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Environment-Assisted Degradation Of Beta Titanium Alloy Ti-15V-3Cr-3Al-3Sn

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Abstract: The beta titanium alloy Ti-15V-3Cr-3Al-3Sn (Ti15-3) holds promise as a fastener material due to its high strength, excellent hardenability and formability. An important requirement for fastener applications is resistance to environment-assisted degradation (EAD). Slow strain rate testing was carried out to evaluate resistance to EAD of unaged and aged Ti15-3; testing was also carried out on titanium alloy Ti-6Al-4V (Ti6-4), a frequently used fastener material, for the sake of comparison. Results indicate that Ti15-3 shows superior performance to Ti6-4 and hence better candidate material from the EAD point of view.
Key Words: Titanium alloy 15-3, Fastener application, Environment-assisted degradation, Hydrogen embrittlement.

1. Introduction

A combination of high strength and good resistance to corrosion and environment-assisted degradation (EAD) are among important requirements for materials to be used as fasteners in aerospace and marine sectors. As more complex and higher pressure systems are being built, larger size fasteners with higher ultimate tensile strength levels are becoming necessary. The α+β titanium alloy Ti-6Al-4V (Ti6-4) has been a common marine fastener material. But it has size limitations, due to inadequate hardenability; uniform through-thickness properties cannot be obtained in Ti6-4 fasteners ≥ ~ 20 mm in diameter[1]. Ferrero[2] evaluated nine different titanium alloys for high strength fastener applications for both aerospace and automotive industries. These include β-rich α+β alloys and β alloys. Based on detailed characterization of mechanical behavior, he found that all nine alloys prima-facie meet the requirements. For example, they were all found to meet the minimum tensile strength target of 1379 MPa. All these alloys, being β-rich or 100 % β, enjoy better hardenability than Ti6-4. Esakul and Ahmed[3] reviewed the performance of several titanium alloys, among others, for use in the form of high strength fasteners for offshore and subsea applications. These included α+β alloys, β-rich α+β alloys and β alloys. The α+β alloys have a size limitation, as is the case with Ti6-4 alloy. The other two classes of alloys enjoy better hardenability than Ti6-4 and can be processed to yield strength levels higher than 1000 MPa[4].

However, there are some serious problems limiting the potential of titanium alloys for fastener applications. These are prominently the poor formability and the questionable resistance to EAD[3]. The α+β alloys and the β-rich α+β titanium alloys are relatively difficult to form. The β alloys, in contrast, have excellent hot and cold formability. The α+β alloys have questionable resistance to EAD and so is the case with several β-rich α+β alloys and β alloys[3]. Based on their review of high strength fastener materials, Esaklul and Ahmed[3] identified three β alloys –

Ti-10V-2Fe-3Al (Ti10-2-3), Ti-15V-3Cr-3Al-3Sn (Ti15-3), Ti-15Mo-2.6Nb-3Al-0.2Si (TIMETAL 21S) – as promising, considering the high strength to which they can be processed, the high hardenability and good EAD resistance they are expected to have. The present research deals with evaluation of one of these three alloys, i.e., Ti15-3. This alloy was chosen based on the following considerations:

- It is more extensively used in industry than the alloy 21S.
- Resistance to stress corrosion cracking (SCC) is an important consideration for fastener application. It is known that β stabilizers such as molybdenum, vanadium and niobium are beneficial by way of reducing the susceptibility to SCC[4]. With 15 % vanadium in the alloy composition, Ti 15-3 is expected to enjoy higher resistance to SCC than Ti10-2-3 with 10 % vanadium.
- It has excellent cold formability in the solutionized condition. It can be produced with a wide-ranging strength (1060-1600 MPa), by varying the processing parameters.

The alloy Ti15-3 thus holds good promise for high strength fastener applications. It would be also relevant to compare the EAD of Ti15-3 with that of Ti6-4, the alloy being used currently for fastener applications. Such comparison forms part of the study reported here.

