ON DAMAGE-TOLERANT PROPERTIES TEST AND PREDICTIONS OF TITANIUM ALLOYS USED IN THE PRESSURE HULL OF MANNED SUBMERSIBLES

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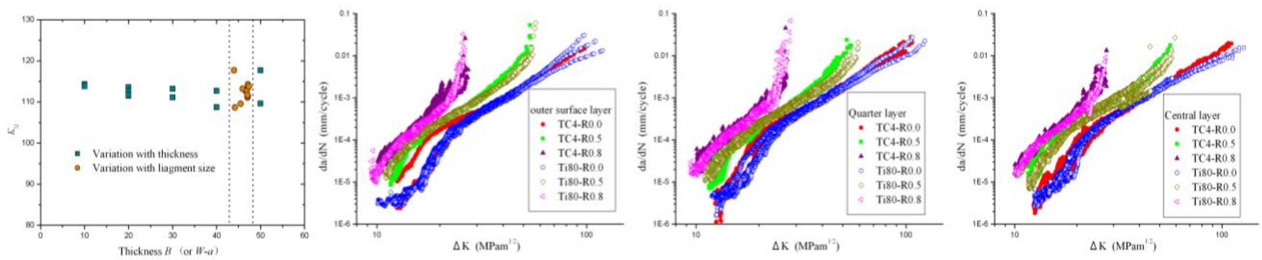
Abstract The current material selection and design rules for the spherical pressure hull of manned submersibles have paid more attention to the synthetic properties of materials of interest for high safety and reliability. Damage-tolerant properties such as fracture toughness and crack growth rate are considered as well as static strength and fatigue life. Tests are conducted on two types of titanium alloys used in submersibles. And an improved crack growth rate model proposed by the authors is used for wide range prediction of their crack growth rate.
Keywords Damage-tolerant properties; titanium alloys; fracture toughness; fatigue crack growth rate; manned submersibles

1 INTRODUCTION

The manned pressure hull of submersibles provides a safe living space for pilots and scientists, which should be designed to have enough strength and should be as light as possible. The current available material selection and design rules of submersible structures from ship classification societies are based on the philosophy of strength design, namely, the ultimate strength of the hull should be higher than the specified collapse pressure, and the local stress should be limited according to the strength, fatigue, and creep property of the material[e.g.1]. Nowadays, higher requirements have been made for improved safe and economic design and operation of the submersibles, and the material selection criterion has paid more attention to the synthetic properties of materials of interest. Damage-tolerant properties will be considered for more optimized design principle in the future. Titanium alloys with relatively high ductility, maturity, welding properties and corrosion resistance are widely used in the existing pressure hulls of submersibles. And several types of titanium alloys have been developed for this purpose. Fracture toughness and fatigue crack growth rate are the two main damage-tolerant properties which are affected largely by the microstructure, the forging processing, and the heat treatment processing. For the material selection and design of a 4500m depth manned submersible in China, tests are conducted on two types of selected titanium alloys of interest (Ti80 and TC4 ELI) for submersibles and these results are presented and discussed in the present paper. Furthermore, to save cost and material test time, an improved crack growth rate model proposed by the authors is used for wide range prediction of their crack growth rates.

2 DAMAGE-TOLERANT PROPERTIES TEST

Sets of K_C compact-tension (C-T) specimens of different thickness are machined out from 90mm thick plate for spherical base material of the pressure hull made of Ti80 and Ti-6Al-4V ELI (abbreviated as TC4 ELI). Each set contains at least five specimens of different thickness including 10mm, 20mm, 30mm, 40mm and 50mm. Among them, the specimen with thickness of 50mm is designed according to the American standard ASTM E399 while others are designed to be non-standard with the same width, to eliminate ligament effect. At the same time, sets of standard C-T specimens of 50mm from three layers of the 90mm thick plate were used for crack growth test under three load ratios, i.e. 0.0,0.5,0.8. Fig.1 gives the typical test results. From the test results on the designed non-standard specimens, an interesting phenomenon can be found that K_Q (results on Ti 80 are shown here, while similar results can be obtained for TC4 ELI) almost unpredictably keeps constant with varied specimen thickness though the requirement of F_Q/F_{max} were not satisfied according to the current standard which are now questioned by many researchers [e.g.2] on whether they are oversize or inadequate and need further research. And the crack growth rates of the two titanium alloys under discussion are in almost the same tendency under different load ratios.



