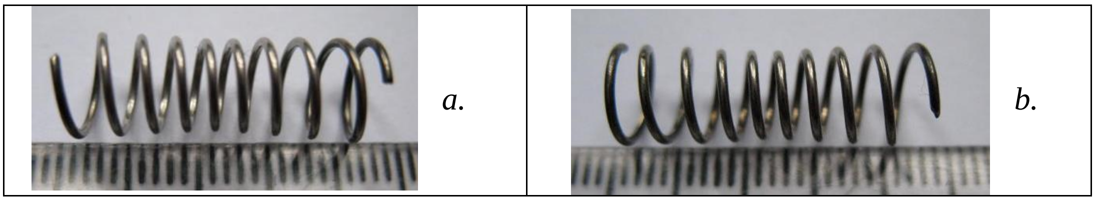



Fig. 2. Light - colored spring fragments
a) fragment with 9 coils; b) fragment with 9 and 1/4 coils.

The typical aspect of the unbroken springs end zones is illustrated in Fig.. 3. One may see that, at both ends of the spring, the last coil is slightly bent over a length equal to approximately ¼ of the circumference. In fact, the springs do not have the ends formed in such a way as to present parallel seating surfaces on the entire circumference, which would be the needed geometry in order to ensure a correctly submitted stress during axial compression.[3],[4],[5],[12]

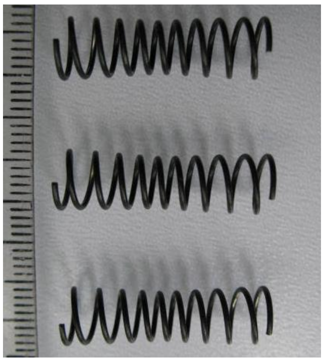


Fig. 3. Typical aspect of unbroken springs end zones

Macroscopically, the springs surfaces regardless their colour, appear relatively smooth, without blows. Examined with a magnifying glass, some surfaces show dark coloured points or small material detachments. On coils 2 ÷ 3 some springs show traces of friction, both on the inner and outer diameter [6]. Observed under the optical microscope, the ends of the unbroken springs (Fig. 4a) can be easily differentiated from those of the springs that failed in service (Fig. 4b).

a) b)

Fig. 4. Spring end profile view: a) unbroken spring; b) broken spring

### 2.2. Dimensional analysis

The unbroken springs have 10 coils, a length of approximately 25 mm and show a hyperbolic profile, meaning that the spring outer diameter spring increases progressively from the middle of the length to the extremities. Also, the coils pitch of the is uneven, smaller in the central area and increasing towards the extremities. The size measurements results are summarized in Table 1.

*Table 1.*

**Dimensions of the examined springs, mm**

| Characteristics | Dark coloured springs | | Light coloured springs |
|---|---|---|---|
| | Unbroken | Broken | |
| Wire diameter | 0,71 | 0,71 | 0,71 |
| Outer diameter in end areas | 7,0 ÷ 7,39 | - | 7,19 ÷ 7,38[1)] |
| Pitch in end areas | 2,8÷3,0 | 2,8÷3,0 | 2,8÷3,0[1)] |
| Outer diameter in middle zones | 6,30 ÷ 6,50 | 6,33 ÷ 6,51 | 6,33 ÷ 6,60 |
| Pitch in middle zones | 2,2÷2,3 | 2,2÷2,3 | 2,2÷2,3 |
| Total length | 24,0 ÷ 25,8 | 20,2 ÷ 21,3 | 21,3 ÷ 22,1 |

Obs. The measurement was done at the unbroken end

Some remarks may be made following the macroscopic analysis:

- there were no differences in springs geometry to be reported, no matter their different colour shades;
- unbroken springs have 10 coils; 17 broken springs gave way in segments placed in their extremities (7 ÷ 9 ¼) and only in 3 cases in the springs central segments;
- as a consequence of the springs extremity features, their lengths are difficult to be measured, the obtained results presenting a significant dispersion;
- the broken springs exhibit special feature surfaces at one of the ends, as can be seen in Fig. 4.

