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Prediction of titanium alloy component life by developing an oxidation model

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The excellent balance of strength, ductility, oxidation/corrosion resistance and micro-structural stability of titanium alloys as compared with competitive materials like steels or nickel based super alloys, has resulted in near alpha titanium alloys becoming popular for fabrication of compressor components in advanced gas turbine engines. There is a growing interest in increasing the temperature tolerance of near alpha titanium alloys with a view to increasing engine efficiency by increasing the temperature. There is also a possibility that an increase in temperature tolerance might permit these titanium alloys to be used for components currently made of nickel based super alloys with consequent reduction in component weight. Some of the conventional near alpha titanium alloys exhibit excellent creep resistance and good structural stability at temperatures up to 500 °C. However, when such alloys are exposed to air at temperatures approaching 600 °C and above, they are subject to significant and detrimental surface modification. The major factor involved in surface modification is the uptake of oxygen into solid solution by titanium. At 600 °C and above, the reaction kinetics allow rapid diffusion of oxygen into the region adjacent to the exposed surface. About 33 atomic percent of oxygen dissolves in titanium. The dissolved oxygen forms a hard brittle zone in the titanium alloy. The oxygen-dissolved zone is known as "alpha case" and its formation can substantially degrade the structural integrity of the affected titanium alloy by loss of tensile ductility and of fatigue resistance, even though the interior of the alloy is not subject to structural modification. The predominant factors in alpha case formation are the presence of oxygen, exposure time and the temperature. α-case formation is critical to the life expectancy of titanium alloys when used in aero-gas turbine engines. It severely limits the high temperature capability of titanium alloys with respect to mechanical properties and causes failures during service. In order to enhance the efficiency of gas turbine engines, it is essential to avoid failures during service. It is possible only if the life of components under simulating conditions is known. For this purpose, each component material has to be tested in the laboratory for evaluation of service life, which is a time consuming and costly process. Hence, there is a need to predict the depth of α-case for titanium alloys after exposure of definite number of hours, at a variety of elevated temperatures.

A systematic study was carried out on bare titanium alloy, IMI 834 at different elevated temperatures and a degradation mechanism was proposed under oxidizing environments [1, 2]. It was established that the formation of alpha case and oxide scale are the two principal factors in degradation of the titanium alloys at elevated temperatures. Of the two, α-case formation is the dominant degradation mechanism particularly at higher temperatures i.e., 800 ° and above [1, 2]. Surface engineering of the titanium alloy results in significant improvement not only in elimination of alpha case more effectively but also in the prevention of oxide scale formation [3–7]. Many researchers employed a variety of surface modification techniques [8–12] as a method to limit oxygen ingress into the titanium alloys. But, these methods are not very effective when compared to the recently developed coatings where combined surface engineering techniques have been employed [4–7].

With a view to relating these relatively high temperature exposures to the potential uses and the mechanical property temperature limit of IMI 834, an oxidation model has been developed for the alpha case formation i.e., oxygen ingress into the titanium alloy. Analysis of the alpha cases as measured by the depth of hardening was undertaken after a number of exposures at different temperatures ranging from 600 to 800 °C and 3 to 200 h in order to determine experimentally the oxygen dissolved region and thereby to correlate the predicted data. From the studies, it was observed that the life of compressor components fabricated from the titanium alloys is primarily dependent on the formation of α-case in the subsurface of the titanium alloy components. It was also observed that α-case formation is typically dependent on the exposed temperature. Further, it is known that the compressor components experience temperature discontinuities during service conditions thus causing failure prematurely by affecting their mechanical properties. Therefore, it is highly desirable to predict the depth of α-case for titanium alloys at a variety of elevated temperatures. This will be extremely useful to assessing the life of compressor components in gas turbine engines and thereby helping to eliminate failures during service.

An oxidation model has been developed successfully on the basis of several experiments at a variety of temperatures for different time intervals for the α-case formation or oxygen ingress into the titanium alloy. The Arrhenius equation has been modified appropriately and then used for predicting the α-case formation in the titanium alloys [13].