(a) (b) (c) (d)

Fig.1 Typical test results of damage-tolerant properties. (a) Conditional fracture toughness K_Q of Ti80 versus specimen thickness; (b-1) crack growth rates of specimens from outer surface layer; (b-2) crack growth rates of specimens from quarter layer; (b-3) crack growth rates of specimens from central layer.

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3 PREDICTION BASED ON THE IMPROVED CRACK GROWTH RATE MODEL

A good crack growth rate relation should be established for accurate prediction of fatigue life based on fatigue crack propagation theory. Recently, we further improved McEvily's model for the purpose of explaining more fatigue phenomena. Details can be referred to ref.[3]. The improved crack growth model can be described as:

$$\mathrm{d}a/\mathrm{d}N=\frac{\mathrm{A}\left[\Delta K_{\mathrm{eff}}-\Delta K_{\mathrm{effth}}\right]^{m}}{1-(K_{\max}/K_{\mathrm{Cf}})^{n}}\quad(1)\ \text{where, } \Delta K_{\mathrm{eff}}=\begin{cases}K_{\max}\cdot(1-f_{\mathrm{op}}) & R<0.7\\ K_{\max}-K_{\min} & R\geq 0.7\end{cases}\quad \begin{cases}K_{\max}=\sqrt{\pi r_{\mathrm{e}}\left(\mathrm{Sec}\dfrac{\pi}{2}\dfrac{\sigma_{\max}}{\sigma_{\mathrm{v}}}+1\right)}\left(1+Y(a)\sqrt{\dfrac{a}{2r_{\mathrm{e}}}}\right)\sigma_{\max}\\ \dfrac{\sigma_{\mathrm{v}}}{\sigma_{\mathrm{u}}}=\dfrac{\pi}{2}\cdot\dfrac{1}{\cos^{-1}(\frac{1}{\alpha^{2}-1})},\ \alpha=\dfrac{K_{\mathrm{IC}}}{\sigma_{\mathrm{u}}\sqrt{\pi r_{\mathrm{e}}}\left(1+\frac{Y(r_{\mathrm{e}})}{\sqrt{2}}\right)}>\sqrt{2}\end{cases}$$

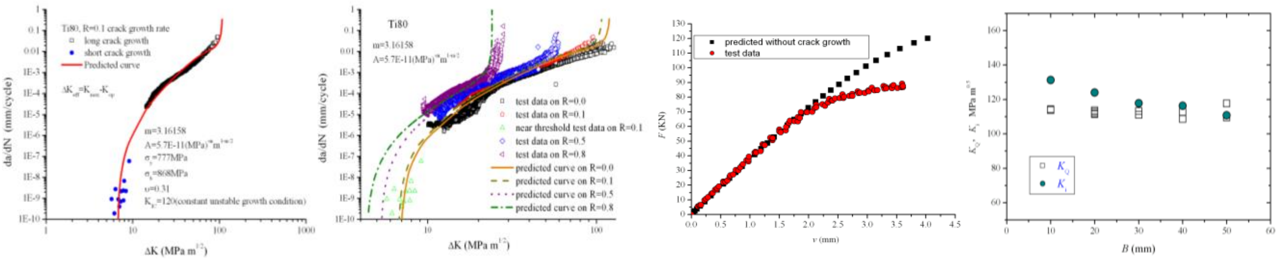
Considering this phenomenon that at higher load ratio the experimental data are closure free, we propose that the term ΔK_{eff} in the constitution relation is expressed by the above piecewise function. And Newman's function [4] for f_{op} is modified by introducing a constraint factor $\alpha^{'}$ as follows,