## 3. Microfractographic analysis

The analysis was performed on an scanning electron microscope FEI. The morphologies of the spring coils and breaking surfaces were investigated, as well as the chemical compositions of some spring areas exhibiting particular features.

In the first stage, the aspect of the spring wire surface along the coils was analyzed. In Figs. 5 and 6 images of dark and light coloured surfaces of springs, respectively, can be seen, as well as several results of chemical composition determinations carried out using the EDS technique.

Light-coloured spring surfaces appear relatively clean up to high magnifications. Hard (undeformed) precipitates representing carbides of Nb, Ti and Cr can be observed in the matrix as well as small voids probably resulted from precipitates tearing from the same matrix. [7] [11]

The surfaces of the dark-coloured springs appear relatively uneven along the wire pulling direction. Obviously, the morphology change resulted from the metal interaction with the technological medium. The examination also identified the presence of compounds containing carbon and oxygen on the surfaces, elements that are not present on the light-coloured surfaces. However, a connection between the darker coloured springs surfaces unevennesses and the operating behavior of the respective springs could not be highlighted.

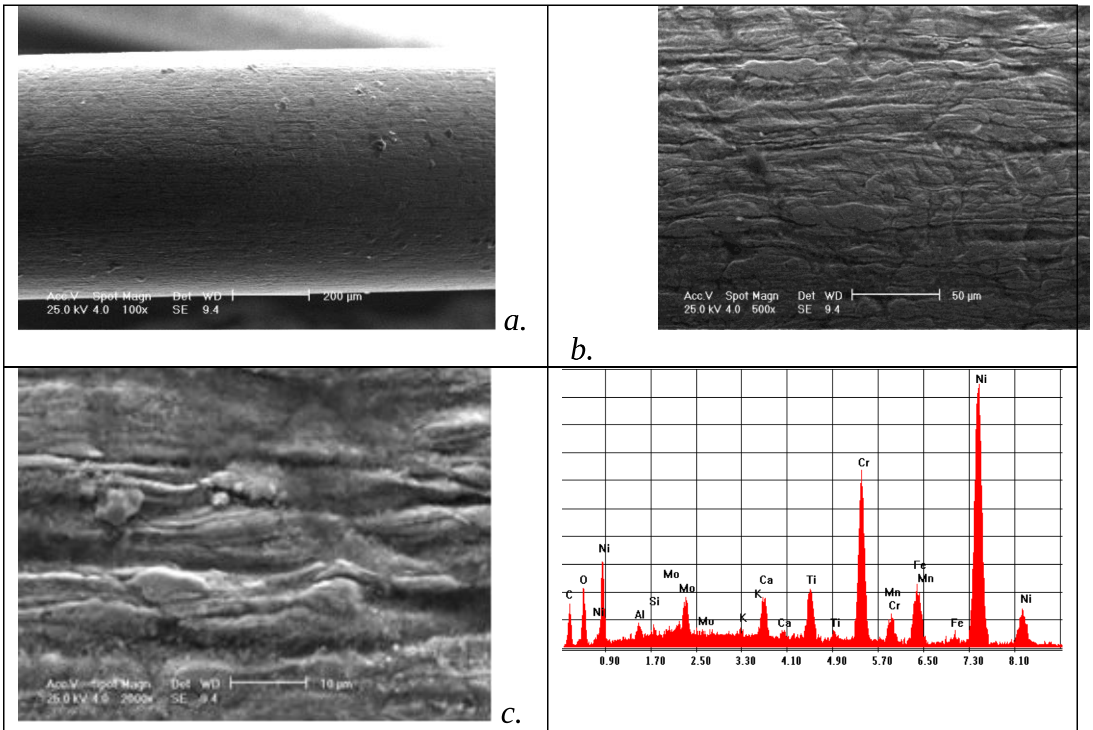



Fig. 5. Secondary electron images of the dark coloured spring surface
[a) ×125; b) ×600; c) ×2000] and qualitative EDS analysis on the spring surface

