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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF Ti-6Al-4V ALLOY BEHAVIOUR UNDER DIFFERENT EXPLOITATION CONDITIONS

EKSPERIMENTALNO I NUMERIČKO ISTRAŽIVANJE PONAŠANJA Ti-6Al-4V LEGURE PRI RAZLIČITIM USLOVIMA EKSPLOATACIJE

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Keywords
- Ti-6Al-4V
- finite element method
- hip implants
- corrosion

Abstract

The paper involves experimental testing of titanium alloy Ti-6Al-4V specimens, based on which numerical models are made to provide the basis for further investigation. Due to the exploitation conditions these implants are subjected to, experimental tensile tests are performed on three types of specimens: regular type, and specimens previously subjected to the effects of humid and salty environment. The goal is to determine how these extreme conditions affect mechanical properties of Ti-6Al-4V alloy, along with the development of numerical models which could accurately simulate the behaviour of real specimens.

Ključne reči
- Ti-6Al-4V
- metoda konačnih elemenata
- veštački kuk
- korozija

Izvod

U radu je prikazano eksperimentalno ispitivanje epruveta legure titana Ti-6Al-4V, na osnovu kojeg su urađeni numerički modeli koji služe kao osnova za dalja istraživanja. Zbog radnih uslova kojima su izloženi implanti izrađeni od ovog materijala, eksperimentalno ispitivanje zatezanjem je rađeno u tri varijante: na neoštećenim epruvetama, kao i na epruvetama koje su bile izložene uticaju vlažne i slane sredine. Cilj je bio da se utvrdi kako ovakvi ekstremni uslovi utiču na mehaničke osobine Ti-6Al-4V legure, a i da bi se razvili numerički modeli koji bi verodostojno prikazali ponašanje realnih epruveta.

INTRODUCTION

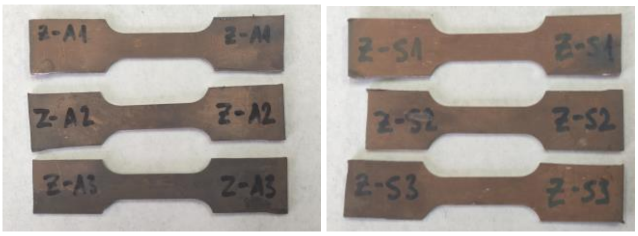
Titanium alloys are widely applied in biomedicine, mainly due to favourable characteristics such as good mechanical properties, resistance to corrosion, and biocompatibility (they are not toxic as some other commonly used materials) /1-4/. The Ti-6Al-4V is among the most commonly used alloys /5-7/ and has been the subject of extensive research. In this particular case, the focus will be on its performance under different extreme conditions, largely related to corrosion. The goal is to determine the level of degradation of mechanical properties, mainly yield stress and tensile strength after specimens were subjected to wet and salty environments. This is important since these mechanical properties directly affect the resistance to fatigue crack growth of hip implants. Due to the loads to which hip implants are subjected to during everyday activities, fatigue represents and important aspect when determining the remaining life.

The development of basic numerical models, using experimentally obtained data from tensile tests, for all three types of specimens - regular, humid, and salty, is also included in the paper. At this stage, the main goal is to determine the level of agreement between experimental and numerical results, and to identify any potential problems that require attention.

EXPERIMENTAL PROCEDURE

The experimental stage involves tensile tests, performed using an INSTRON tensile testing machine of 250 kN capacity. A total of 9 tensile test specimens are made from Ti-6Al-4V. Specimens have the following dimensions: cross-section 10×1.8 mm and gauge length 30 mm. It should be noted that the exact cross-sections for each specimen are measured, to the second decimal, and these accurate values are also used later for numerical simulations. These 9 specimens are divided into three groups:
- regular, 'undamaged' specimens, denoted as Z-A1, Z-A2 and Z-A3;
- specimens were kept in humid conditions, denoted as Z-V1/2/3;
- specimens kept in salty conditions, denoted as Z-S1/2/3.

Specimens from all three groups are shown in Fig. 1. Prior to tensile testing, specimens from groups Z-S and Z-V are kept in salty and humid chambers, in order to simulate real exploitation conditions to which these alloys are often subjected.