While β-Ti alloys can in general be processed to high strength levels, there is matter of serious concern that they have higher solubility for hydrogen and higher hydrogen uptake rates that result from much larger hydrogen diffusion coefficient for β-Ti. The subject of hydrogen environment- assisted cracking of beta titanium alloys has received much attention[5]. Beta titanium alloys are reported to be susceptible to severe hydrogen assisted cracking[5]. It has since been established that brittle hydride phases are not involved in hydrogen assisted cracking[6]. It has further been reported that a threshold amount of aging is a prerequisite for hydrogen assisted damage[7].

Broadly two types of test procedures have been adopted by the previous workers to evaluate the EAD susceptibility of beta titanium alloys. One of them is to use smooth specimens and carry out slow strain rate testing (SSRT). Several compositions have been studied – Beta-C by Azkarate and Pelayo[8] and Wolfe[9], 21S by Bavarian[10], 15-3 by Gagg and Toloui[11]. The alloys showed generally good EAD resistance except that Ti15-3 suffered from EAD at intermediate loading rates and electrode potentials[11]. The other test procedure was based on use of fatigue pre-cracked specimens. Loading was done either with a constant actuator displacement rate or a constant crack mouth displacement rate or a constant specimen extension rate. The corrosive medium was typically an aqueous chloride. Young and Gangloff[12] and Young[13] studied 21S and Ti15-3 alloys. Ti15-3 was found to have a better resistance to EAD in aqueous chloride environments. Intergranular fracture was the result of EAD in Beta 21S. Fracture remained transgranular, in contrast, in Ti15-3. In precipitation hardened condition Beta-C was found to be susceptible to EAD in aqueous NaCl and the fracture occurred in intercrystalline manner[7, 14, 15]. Meyn and Pao[16] brought out that neither the environment nor the extension rate had any effect on the SSRT behavior of Ti15-3 in aqueous NaCl; in contrast, Ti6-4 was susceptible and stress corrosion cracking occurred. It appears from the studies based on fatigue precracked specimens that Ti15-3 is the most promising from the EAD point of view.

The present study to determine the susceptibility of Ti15-3 material to EAD was carried out on notched specimens; the notch helps to localize the crack nucleation site. Susceptibility to EAD has been evaluated by conducting SSRT tests in laboratory air environment and two corrosive environments – artificial sea water and 3.5 % NaCl. Testing was done under free corrosion conditions as it is truly representative of hydrogen entry conditions, unless when a cathodic protection system is in place. Three different strain rates were used for the testing. The Ti6-4 material was also subjected to SSRT under comparable conditions, to examine if Ti15-3 works out to be a better fastener material. The Ti15-3 material has been studied in both solution treated (henceforth referred to as ‘unaged’) and solution treated and aged (henceforth referred to as ‘aged’) conditions; the latter condition would be very relevant for manufacture of high strength fastener applications.

2. Experimental

The Ti15-3 beta titanium alloy used in this investigation was supplied M/s GE Wick (China). The as-received material was in solution treated condition conforming to ASTM B265. Solution treatment was carried out above the β transus temperature. The material was in the form of sheet with dimensions 3 mm thick, 820 mm wide and 2065 mm long. The Ti6-4 α+β titanium alloy used in this investigations also supplied by M/s GE

Wick. The material was in the form of rectangular bars. It was in mill annealed condition. Details of chemical composition are given in Table 1.

Table 1 Chemical Composition of Ti15-3 and Ti6-4 (in weight %)

Alloy	**Ti**	**V**	**Cr**	**Sn**	**Al**	**Fe**	**C**	**N**	**H**	**O**
Ti15-3	remaining	15.1	3.0	3.1	3.0	0.18	0.008	0.027	0.003	0.009
Ti6-4	remaining	4.0	-	-	6.0	0.1	0.03	0.01	0.003	0.15

Studies on Ti15-3 were carried out in two heat treatment conditions – (i) as-received (solution treated) condition and (ii) aged condition. As-received (unaged) material was aged in a tube furnace for 8 hours at 540 ^{o}C in argon atmosphere to attain the aged condition. Figure 1(a) shows the microstructure of the as-received condition, while Fig. 1(b) gives the microstructure for aged condition.