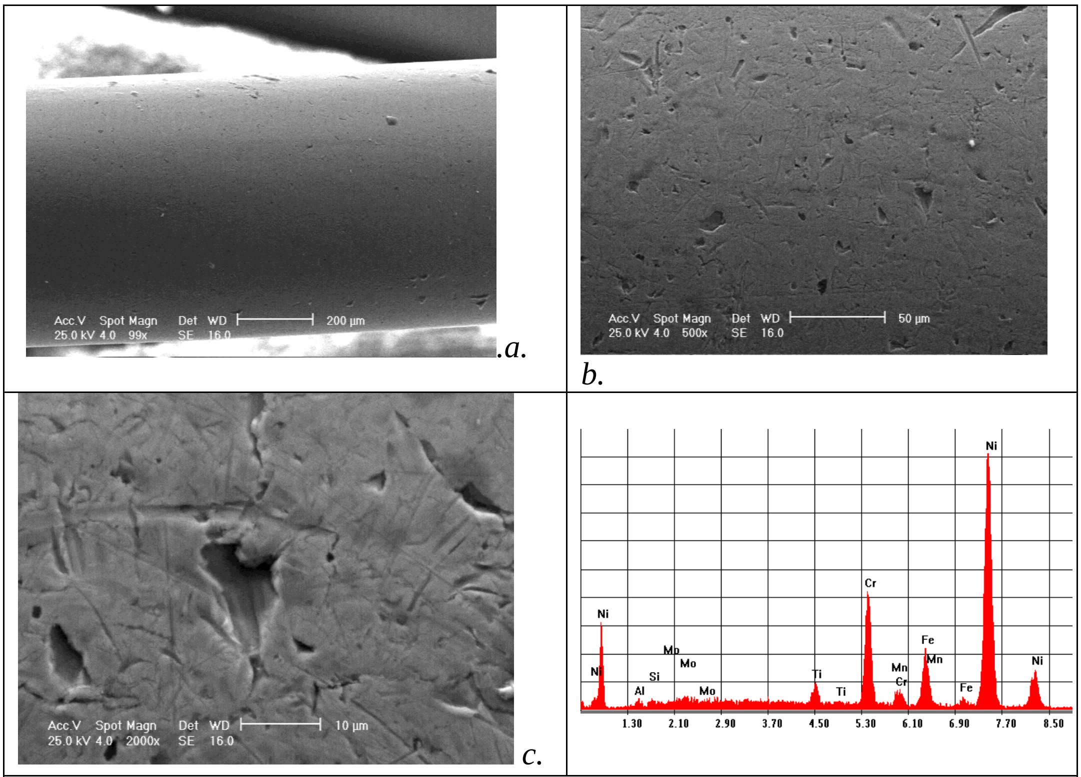



Fig. 6. Secondary electron images of the light coloured spring surface
[a) ×125; b) ×600; c) ×2000] and qualitative EDS analysis on the spring surface

Further on the spring wire profiles near the breaking surfaces were analyzed. Fig. 7 shows a spring coil inner and outer surface close to the spring extremity and Fig. 8 shows the inner surfaces of some broken springs. The images reveal traces of wear processes that affected the spring wires circular profile. These effects can be considered as resulting from two probably interdependent actions: a) spring incorrect displacement under load as a result of the end zone defective profile; b) large spring deflections that determined contact and overlapping of adjacent coils of the springs extremities.[8] [11]