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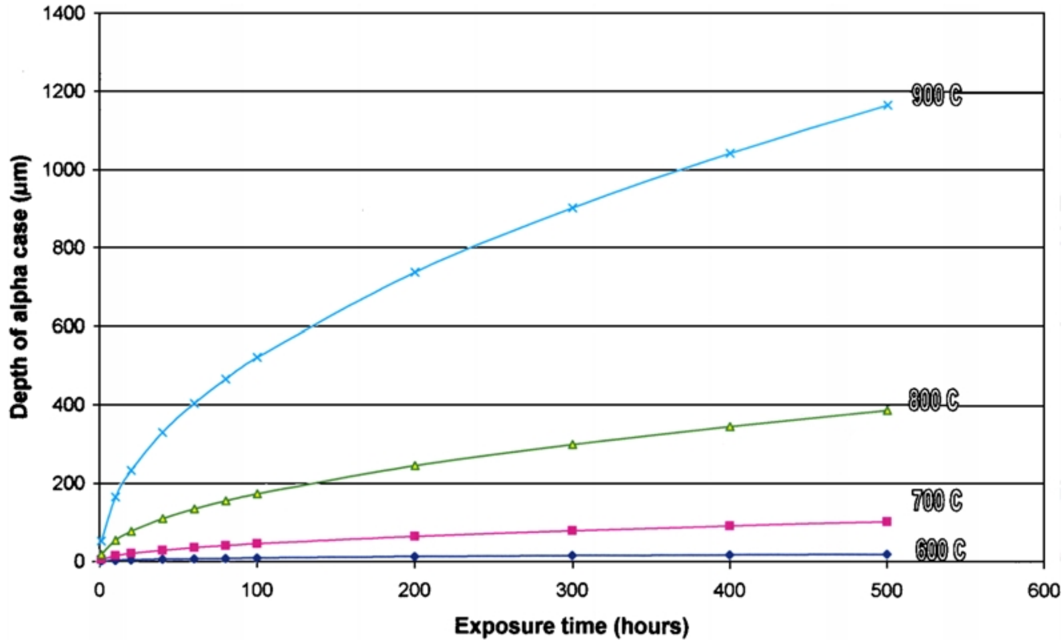

Figure 1 Predicted depth of α-case for titanium alloy IMI 834 at different exposed temperatures.

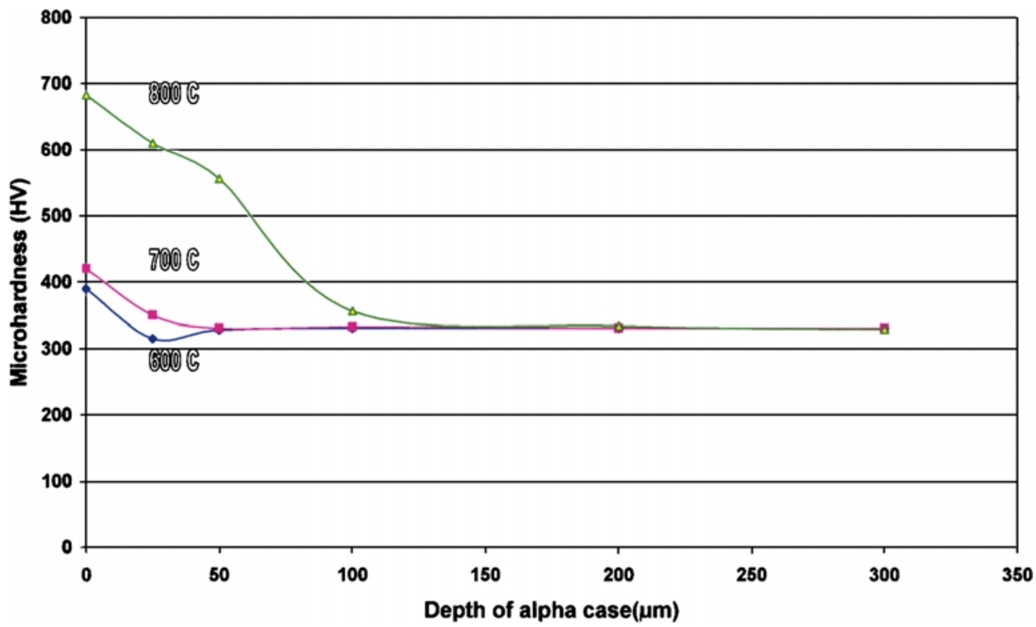

Figure 2 Measured micro hardness profiles of titanium alloy, IMI 834 after 100 h of oxidation at various temperatures showing the depth of α-case.

