Review on Fatigue Performance of Aluminum Alloys after Creep Age Forming

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Abstract. The process and characteristics of creep age forming technology was introduced. The influence of the creep age forming process on the fatigue performance on aviation aluminum alloy was discussed. Researches from three aspects were reviewed respectively—the fatigue damage mechanism of the creep age forming material, the influence of creep age forming process parameters on the performance of material fatigue, and creep age formed material life prediction mode. The trend of the creep age forming technology and the problems that may exist in its application in the field of aerospace were analysed. Finally, the major research direction was pointed out that fatigue properties of aluminum alloy materials and components based on the creep age forming technology should be studied deeply.

1. Introduction
High performance aerospace equipment is designated for the main task of the national economic development strategy and as the important direction, it brings Chinese aerospace equipment industry into a high-speed development period. The fatigue resistance performance of aluminum alloy as the key indicators and the important basis for safe running in the aviation and aerospace fields. In aerospace accidents, more than 80% are caused by material fatigue failure, lead to the global average, about 800 people die each year from air disasters. Therefore, in order to improve the safety of the equipment and market competition capacity, the key performance indicators for the aerospace equipment put forward higher requirements, such as: large aircraft to achieve 90000 flight hours, 80000 flights landing and 30 calendar year of service life; Compared with the third generation fighter aircraft, the flying time of the fourth generation fighter aircraft raise from 2000 hours to 6000 hours and the service life rose from 20 years to 30 years, et al. [1]

In order to meet the requirements of our social and economic development and national defense construction on the quantity and quality of aviation equipment, one of the key issues is to provide high performance materials for aviation equipment. Since the 50's of last century, some European and American countries begun to research the new technology, that is creep age forming. The creep age forming process synthesis consider the manufacturing environment which mainly for forming and the heat treatment environment which mainly for performance. The metal obtains the slow deformation at a certain temperature and stress conditions, which along with the combined effects of creep, stress relaxation, and aging, after processing, service performance of materials and components can be improved. This technology has more advantages than stretch forming, roll bending, and shot peening.
forming. Since the 1980 s, the creep age forming technology has been used to manufacture the large aircraft wing skin and wall board of Boeing and Airbus, MD, et al. [2].

In this paper, on the basis of reading a large number of domestic and foreign literature, it will summarize the research status of the creep age forming technology and fatigue in aerospace aluminum alloy, meanwhile, put forward some reference suggestions for the future research work.

2. The Principle of Creep Age Forming Technology

2.1. Typical Creep Age Forming Process.
The creep age forming is a new manufacturing technology which is developed on the basis of material mechanisms of stress relaxation and aging strengthening. Shown in Figure 1, the typical creep age forming process includes three processes [3]:

Figure 1. Basic principles of typical creep age forming technology

(1) Preloading. According to the requirements of forming surface, a certain initial stress/strain will load on the preforming parts, which lead to produce a certain amount of initial elastic strain, then fixed in a special mold which is designed by accurate calculation or according to the experience and which take springback compensation into account.

(2) Keeping under constant temperature. Put the fixed frock in the heating equipment, such as furnace, autoclave, and then keep for a period of time. In this process, due to the combine influence of the creep/stress relaxation and the aging strengthening, the elastic deformation of material can be converted to the permanent plastic deformation, at the sometime, the microstructure also changed accordingly, thus, the macroscopic properties changed. Research shows that the temperature is the main factors influencing the material creep rate, under low aging temperature conditions, the material’s creeping rate is slow, so, it's unable to obtain the ideal shape in limited time, however, under high aging temperature conditions, the material easily appeared overaging phenomenon, which affect the material performance.

(3) Unloading. After a predetermined aging time and remove form frock, you can see that some elastic deformation has been converted into a permanent plastic deformation. Due to the mold has been compensated for springback, therefore, the party obtains the required shape at the same time obtain aging strengthened.

2.2. The Advantages of the Creep Age Forming Technology.
The conventional forming techniques such as stretch forming, roll forming, peen forming, they have some defects such as the precision is not high, the internal residual stress is large, the forming structure partial damage is serious and the reliability is low, which affecting the performance of forming structure, therefore, there are need a new forming technologies to manufacture large aircraft. When apply the creep age forming technology on the aircraft wing panels, there are some advantages than those conventional forming technologies [4,5]: (1) It is greatly reduced the risk of cracking parts to machining,
(2) It improves the microstructure the strength of the material; (3) It has high forming accuracy, repeatability and forming efficiency; (4) After forming, the interior stress is almost zero.

Just because of those, the creep age forming technology has been widespread concern and research, and among the important process of aerospace manufacturing in the future, Although China is behind the foreign currently in the fields of research and application of this technology, basic research remains to be further and process should be improved, it has wide application prospects[6].