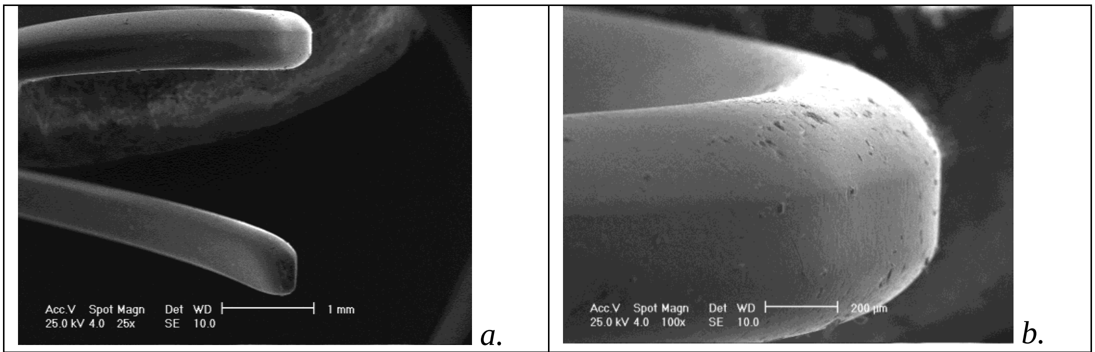



Fig. 7. The inner and outer profile of a broken spring wire.

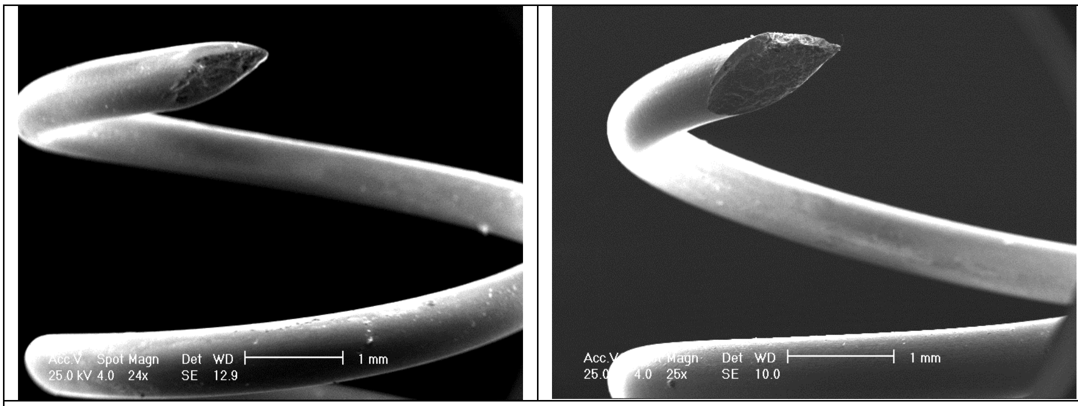
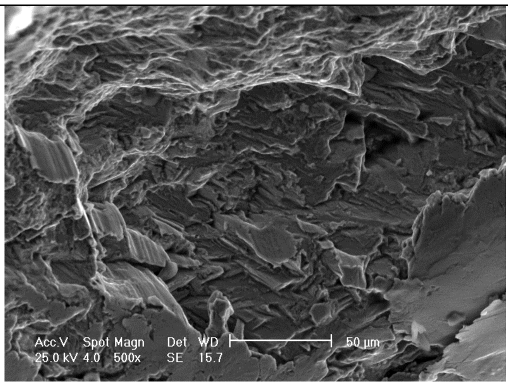


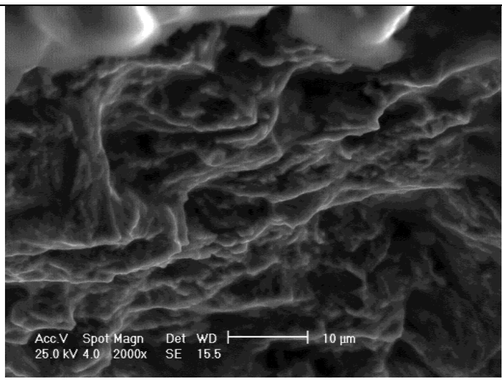

Fig. 8. The wire aspect inside some broken springs.