Fig. 1 provides the predicted depth of α-case as a function of exposure time at different elevated temperatures in the titanium alloy. The depth of α-case is low (15 μm) at 600 °C, increases slightly (45 μm) at 700 °C. At 800 °C, it is ~175 μm, which is significantly higher after exposure of 100 h. Experimentally measured α-case depths for the specimens exposed at different elevated temperatures are shown in Fig. 2. As can be seen, the depth of α-case is minimum (12 μm) at 600 °C, increases marginally (40 μm) at 700 °C and is significantly higher (140 μm) at 800 °C. In essence both predicted and experimentally measured α-case depths followed the same trend. It is important to mention that oxygen dissolution increases enormously at and above 800 °C affecting the mechanical properties of the alloy.

On the basis of measured parameters for IMI 834 for different times and at different temperatures, the life of an alloy (without affecting mechanical properties) is evaluated as follows:

4.4 h exposure at 900 °C

= 40 h at 800 °C

= 570 h of exposure at 700 °C

= 15 000 h at 600 °C

In other words, if the component fabricated from the titanium alloy, IMI 834 continuously operates at its maximum mechanical property temperature limit of 600 °C at its designed service life of 15 000 h, then the

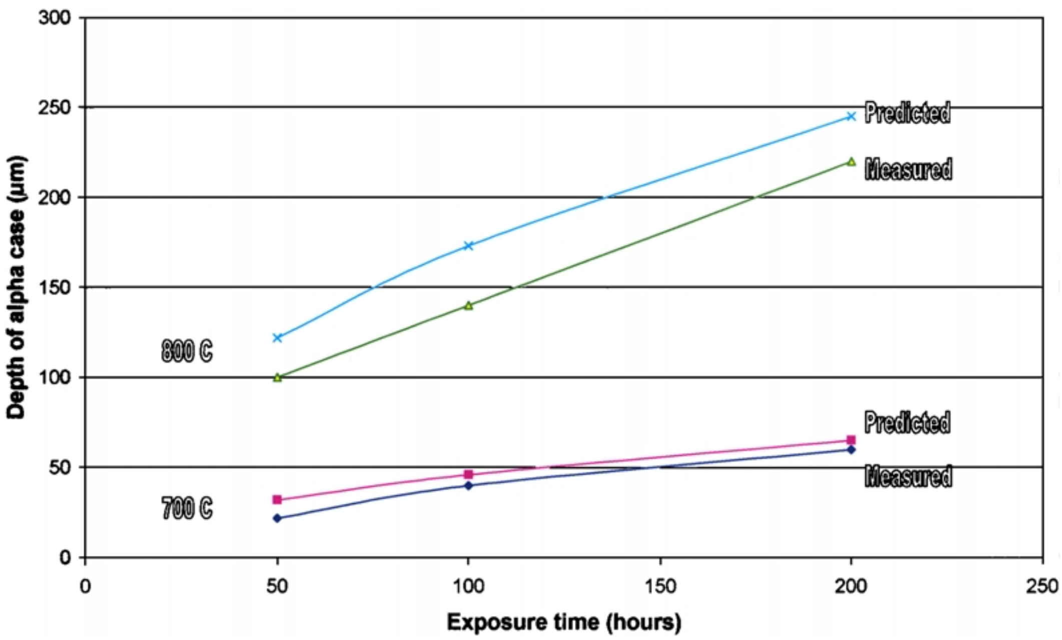

Figure 3 Comparison between the measured and predicted α-case depths at 700 and 800 °C.

expected depth of alpha case i.e., oxygen dissolved region would be 109 μm. It is calculated by using the modified Arrhenius Equation 13. This would be equivalent to an exposure of 570 h at 700 °C, 40 h at 800 °C or 4.4 h at 900 °C.