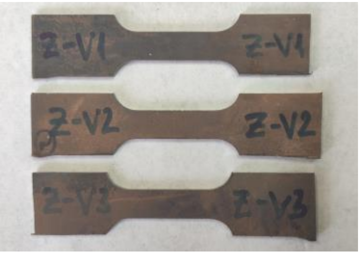


Figure 1. Tensile test specimens used in the experiment.

EXPERIMENTAL RESULTS

The obtained results for all 9 specimens, include yield stress, tensile strength, and elongation at failure. Examples of obtained stress-strain diagrams for each group are shown in Fig. 2, whereas Table 1 shows the obtained stress values for all specimens in a comprehensive form, and this table is used as the main source of input data for numerical simulation, while also providing a basis for the comparison of numerical- with experimental results.

It can be seen in Table 1 that there are two extreme values of force at failures in regular and salty specimens, which can be easily explained by a larger cross-section in the case of specimens Z-A2 and Z-S2. Specimens from the humid group have more consistent cross-sections, resulting in similar values of force at failure. For this reason, a total of 5 specimens are modelled using finite element method - two from the first two groups due to certain differences, and one from the third group. Specimen Z-A2 is particularly interesting due to much higher elongation of 16.2 %, compared to the rest, where it ranged from 10.1-12.8 %.

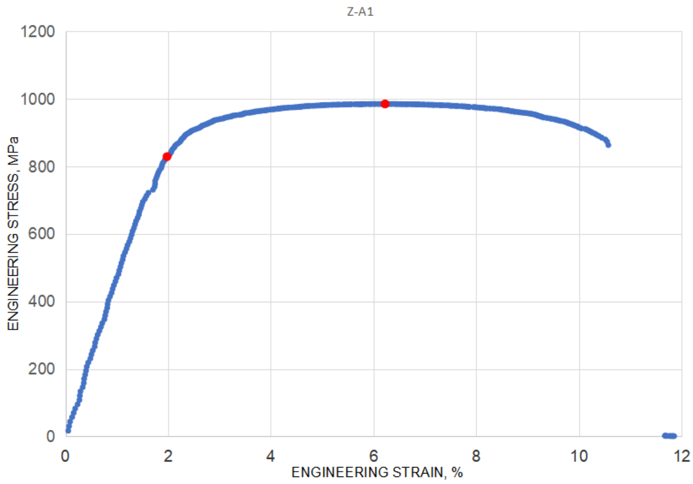


Figure 2. Stress-strain diagram for undamaged specimen.

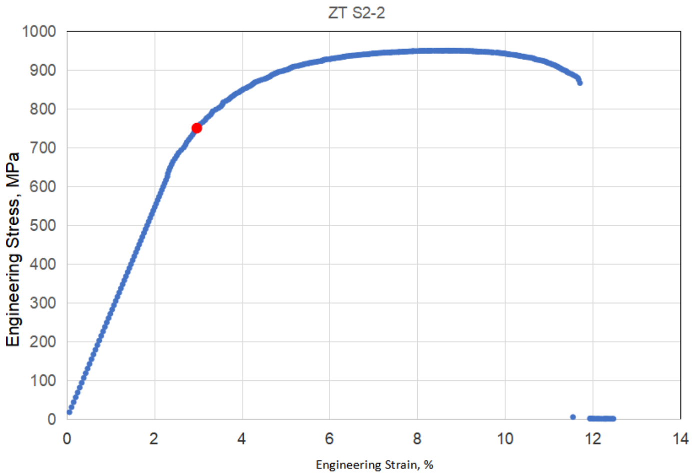


Figure 3. Stress-strain diagram for specimen in salty environment.

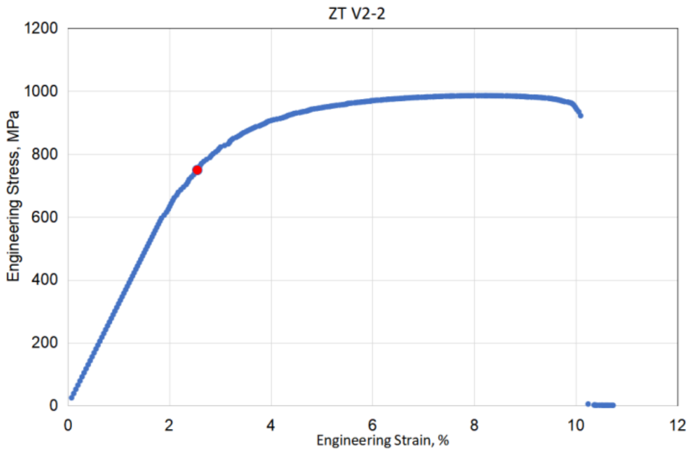


Figure 4. Stress-strain diagram for specimen in humid environment.