The microstructure comprises of 100 % metastable β phase in unaged condition. After aging precipitation of α phase took place uniformly in the β matrix. Figure 1(c) shows the microstructure of Ti6-4 material. It comprises of two phase α+β microstructure, α phase being dominant one; volume fraction of β phase is relatively small. For developing the microstructure the specimens were metallographically polished and etched with Kroll's reagent, comprising of 6 ml HNO_3, 2 ml HF and 92 ml distilled water, for 30 seconds. The nominal strength and ductility values of Ti15-3 and Ti6-4 in tested conditions are shown in Table 2

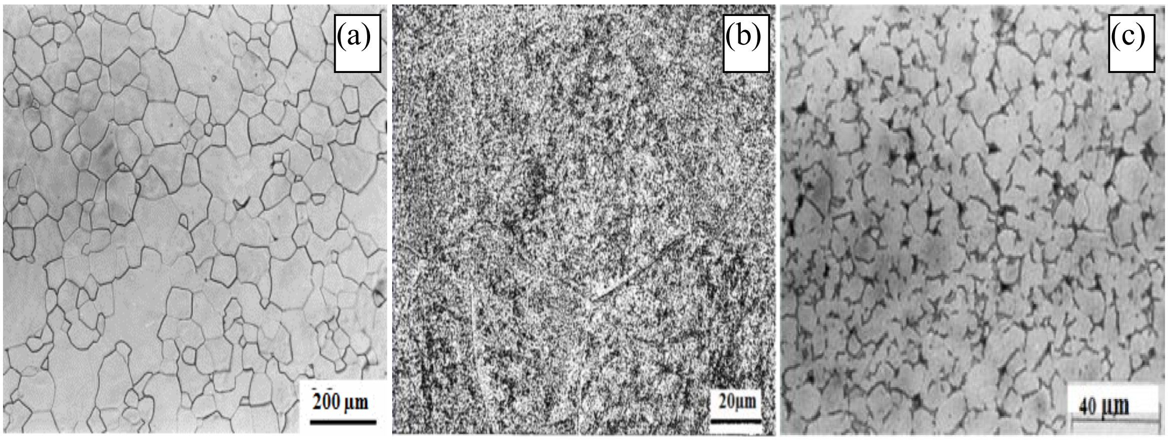
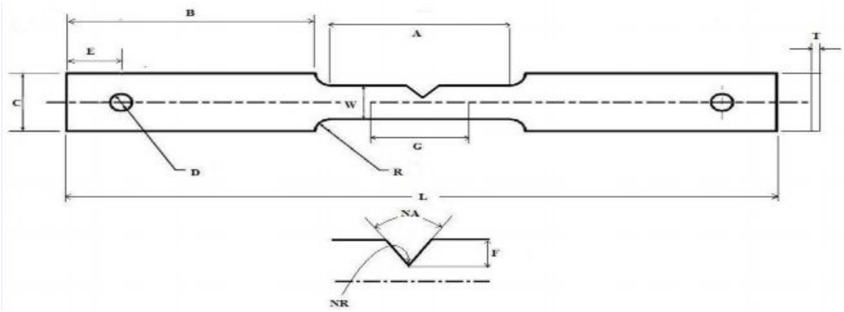


Fig. 1 Optical Microstructure (a) Ti15-3 (as received – unaged condition) ; (b) Ti15-3 after aging at 540˚C for 8 hours (aged condition) and (c) Ti6-4 (as received – mill annealed)

Table 2 Nominal strength and ductility values of the alloys in the tested conditions