The processes that led to the spring breaks were identified by analyzing the particularities of the breaking surfaces, shown in Fig. 8, but also in Figs. 9 and 10. The following statements can be made:

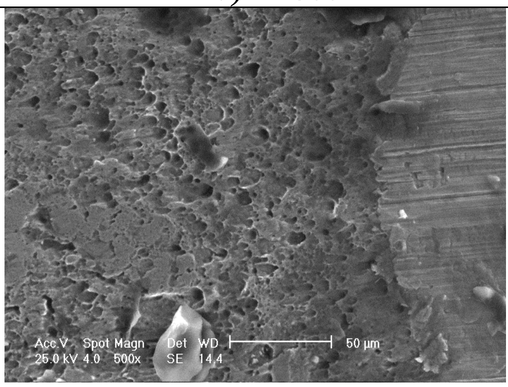
- the springs broke as a result of combined torsional and bending stresses, which is why the breaking surfaces are relatively flat and have a 45° axial tilt (Fig. 4.b);



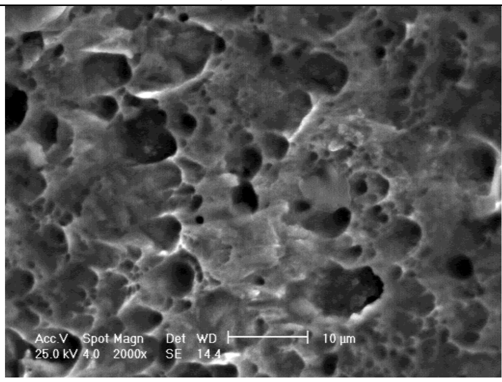

*a) × 500*




*b) × 2000*

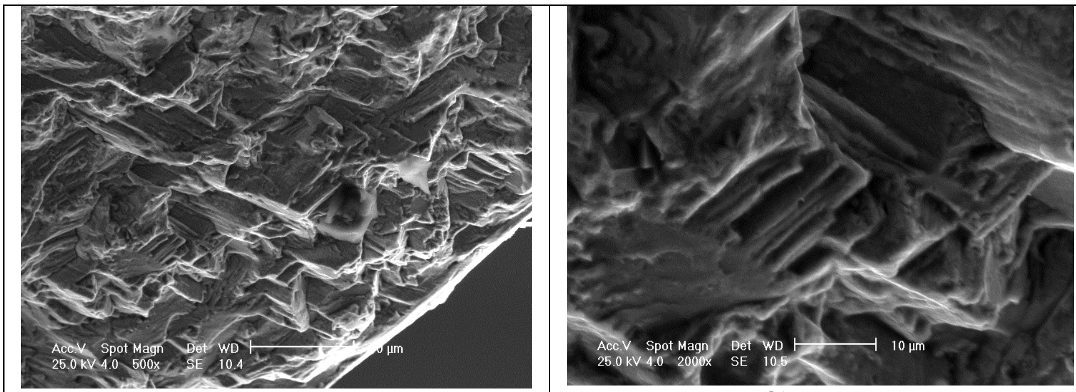



*c) ×500*




*d) × 2000*

Fig. 9. Broken spring surface details in Fig. 8, left.




*a) ×500* *b) × 2000*

Fig. 10. Broken spring surface details in Fig. 8, right.

- the breaks initiation occurred on the springs inner surfaces, in many cases being favored by the existence of the wire local damage through related wear processes (Fig. 5 a, b and Fig. 6 a, b);

- after a progressive evolution of the crack front, failure occurred suddenly due to overloading of the remaining section (Fig. 9 c, d). Kink bands seen in Fig. 10 b are structures common in metals plastic deformation, fracture being the final effect of it.

## 4. Microstructure and eds chemical composition analysis

The typical microstructural aspect of the material is shown in Fig. 11. The images were obtained on a QUANTA 450 FEG electron microscope. The nature and chemical compositions of the metallographic structures were investigated by the EDS technique (energy dispersive spectroscopy).