NUMERICAL MODELS OF TENSILE TESTS

Numerical analyses in this research are performed using the well-known finite element method, /8-15/, in Abaqus®. All models are made in three sizes, to account for the cross-section variations observed in different specimens. Some of the models, including the finite element meshes, are shown in Figs. 5-7. These mesh sizes are determined iteratively, in order to ensure the convergence of results, being a common practice in FEM calculations.

As can be seen from the below figures, all models have very similar finite element meshes in terms of size, as expected due to similar, simple geometry. Finite element sizes range from ~ 0.4 mm in remote areas to 0.1 mm in the most critical areas of models (around their mid sections).

Table 1. Mechanical properties of all specimens, including measured cross-section sizes for Ti-6Al-4V.

Specimen	Width, b [mm]	Thickness, d [mm]	Force at failure F_{max} [kN]	Yield stress, $R_{p0.2}$ [MPa]	Tensile strength, R_m [MPa]	Elongation, A [%]
Z-A1	9.96	1.80	17.7	829	985	10.60
Z-A2	10.05	2.03	20.1	792	983	16.20
Z-A3	9.92	1.79	17.5	854	986	11.80
Z-S1	10.20	1.85	17.7	763	938	12.80
Z-S2	10.02	1.97	18.8	750	950	11.70
Z-S3	10.10	1.86	17.5	754	932	12.00
Z-V1	10.10	1.89	18.4	760	965	12.00
Z-V2	10.06	1.89	18.6	749	985	10.10
Z-V3	10.10	1.87	18.3	800	965	12.80

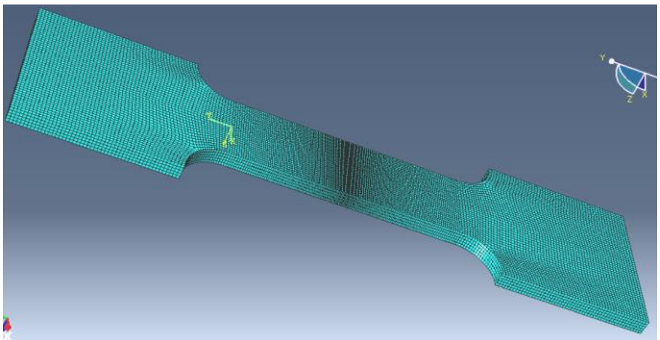


Figure 5. Finite element mesh for ZA specimens.

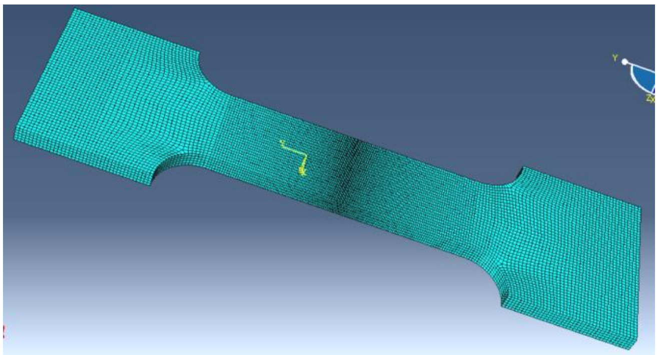


Figure 6. Finite element mesh for ZS specimens.

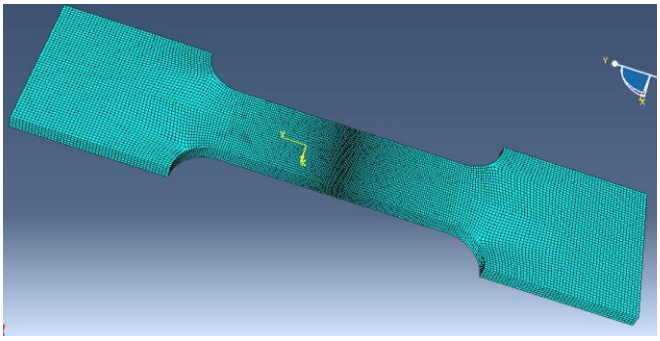


Figure 7. Finite element mesh for ZV specimens.