Material	**Yield strength (MPa)**	**Ultimate tensile strength (MPa)**	**% Elongation**
Ti15-3 unaged	1010	1110	16
Ti15-3 aged	1210	1340	11
Ti6-4 mill annealed	880	950	14

The drawing of notched tensile specimen adopted for conducting SSRT is shown in Fig. 2. The specimens were machined out of the sheet in case of Ti15-3. Specimens conforming to the same drawing were machined out of the rectangular bar material in case of Ti6-4. The notches were



G - Gauge length	= 32
W - Width of gauge section	= 6
D - Diameter of hole or pin	= 6
R -Radius of the fillet	= 5
E - Edge distance from pin	= 12
L - Over-all length	= 140
F - Width of notch	= 2
B - Length of grip section	= 50
A - Length of reduced section	= 40

Fig. 2 Drawing of the notched tensile specimen adopted for conducting SSRT (Dimensions are in mm)

polished with a cotton thread with application of diamond paste. The value of stress concentration factor k_t works out to 2.98. The Ti15-3 specimens corresponding to both unaged and aged conditions were subjected to SSRT; the three strain rates used in this study were 10^{-5}, 10^{-6} and 10^{-7} s^{-1}. The Ti6-4 specimens in as-received condition were subjected to SSRT at only one strain rate - 10^{-6} s^{-1}. The SSRT on Ti15-3 in unaged condition was carried out in three environments: (i) air having relative humidity of 30 – 40 % (henceforth referred to as 35 % RH air), (ii) synthetic sea water and (iii) 3.5 % NaCl solution in water (henceforth referred to as 3.5 % NaCl). The synthetic sea water was prepared by the method devised by Kester[17]. For each combination of test parameters, one test specimen was tested. While it is advisable to test more than one specimen to arrive at an average / representative value, the limited availability of test material came in the way.

The tests were all carried out at ambient temperature. The SSRT on Ti15-3 in aged condition was carried out in two environments – (i) 35 % RH air and (ii) 3.5 % NaCl. The SSRT on Ti6-4 was also conducted in these two environments. The susceptibility to cracking in synthetic sea water / 3.5 % NaCl was calculated as the ratio of time to failure in corrosive environment to failure in 35 % RH air:

$$\text{Ratio of time to failure} = \frac{\text{Time to failure in corrosive environment}}{\text{Time to failure in 35 \% RH air}} \quad (1)$$

The susceptibility to cracking in synthetic sea water / 3.5 % NaCl was also calculated in terms of percent loss of plasticity:

$$\text{Percent loss of plasticity} = \frac{\text{\% Elongation in 35 \% RH air} - \text{\% Elongation in corrosive environment}}{\text{\% Elongation in 35 \% RH air}} \quad (2)$$

The susceptibility to cracking in synthetic sea water / 3.5 % NaCl was also calculated in terms of fractional loss of notched tensile strength (NTS) in the corrosive environment compared to air environment:

$$\text{Percent loss of notched tensile strength} = \frac{\text{NTS (in air)} - \text{NTS (in corrosive medium)}}{\text{NTS (in air)}} \quad (3)$$

At the end of SSRT, the broken tensile specimens were examined in a scanning electron microscope to get information about the operating modes of fracture.

3. Results And Discussion

3.1 Studies on Ti15-3

Table 3 summarises the SSRT results generated on Ti15-3 in unaged condition. Table 4 is a compilation of SSRT results obtained on Ti15-3 in aged condition. As mentioned in Section 2, no testing was conducted in artificial sea water in the aged condition.