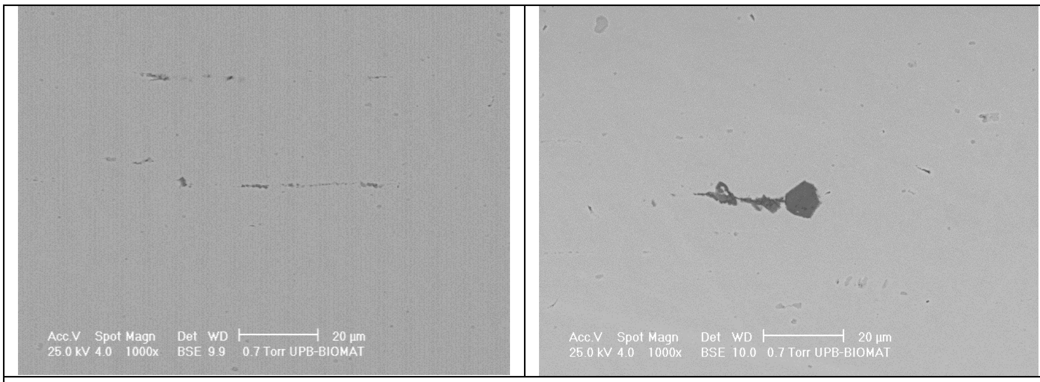



Fig. 11. Spring material microstructure (Vilella's reagent; ×1000)

The X-ray emission spectra obtained in various areas of the austenitic matrix are given in Fig. 12. Quantitatively, the main atomic elements contents of the alloy are given in Table 2.

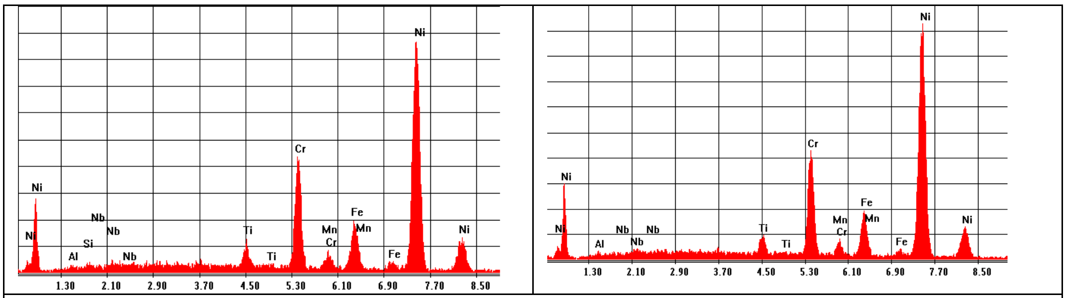



Fig.12. Qualitative EDS analysis regarding the composition of the base metal of some springs.

Using the same technique, the precipitates found in the alloy structure were analyzed. Part of the analysis images are given in Fig. 13. These are carbides and carbonitrides of Ti, Nb and Cr.

Regarding the above results, the following are to be noted:

- chemical composition determination by the EDS technique involve small material volumes, proportional to the spot size that explores the material; they are only informative data and no comparison with the reference data, which have the meaning of average values at the level of the entire mass of the material under analysis, is to be made;

- the results of the chemical composition determinations carried out on the analyzed springs confirm, in terms of nature and percentages, the data provided by the spring supplier's document for the analyzed chemical elements;[6], [9]

*Table 2.*

**Informative chemical composition of springs**

| | Provisioned composition[1)] | Wire Φ 0,70[2)] | Spring 1[3)] | Spring 2[4)] | Spring 3[5)] | Spring 4[6)] |
|---|---|---|---|---|---|---|
| C | ≤ 0,08 | 0,062 | - | - | - | - |
| Si | ≤ 0,50 | 0,21 | - | - | 1,00 | 0,90 |
| Mn | ≤ 1,00 | 0,030 | 0,76 | 0,57 | 0,26 | 0,90 |
| P | ≤ 0,020 | 0.009 | - | - | - | - |
| S | ≤ 0,015 | <0,001 | - | - | - | - |
| Cr | 14,0÷17,0 | 15,51 | 15,66 | 15,90 | 16,09 | 15,42 |
| Ni | ≥70,0 | 71,70 | 68,82 | 70,52 | 69,04 | 68,59 |
| Nb | 0,70÷1,20 | 0,856 | 2,88 | 1,70 | 1,96 | 1,87 |
| Ti | 2,25÷2,75 | 2,35 | 2,68 | 2,36 | 2,67 | 2,77 |
| Al | 0,40÷1,0 | 0,540 | 1,0 | 1,08 | 1,05 | 0,99 |
| Cu | ≤ 0,50 | 0,02 | - | - | - | - |
| Co | | 0,02 | - | - | - | - |
| Fe | 5,0÷9,0 | 8,53 | 8,22 | 7,89 | 7,94 | 8,57 |
| Ta | | <0,002 | - | - | - | - |
| B | | 0,0048 | - | - | - | - |