Boundary conditions and loads are defined based on the real experiment, as is common practice in these cases. One part of each model is fixed in the same way as it would be on the tensile testing machine, whereas, the opposite end is free, where the load is applied. The load for each model is defined based on the maximal forces and cross-section areas, which varied between different specimens. This is done due to the fact that defining a concentrated force is very impractical in Abaqus® /10, 14/, and using distributed load, i.e. negative pressure in this case, provides far more accurate results. Boundary conditions and loads are shown in Fig. 8.

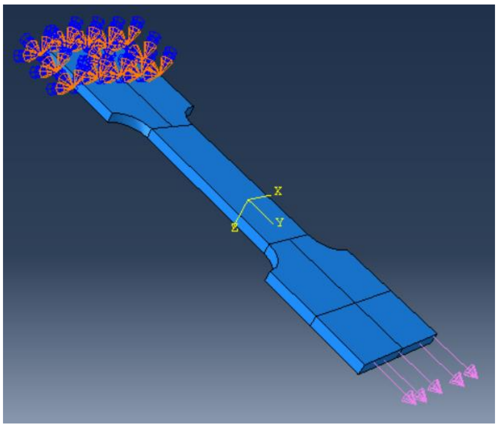


Figure 8. Boundary conditions (upper part of model) and loads (lower surface).

All finite element simulations are performed in elastic-plastic strain domain, with material properties defined in accordance with Abaqus® procedures with engineering stress-strain curves converted into true stress-strain curves, as described in /9, 16/.

COMPARISON OF NUMERICAL AND EXPERIMENTAL RESULTS

Results of FEM simulations are shown in Figs. 8-12, for stresses and strain, along with their distribution in specimen models.

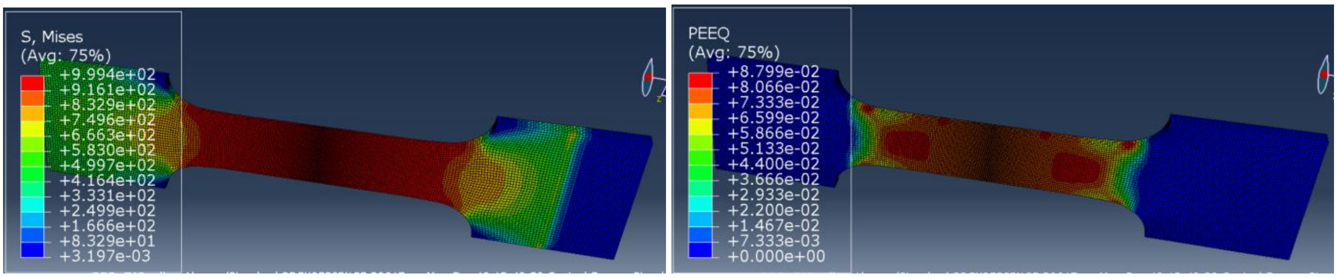


Figure 8. Results of FEM simulations for specimen model Z-A2.

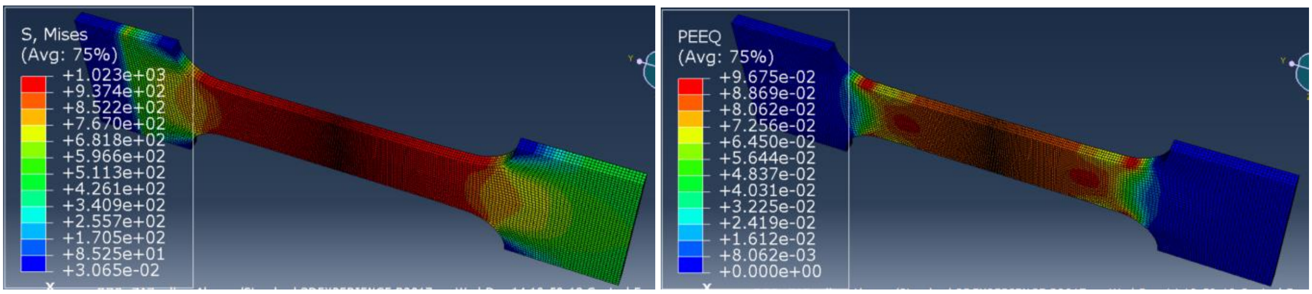


Figure 9. Results of FEM simulations for specimen model Z-A3.