Table 3 Slow strain rate test results for Ti-15-3 (unaged condition) in different environments at different strain rates

Strain Rate s^{-1}	Medium	Elongation (%)	Time (h)	Max. stress (MPa)
1×10^{-5}	Air	3.71	1.43	540
1×10^{-5}	Artificial seawater	3.45	1.38	538
1×10^{-5}	3.5 % NaCl	3.52	1.40	539
1×10^{-6}	Air	3.65	13.87	540
1×10^{-6}	Artificial seawater	3.38	13.24	523
1×10^{-6}	3.5 % NaCl	3.43	13.70	529
1×10^{-7}	Air	3.47	126.74	535
1×10^{-7}	Artificial seawater	2.95	117.32	520
1×10^{-7}	3.5 % NaCl	3.23	120.03	525

Table 4 Slow strain rate test results for Ti-15-3 (aged condition) in different environments at different strain rates

Strain rate (s^{-1})	Medium	Elongation (%)	Time (h)	Max. stress (MPa)
1×10^{-5}	35 % RH air	3.7	1.44	712
1×10^{-5}	3.5 % NaCl	3.46	1.36	703
1×10^{-6}	35 % RH air	3.35	15.34	707
1×10^{-6}	3.5 % NaCl	3.06	13.94	685
1×10^{-7}	35 % RH air	3.04	129.23	564
1×10^{-7}	3.5 % NaCl	1.16	112.89	532

3.1.1 Degradation in 35 % RH air

3.1.1.1 Influence of strain rate on plasticity and time to failure in unaged condition

It can be seen that the % elongation in SSRT decreases with decreasing strain rate – it is 3.71 % for 10^{-5} s^{-1}, 3.65 % for 10^{-6} s^{-1} and 3.47 % for 10^{-7} s^{-1}. The time to failure rationalized for the strain rate shows a corresponding drop. At 10^{-5} s^{-1} it is 1.43 h; at 10^{-6} s^{-1} it is 13.87 h, less than 10 times 1.43 h, i.e., 14.3 h. At 10^{-7} s^{-1} it is 126.74 h, less than 100 times 1.43 h, i.e., 143 h. This suggests that even in 35 % RH, some degree of embrittlement is taking place.

3.1.1.2 Influence of strain rate on plasticity and time to failure in aged condition

It can be seen that the % elongation in SSRT decreases with decreasing strain rate – it is 3.7 % for 10^{-5} s^{-1}, 3.35 % for 10^{-6} s^{-1} and 3.04 % for 10^{-7} s^{-1}. The time to failure rationalized for the strain rate shows a significant drop at the lowest strain rate. At 10^{-5} s^{-1} it is 1.44 h; at 10^{-7} s^{-1} it is 129.23 h, less than 100 times 1.44 h, i.e., 144 h. This suggests that even in aged condition some degree of embrittlement is taking place in 35 % RH air.

3.1.1.3 Behavior of notched tensile strength in unaged and aged conditions

The notched tensile strength remains essentially insensitive to strain rate in unaged condition. The values obtained are 540, 540 and 535 MPa for 10^{-5} s $^{-1}$, 10^{-6} s $^{-1}$ and 10^{-7} s $^{-1}$ respectively. In the aged condition there is significant drop with decreasing strain rate, particularly when tested at lowest strain rate. The value of 712 MPa at 10^{-5} s $^{-1}$ drops to 564 MPa at 10^{-7} s $^{-1}$. This suggests that the aged condition is more susceptible to EAD than the unaged condition.

3.1.1.4 Embrittlement in 35% RH air environment

As brought out in the Introduction Section, hydrogen environment-assisted cracking has been also reported for titanium alloys, including beta titanium alloys. What is interesting is that the moisture in the air, even at 35% RH level, appears to be sufficient to serve as a source of hydrogen. The notch in the notched specimens used in the present study acts as stress concentrator and serves as a site for hydrogen accumulation and damage initiation. Hydrogen embrittlement is known to result in crack initiation at stress concentrator present on the surface[18], the notch in the present case. Nageswara Rao[19] studied EAD in maraging steel grade 18Ni2400 using the same SSRT technique and reported that some embrittlement of the material occurs even during SSRT in 30% RH air. What is also worth noting is that embrittlement also occurs in unaged condition, associated with a relatively low strength level. Behavior of notched tensile strength, however, suggests that the aged condition is more susceptible to environmental degradation than the unaged condition. This could be related to the higher strength level associated with the aged condition. It has been well documented that the susceptibility to EAD increases with increasing strength of the material[18].