$$f_{\mathrm{op}}=\begin{cases}\max\{R,A_0+A_1R+A_2R^2+A_3R^3\} & 0\leq R<1\\ A_0+A_1R & -2\leq R<0\end{cases}$$

$$\begin{cases}A_0=(0.825-0.34\alpha^{'}+0.05\alpha^{'2})\cdot[\cos(\pi\sigma_{\max}/2\sigma_{\mathrm{fl}})]^{1/\alpha^{'}};\ A_1=(0.415-0.071\alpha^{'})\cdot\sigma_{\max}/\sigma_{\mathrm{fl}}\\ A_2=1-A_0-A_1-A_3;\ A_3=2A_0+A_1-1;\ \sigma_{\mathrm{fl}}=(\sigma_{\mathrm{Y}}+\sigma_{\mathrm{u}})/2\\ \alpha^{'}=1/(1-2\nu)+[1-1/(1-2\nu)]/[1+0.8861\cdot(t/(K_{\max}/\sigma_{\mathrm{Y}})^2)^{3.2251}]^{0.75952}\end{cases}\quad(2)$$

$$\Delta K_{\mathrm{effth}}(R)=\begin{cases}K_{\max}(a_{\mathrm{th}})\cdot\left[1-f_{\mathrm{op}}(a_{\mathrm{th}})\right] & R<0.7\\ \Delta K_{\mathrm{th}}(R) & R\geq 0.7\end{cases}\quad(3)\quad \text{where, } \Delta K_{\mathrm{th}}(R)/\Delta K_{\mathrm{th0}}=\begin{cases}(1-R)^{\beta_1} & -5\leq R<0\\ (1-R)^{\beta} & 0\leq R<0.5\\ (1.05-1.4R+0.6R^2)^{\beta} & 0.5\leq R<1\end{cases}$$

Eq.(3) can be used to determine the value of $\Delta K_{\mathrm{effth}}$ and we recommend the values of β and β_1 are 0.4 and 0.36 respectively for titanium alloys. Figs.2(a)-(b) give the predicted results with test data which agree well and validate the accuracy of the prediction method. But the prediction error in the unstable region reflect the inaccuracy of the assumption of $K_{\mathrm{Cf}}=K_{\mathrm{IC}}$. Fig.2(c) is the comparison of Load vs. crack mouth opening displacement between numerical results (without crack growth) and test data (with crack growth) for CT-20mm specimen, from which the cleavage initiation load and the corresponding K_{i} can be determined. Fig.2(d) shows the fracture toughness K_{i} vs. specimen thickness. A decreasing tendency can be observed. The crack tip strain state is affected by specimen thickness, load ratio and other factors. When the load ratio is larger, the critical K at crack unstable growth should be larger to make the prediction more accurate. Only analysis results of Ti80 are presented here due to page limit.



(a) (b) (c) (d)

Fig.2 Predicted results.(a) comparison between test and predicted results of Ti80 on R=0.1; (b) comparison between test and predicted results of TC4 ELI on R=0.1; (c) Comparison of Load vs. crack mouth opening displacement between numerical results (without crack growth) and test data (with crack growth) for CT-20mm specimen; (d) Fracture toughness K_{i} vs. specimen thickness.

4 SUMMARY AND CONCLUSIONS

Damage-tolerant properties tests are conducted on two types of selected titanium alloys of interest (Ti80 and TC4 ELI) for submersibles. And an improved crack growth rate model proposed by the authors is used for wide range prediction of their crack growth rates. Conclusions can be made from the tests and analyses, (1) the crack growth rates of the two selected titanium alloys under discussion are in almost the same tendency under different load ratios; (2) the prediction results based on the improved crack growth rate model can agree well with the test data; (3) It is recommended that the cleavage initiation fracture toughness is a potential reliable parameter to express unstable fracture toughness for more accurate prediction.

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