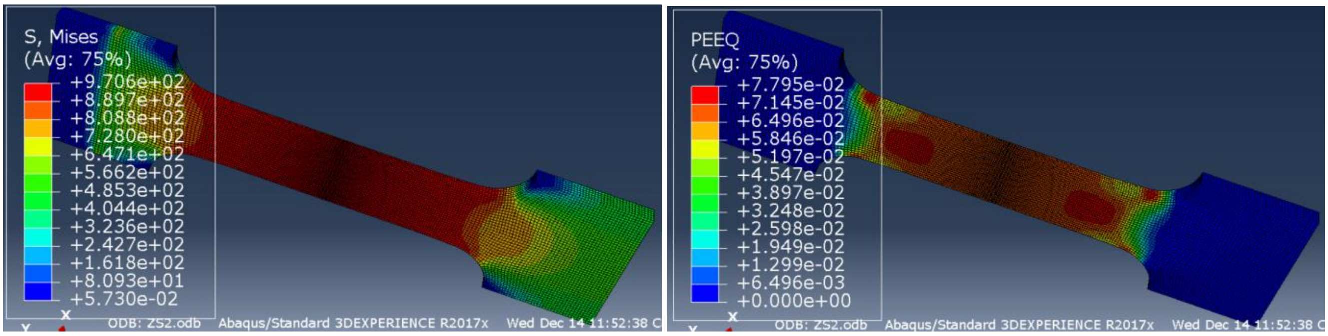


Figure 10. Results of FEM simulations for specimen model Z-S2.

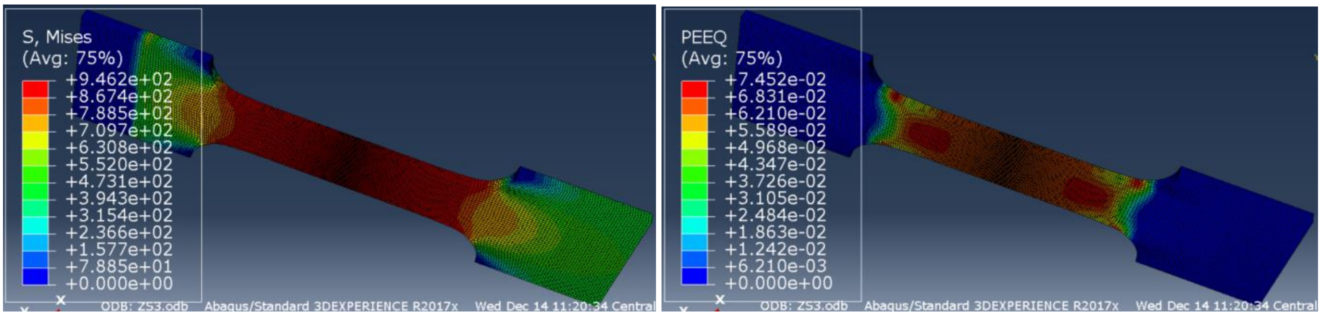


Figure 11. Results of FEM simulations for specimen model Z-S3.

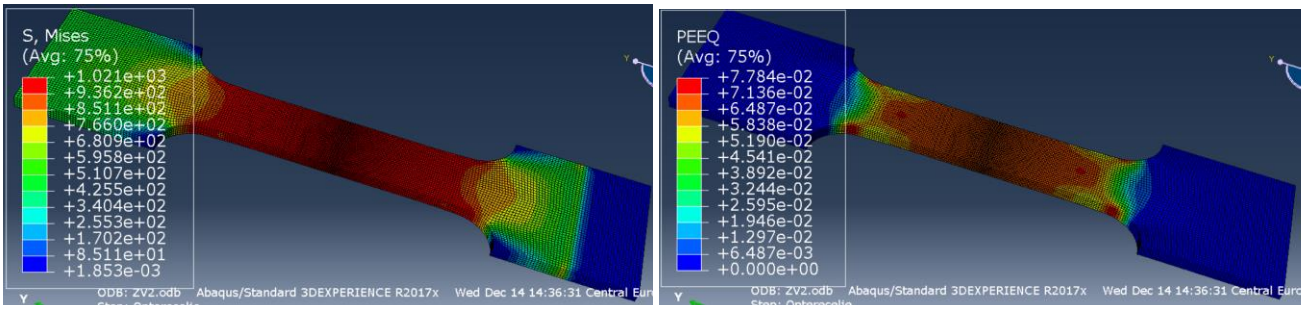


Figure 11. Results of FEM simulations for specimen model Z-V2.