3.1.2 Degradation in synthetic sea water and 3.5 % NaCl environments

3.1.2.1 Unaged condition

Table 5 gives values of ratio of time to failure, percent loss of plasticity and percent loss of notched tensile strength in artificial sea water and 3.5 % NaCl environments for Ti15-3 alloy tested in unaged condition. These values have been calculated from the experimental data presented in Table 3 using equations 1, 2 and 3 respectively.

Table 5 Ratio of time to failure, percent loss of plasticity and percent loss of notched tensile strength for Ti15-3 for the three strain rates adopted

Condition		Medium					
		Synthetic seawater			3.5 % NaCl		
	Strain rate s^{-1}	Ratio of time to failure	Percent loss of plasticity	Percent loss of notched tensile strength	Ratio of time to failure	Percent loss of plasticity	Percent loss of notched tensile strength
Unaged	10^{-5}	0.96	7.0	0.4	0.99	5.1	0.2
	10^{-6}	0.95	7.5	3.1	0.98	6.2	2.0
	10^{-7}	0.92	15.0	2.8	0.94	6.9	1.9
Aged	10^{-5}				0.94	6.48	1.26
	10^{-6}				0.90	8.65	3.11
	10^{-7}				0.87	12.55	5.67

Values presented in the table cover all the three strain rates adopted for testing. For both environments it is seen that there is a monotonic drop of ratio of time to failure with decreasing strain rate. Further the percent loss of plasticity increases monotonically with decreasing strain rate, irrespective of the environment. That increasing degree of environmentally assisted damage takes place with decreasing strain rate during SSRT runs is only to be expected. The loss of notched tensile strength increases significantly from 10^{-5} s $^{-1}$ to 10^{-6} s $^{-1}$ but shows little change from 10^{-6} s $^{-1}$ to 10^{-7} s $^{-1}$.

Ratio of time to failure values in the range 0.8 to 1.0 normally denote high resistance to EAD[19]. Even at the lowest strain rate tested, the ratio of time to failure values are higher than 0.9 in both artificial sea water and

3.5 % NaCl environments. This suggests that the alloy shows good resistance to EAD in both these environments.

It can be seen that ratio of time to failure values are lower in artificial sea water compared to 3.5 % NaCl at all strain rates. Further percent loss of plasticity and percent loss of notched tensile strength values are higher for the artificial sea water compared to 3.5 % NaCl. There is published literature bringing out that 3.5 % NaCl and synthetic seawater can lead to very different corrosion rates. For example, studies by Moeller[20] have shown that 3.5% NaCl leads to nearly four times higher corrosion rate in case of mild steel compared to synthetic seawater. However, this may not be so with all materials, as pointed by these authors. The present study shows that for the subject beta titanium alloy 3.5 % NaCl is distinctly more corrosive than synthetic seawater. Further study is required to understand the corrosion mechanisms coming into play and to explain the difference in the corrosion rates between the two environments.

3.1.2.2 Aged condition

Also included in Table 5 are values of ratio of time to failure, percent loss of plasticity and percent loss of notched tensile strength at the three strain rates in 3.5 % NaCl for the Ti15-3 alloy tested in aged condition. These values have been calculated from the experimental data presented in Table 4 using equations 1, 2 and 3 respectively. It is seen that there is monotonic drop of ratio of time to failure with decreasing strain rate. Further the percent loss of plasticity and percent loss of notched tensile strength increase monotonically with decreasing strain rate. This is in line with the expected tendency that increasing degree of EAD takes place with decreasing strain rate during SSRT. Even at the lowest strain rate, the ratio of time to failure value is 0.87, suggesting that even in aged condition the alloy shows good resistance to EAD in 3.5 % NaCl.