Obs.: 1) According to the technical literature; 2) According to the supplier's document; 3, 4) Approximative composition of dark coloured springs; 5, 6) Approximative composition of light coloured springs.

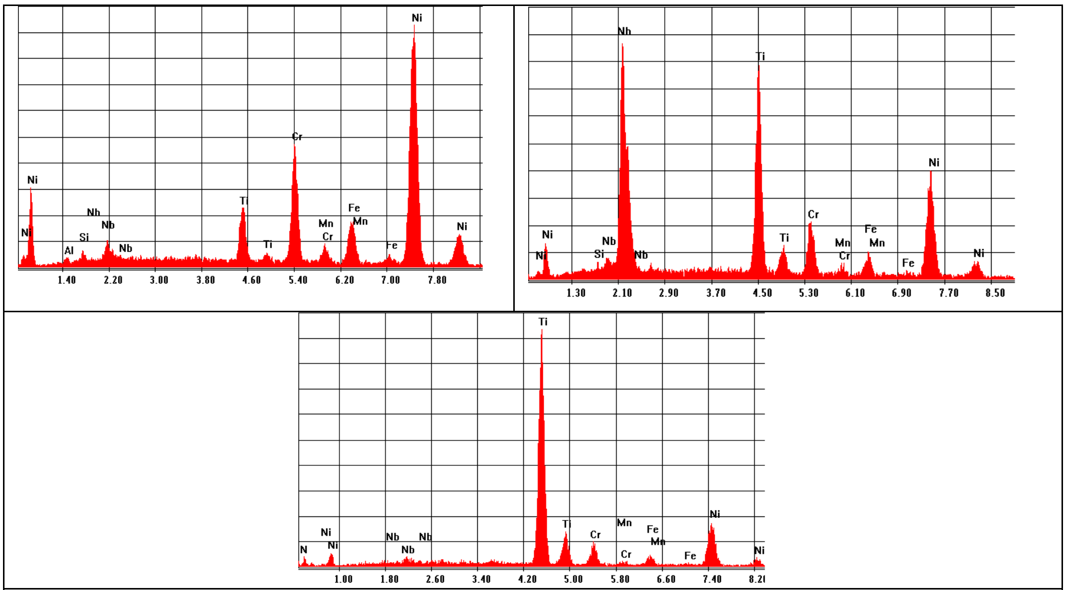



Fig. 13. Qualitative EDS analysis regarding the chemical composition of some precipitates present in the microstructure of the spring material

- no significant differences in chemical compositions were identified between the springs with different colour shades.

## 5. Mechanical characteristics

The supplier's documents mention a tensile strength value of 1461 N/mm$^2$ for the 0.70 mm wire. The technical literature data for INCONEL X750 mentions mechanical characteristics in a relatively wide band, depending on the heat treatment technology, or the cold deformation degree.

Table 3 shows the tensile strength values of INCONEL X750 depending on the applied heat treatment.

*Table 3.*

**Tensile strength of the X750 superalloy depending on the delivery condition**

| | Wire delivery condition | Spring delivery condition | Tensile strength, N/mm$^2$ |
|---|---|---|---|
| 1 | Aged | Aged (650°C/4h/air) | 1100÷1500 |
| 2 | Aged | Quenched without polymorphic change 1150°C/2h/air; Stabilization 843°C/24h/air Aged 740°C/20h/air | 1350÷1750 |
| 3 | Aged | Aged (730°C/16h/air) | 1300÷1450 |

The analyzed springs could not be submitted to a tensile stress test. The only test available was the hardness one. The results obtained by determinations made on a BUEHLER microhardness testing machine are given in Table 4.