Stress levels in numerical models are slightly higher than those obtained in the experiment, ranging from 1.5 % (Z-S3 model) to 3.6 % (Z-A2 and Z-V2). This is expected due to the simplicity of the models and loads. Both numerical and experimental results provide insight into how the mechanical properties of Ti-6Al-4V specimens have degraded, depending on the conditions under which they were kept, prior to tensile tests. Undamaged specimens had, of course, shown the best behaviour with average yield stress of 825 MPa and tensile strength of 985 MPa. Specimens from the Z-S group, subjected to a salty environment were affected more severely than the rest, with yield stress values averaging at 756 MPa, and tensile strength decreasing to an average of 940 MPa. Mechanical properties of specimens subjected to humid conditions are between the other two groups - the average yield stress is 770 MPa, and the tensile strength is 972 MPa. It can be concluded that extreme exploitation conditions resulted in a more prominent drop in yield stress, compared to the tensile strength, which did not decrease as much, relative to the undamaged specimen value. While the salty environment specimens had shown lowest mechanical property values, they were also the most consistent, with very small differences between specimens in this group, whereas other two had some extremes, as can be seen in Table 1.

As for experimentally determined elongation, individual values for specimens, from Z-S and Z-V groups, are mostly higher compared to the undamaged specimen group - suggesting an increase in the plastic reserve under less favourable exploitation conditions. In this case, the term ‘mostly’ refers to the result obtained for the Z-A2 specimen, the obviously extreme value of 16.2 % for elongation, which considerably deviates from the rest (10-12.8 %, as seen in Table 1).

Numerical results for plastic strain further emphasise the anomalous nature of this particular specimen/model. By comparing the numerically obtained values of strain in the specimens, it can be seen that they are always lower, by a factor of around 25 %, as they range from 7.5 to 9.7 %, with one notable exception - model Z-A2, which corresponds to the tensile test specimen with real elongation of 16.2 %. In this case, the numerical value of strain equal to 8.8 % is similar to all the other models but is much lower than its experimental counterpart. Considering the distribution of all other values of both stress and strain, this suggests that there may have been a problem with this specific specimen, which could be related to material imperfections, or an error in the experiment itself.

CONCLUSION

The research involved experimental testing of Ti-6Al-4V specimens under different conditions in order to determine how these conditions would affect its mechanical properties, and to develop numerical models which would be a basis for further work related to the behaviour of hip implant materials, such as the aforementioned titanium alloy. Tensile tests performed for specimens subjected to three different environments (regular, salty, humid) had shown a certain level of material properties degradation, which was more evident in the case of yield stress than tensile strength, accompanied by a slight increase in plasticity. It is concluded that salty environment is the most detrimental to the mechanical properties of Ti-6Al-4V, leading to an 8.3 % decrease in yield stress and around 4.5 % decrease in tensile strength of specimens. The fact that these decreases are not particularly high, confirms that this alloy possesses exceptional corrosion resistance.

Interesting observations were made regarding the strain in specimens and numerical models, as one of the specimens had much higher elongation compared to the rest, but its numerical model did not differ from other models. In addition, this specimen had shown much higher plasticity compared to other groups which were a lot more consistent in that regard. Aforementioned observations suggest that there are additional questions about this specimen - is its extreme result a consequence of improper experimental testing, a defect in the material from which it is made, or something else?

Further research involving this titanium alloy and its application in biomedicine will focus on fatigue properties of hip implants, using the obtained mechanical properties as input data, for all three different environmental cases. This should be particularly interesting, since on one hand, decreased mechanical properties of humid and salty specimens suggest a decrease in fatigue life, but they could still be offset by the increase in plastic reserve which occurs in specimens from these groups.

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