Figures 3a and 3b show scanning electron microscopic images of fracture surfaces of Ti15-3 samples tested at 10^{-6} s^{-1} in aged condition. Figure 3a is for 35 % RH air and 3b is for 3.5 % NaCl. It can be seen that even in 3.5 % NaCl fracture by micro void coalescence dominates. This shows that plasticity is largely retained, in line with the relatively low percent loss of plasticity value (6.2) obtained.

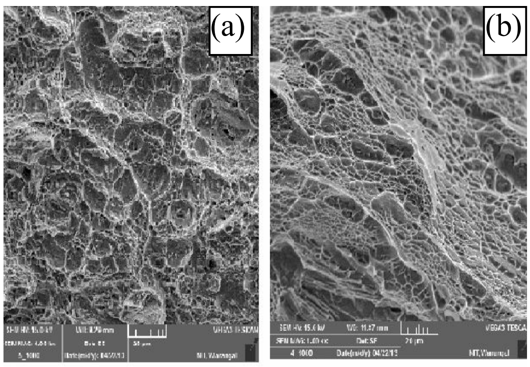


Fig. 3 SEM fractographs (a) 35 % RH air (b) 3.5 % NaCl Ti15-3 in aged condition. Strain rate 10^{-6} (s^{-1})

3.1.2.3 Comparison of degradation in unaged and aged Conditions

Results given in Table 5 can be used to make a comparison of degradation of Ti15-3 in unaged and aged conditions in 3.5 % NaCl. It is seen that ratio of time to failure values are significantly lower and the percent loss of plasticity and percent loss of notched tensile strength values significantly higher for the aged condition. Thus the aged condition exhibits greater degree of susceptibility to EAD.

A parallel can be drawn to the behavior of Beta-C alloy, where after aging the EAD susceptibility increases. However, the aging of Beta-C brings in a change in the fracture mode also, transgranular microvoid based fracture getting replaced by intercrystalline fracture[7]. Such a change in fracture mode is not evidenced in the case of Ti15-3, indicating that EAD in chloride environment is distinctly milder in case of this alloy. The increased susceptibility to EAD of Ti15-3 in aged condition can be related to the substantially higher strength in this condition. Positive correlation between the susceptibility to EAD and strength has been established for a variety of structural materials[18]. One can therefore argue that the higher strength in aged condition is responsible for the higher EAD susceptibility. The one exception to the otherwise good correlation seems to be when the strength increase results from cold working. Somerday and Gangloff [7] reported no increase in the susceptibility to EAD when the alloy Beta-C was cold worked, even though strength increased. However, they did find a strong increase in the susceptibility on aging the alloy as mentioned above.

3.2 Studies on Ti6-4

Table 6 summaries the SSRT results generated on Ti6-4 material in the mill annealed condition. As already mentioned, testing was done at only one strain rate. No testing was done in artificial sea water. There was drop in the % elongation, time to fracture and notched UTS when testing was done in 3.5 % NaCl. The behavior is thus similar to what was observed with Ti15-3. Included in Table 6 are the values of ratio of time to failure, percent loss of plasticity and percent loss of notched tensile strength calculated using equations 1, 2 and 3 respectively. The ratio of time to failure at the intermediate strain rate used for experimentation is 0.91, well in the middle of the range 0.8-1.0, considered relatively safe. This suggests that the alloy Ti6-4 also shows good resistance to EAD in 3.5 % NaCl.

Table 6 Results of SSRT on Ti6-4 in 35 % RH air and 3.5 % NaCl. Strain rate 10^{-6} (s^{-1}).