Another important factor is the correlation between the predicted and experimentally measured α-case formed regions (Fig. 3). The predicted values are slightly higher than the experimentally measured values. It is due to the fact that the oxygen absorbed by titanium alloy during oxidation is used up not only for the formation of oxide scale but also for the α-case formation. Whereas in predicted values, it is assumed that the entire oxygen was used up for creating α-case in the titanium alloy. This may be the reason for the slight deviations between the experimental and predicted values. Alternatively, the marginal difference in the depth of α-case formation between the measured and predicted values can be correlated by taking the oxide scale thickness into consideration. It can be formulated mathematically as follows:

$$\alpha\text{-case}_{\text{pred.}} = \alpha\text{-case}_{\text{meas.}} + \text{Oxide scale thickness}$$

or

$$\alpha\text{-case}_{\text{meas.}} = \alpha\text{-case}_{\text{pred.}} - \text{Oxide scale thickness}$$

The equation is validated by substituting the values obtained for the specimen exposed for 100 h.

$$140 = 173 - 33 \quad \text{at } 800\,^{\circ}\text{C}$$

$$40 = 45 - 5 \quad \text{at } 700\,^{\circ}\text{C}$$

The above equation is valid because of the fact that the titanium alloy initially oxidizes to form oxide scale. Thereafter, the oxygen dissolves in the subsurface of titanium alloy and forms α-case. Therefore, for calculating the total affected region of the titanium alloy components in service, the oxide scale thickness has to be added to the measured α-case depth. In essence, the above equation clearly explains the validity of the developed oxidation model.

As mentioned earlier, it is always possible to observe temperature discontinuities in service. In such circumstances, the combination of α-case depths have to be taken into consideration for calculating total depth of α-case i.e., the life of a component. For example, if the titanium alloy component continuously operates at 600 °C for 5000 h and 15 h (in total period of operation) at 800 °C, then the total depth of α-case would be 130 μm (63 μm at 600 °C + 67 μm at 800 °C). In other words, 15 h operational hike at 800 °C, reduces the life of a component by about 5000 h of the normal operational life i.e., at 600 °C. If the temperature hikes are observed at 700 °C for some time, 800 °C for some other time and normal operation at 600 °C, then the total depth of α-case can be obtained by adding α-case depths at 600, 700 and 800 °C. Failures of components in gas turbines most likely takes place due to non-accountability of these hikes. Therefore, it is essential to understand the consequences of such hikes and the present study provides a valuable answer to these types of problems. In essence, the developed oxidation model helps to predict the component life once the temperatures at which the component operates and the period of operation at each temperature is known. It is also possible to predict the remaining life of a component by using the present oxidation model.

From the present investigation, it is very clear that there is very good agreement between the experimentally measured and predicted depth of α-case formed regions (Fig. 3). Thus, it is possible to predict the α-case formation with reasonably good accuracy in titanium alloys. This study is extremely useful for modern gas turbines to evaluate the life of titanium alloy components without performing actual experiments on the alloys. It also helps to select the titanium alloy components with appropriate thickness for the designed life thereby eliminating failures during service. The major advantage of the developed model is that it is very simple, easy to use and time saving as no experiments need to be conducted on the actual alloy components.

Because of the technological importance of extending the operational temperatures of titanium alloy components primarily for aerospace applications and the danger of forming significant α-cases at elevated temperatures, it is highly essential to develop high performance protective coatings to protect them from both oxidation as well as α-case formation. With this goal, attempts were made and succeeded in developing suitable coatings for titanium alloys [4–7]. The recently developed coating produced through the combination of surface engineering techniques [5] enhances the life of the titanium alloy components considerably by successfully eliminating the oxygen uptake thereby helping in improving the efficiency of gas turbine engines significantly. Even after exposure at 800 °C for 400 h, no α-case formation was observed. The developed coating is found to be more efficient and effective when compared to the earlier coatings developed by the researchers in the field [8–12].

The following conclusions can be drawn:

An oxidation model has been successfully developed for predicting the α-case formation in the titanium alloys

An excellent agreement has been obtained between the predicted and measured α-case depths

The developed model will be extremely useful to assess the life of compressor section components in modern gas turbine engines thereby helping in elimination of failures during service.

High performance coatings have been successfully developed to protect the titanium alloys against α-case formation as well as oxidation thereby enhancing their life significantly.

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