As for steels, equivalences between the hardness values and the tensile strength values are known, as shown in Table 5.

*Table 4.*

**HV50 microhardness values of the spring material**

| | Obtained values | Average value |
|---|---|---|
| Dark coloured springs | 532,1; 552,9; 516,4; 536; 532,1 | 533,9 |
| Light coloured springs | 536,2; 540; 574; 524; 513,7 | 537,6 |

*Table 5*

**Eequivalences hardness values / tensile strength values for steels**.

| HB | HV | $R_m$ (N/mm$^2$) |
|---|---|---|
| 441 | 470 | 1572 |
| 433 | 460 | 1538 |
| 425 | 450 | 1496 |
| 415 | 440 | 1462 |
| 405 | 430 | 1413 |

From the data analysis presented above, one may observe:

- the value of 1461 N/mm$^2$ for the 0.7 mm springs tensile strength, given by the supplier documents, is in the upper range of the literature mentioned values for precipitation hardening heat-treated INCONEL X750; [10],[13]

- the HV50 hardness values determined on the spring samples seem to indicate tensile strength values higher than those reported by the supplier, if hardness/tensile strength equivalences which applies for steels are taken into account; obviously, this must be cautiously assessed considering the lack of data regarding the analyzed material class; also, there is no information regarding the springs requested mechanical characteristics for the current application;

- there are no significant differences in hardness between springs having different color shades.

## 6. Conclusions

The choice of Inconel X750 super alloy for 122 K1 compressor valve springs is a correct one, when considering its high corrosion and mechanical resistance in a wide spectrum of temperatures and working media.

The delivery documents provided by the supplier concern exclusively the spring wire and not the springs as finished products and do not include quality certificates according to the EN 10204 requirements.

The springs examined material has chemical compositions and microstructural aspects similar to those mentioned in the technical literature for Inconel X 750. Evaluated according to the micro hardness values and the hardness/tensile strength equivalences known for steels, the tensile strength of the spring material exceeds the literature values given for the quenching without polymorphic change heat treatment state, specific to this application and is higher than the supplier's documents mentioned value. Being available only as a short length spring, the 0.7 mm wire from which the springs were made cannot be subjected to a tensile test in order to obtain results opposable to the spring supplier.

The examined valve springs have 10 coils, a length of 25 mm and has a hyperbolic profile with an outer diameter at the extremities of 7.2 mm and a coil pitch of 2.9 mm, respectively, an outer diameter in the central area of 6.4 mm and a coil pitch of 2.2 mm (approximate dimensions).

The last coil at each spring extremity is slightly bent over a length that covers approximately ¼ of the circumference, but none of the examined springs had the ends shaped in such a way as to present parallel seating surfaces on the entire circumference, specific to the geometry needed to ensure a correct stress applied on the spring in axial compression.

The springs breaks mainly occurred in the areas of the last three coils towards the end of the spring and occurred following to torsional and bending stresses. The favoring factors for the premature springs breaking were: incorrect geometry in the end areas and, possibly, the excessive resistance of the wire used to make them.

Numerous springs showed internal and external wear at the level of the last 2÷3 coils towards the spring end. These wears could contribute, as favoring factors, to the premature springs breaking. It was estimated that the wear resulted from the friction between the coils from two, probably interrelated, causes: a) the spring incorrect movement under load as a result of the end zone defective profile; b) too large spring deflections which determined the contact and overlapping of adjacent coils in the end areas.

Precipitation hardening specific to solution hardening and ageing leads to an increase in mechanical properties at the expense of corrosion resistance. The internal stresses specific to precipitation hardening create galvanic micro piles that initiate the corrosion process. Consequently, the mixed treatment must be applied in order to stabilize the structure, i.e. the precipitate particles should no longer have semi-coherence with the matrix and show a spheroidzing tendency.

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