	% Elongation	Time to failure (h)	NTS (MPa)
35 % RH air	2.92	11.93	526
3.5 % NaCl	2.59	10.98	513
	Percent loss of plasticity = 11.2	Ratio of time to failure = 0.91	Percent loss of notched tensile strength = 2.47

3.3 Comparison of Ti15-3 and Ti6-4 with reference to EAD

Table 7 compares the ratio of time to failure, percent loss of plasticity and percent loss of notched tensile strength for Ti15-3 in two different conditions – unaged and aged – and Ti6-4 in mill annealed condition. In the unaged condition, the Ti15-3 shows distinctly lower susceptibility to damage in 3.5 % NaCl compared to Ti6-4; the strength values of Ti15-3 in unaged condition are comparable are even higher than those of Ti6-4 and the ductility values of the two materials are quite comparable.

Table 7 Comparative performance of Ti15-3 and Ti6-4 with reference to EAD Strain rate 10^{-6} (s^{-1}); 3.5 % NaCl.

	Ti 6-4	Ti15-3 unaged	Ti15-3 aged
Ratio of time to failure	0.92	0.99	0.91
Percent loss of plasticity	11.2	6.2	8.7
Percent loss of notched tensile strength	2.5	2.0	3.1

The superiority of Ti15-3 to EAD is obvious. In aged condition Ti15-3 shows substantially higher strength than Ti6-4, with ratio of time to failure essentially same as that of Ti6-4 and percent loss of plasticity better than that of Ti6-4. The observed superiority of Ti15-3 to Ti6-4 is in line with the information available in published literature on the relative behavior of β-Ti alloys and the alpha plus beta titanium alloy Ti6-4 with reference to EAD. Young et al, for example, reported that Beta-C was not susceptible to EAD in neutral chloride, with or without cathodic protection, whereas such conditions promoted cracking in Ti6-4[13]. Meyn and Pao[16] found a significant difference in the behavior of Ti6-4 and Ti15-3 alloys. Ti6-4 was found to display true SCC and a radical difference in behavior between salt water on one hand and air or vacuum on the other. In contrast, the Ti15-3 showed no SCC effect of the salt water, the behavior in salt water being substantially the same as in air or vacuum. The unaged condition of Ti15-3 is interesting to the fastener designers, as it offers strength comparable to that of Ti6-4, but with higher EAD. The aged condition of Ti15-3 would be interesting for production of high strength fasteners, with strength levels better than those attainable with Ti6-4 but with comparable levels of EAD indices.

The study reported here and the conclusions reached are based on testing one specimen for each combination of test parameters. Nice would have been to test two or even three specimens. This was not possible due to limited availability of test material. However, in view of the qualitative / semi-quantitative nature of analysis involved, the conclusions reached here are considered to be correct.

4. Conclusions

1) There is evidence of environment-assisted damage occurring in Ti15-3 even in 35 % RH air. This was evidenced even in the relatively soft unaged condition.
2) Testing in artificial sea water and 3.5 % NaCl reduce the ratio of time to failure and increase the percent loss of plasticity values. There is increasing degree of EAD with decreasing strain rate in both environments.
3) Artificial sea water is more corrosive than 3.5 % NaCl; further studies are required to understand this behavior.
4) Aged condition of Ti15-3 exhibits greater degree of susceptibility compared to unaged condition in both 35 % RH air and 3.5 % NaCl. This behavior is attributed to the precipitation of alpha phase during aging leading to higher strength.
5) Ti15-3 in unaged condition shows strength/ductility levels comparable to Ti6-4 but distinctly lower degree of susceptibility to 3.5 % NaCl. Ti15-3 in aged condition shows higher strength level than Ti6-4 but with comparable degree of susceptibility to 3.5 % NaCl. Ti15-3 thus projects itself as a better material for fastener application from the EAD point of view.
6) Ratio of time to failure and percent loss of plasticity are adequate indices to rate the EAD in the titanium alloys under study. Loss of notched tensile strength also appears to be a useful index for rating the EAD.

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