3. Creep Age Forming Aluminum Alloy Fatigue

In the treatment process by creep age forming process, the material structure and evolution process is very complex, which lead to the fatigue characteristics factors that effect on the creep age forming materials become complex. For example, in the coupling field of stress and temperature, the initial strengthening phase precipitation and the segregation characteristic increased by the aging time, which make the composition inhomogeneities increased and easily lead to stress concentration, all of above reason are the incentive for crack initiation; Due to the size of precipitates and direction changes with aging time, it brings the number, position and direction of crack initiation of uncertainty, which lead to macroscopic fatigue performance uncertainty. Moreover, with the increasing of temperature and stress intensity, the creep speed increasing, in the range of aging time prolonging and temperature dropping, the dislocation and twin interface create the interchange mechanism, this is the cause of fatigue crack initiation and propagation; Due to the randomness of dislocation line interface intersection with twin interface, the macroscopic fatigue performance of the material presented randomness. Thus, the fatigue performance of material and structure which formed by creep age forming are controlled by the micro-structure and the parameters of creep age forming.

3.1. Fatigue Damage Mechanism of Creep Age Forming.

In 1998, Sarioglu F [7] studied the effects of aging time on fatigue properties of 2024-T3 aluminum alloy, he tested and analyzed the fatigue crack growth rate with three orientations pieces, including L-T, T-L and 60oC, the results shows that, the aging time can reduce the difference of fatigue crack growth rate anisotropy, and in the same orientation, metastable precipitation can be formed with uniform refinement phase under the condition of under aging, thereby, the fatigue performance of aluminum can be improved and the fatigue crack growth rate can be reduced. In 2000, Pitcher P D [8] studied the creep age forming performance of 2024A, 8090, 7449 aluminum, especially, the crack growth rates assessment of forming material, it is noted that the creep age forming technology can be applied to manufacture the aircraft wing skins with the 2024A, 8090 aluminum alloy. His work provides a reference for the selection of the aging process. In 2000, Siddiqui R A [9] studied the influence of the aging temperature and the aging time on the fatigue life and other mechanical performances. However, the process and conclusions are somewhat simple. In 2001, Brav G H [10] studied the crack growth rate of 2024-T3 alloy at the difference aging conditions and found that the crack growth rate of 2024-T3 was lower in artificial underage stage than in the natural aging stage, but with the aging time gradually extended, the crack growth rate of 2024-T3 alloy showed a gradual increasing trend. The experiences revealed the possible reasons are that during the process of under aging, a large number of high density atomic segregation GP zones which advantages or disadvantages for the fatigue crack growth performance of 2024 aluminum alloy. In 2005, Lumley R N and his partners [11] found that underaging can reduce the fatigue crack growth rate of Al-Cu-Mg-Ag alloy and the fatigue performances are improved. In 2012, Tchitembo F [12] studied the fatigue crack growth rate and local textures of 2099-T83 aluminum-lithium alloy and obtained the similar results. In 2012, Zhan L H of central south university [13] studied the influence of the age forming process parameters on the mechanical performance of 2024 aluminum alloy. However, there has not seen the report about in-depth studies for fatigue damage mechanism of creep age forming.

3.2. Relations between Creep Age Forming Process Parameters and Fatigue.

Creep age forming process research mainly revolves around forming and performance. IN 2003, Ho K C [14] combined the traditional stress and strain analysis and the microstructural evolution to create a
creep / stress relaxation aging constitutive model which unified with sedimentation phase precipitation, grain growth and dislocation based on the creep, stress relaxation and aging kinetics theory, and then carried out springback simulation; IN 2001, Zhu A W [15] studies the influence of the stress on the microstructure and performance of Al-2.5Cu, Al-4Cu and Al-5Cu alloy, noting that stress causes \( \theta / \theta \) phase precipitation was arranged in the direction perpendicular to the stress, and tensile stress cause precipitation of the \( \theta / \theta \) phase arranged in the direction parallel to the stress, also pointed out the directional effect of the stress are affected by the size, the temperature and the alloy composition. In domestic, the research though still in its infancy, basing on the foreign working, parts of work are carried out. In 2010, Zhao F [16], who comes from Dalian University of Technology, studied the fatigue performance of 2A12 age forming aluminum alloy, then found that after aging, the fatigue crack growth rate faster than before, with the aging temperature increasing, the fatigue crack growth rate increasing, and similar to the aging time. In 2011, Jin X [17], who comes from the Beijing University of Aeronautics and Astronautics, carried out the research that the fatigue performance of 7BO4 aluminum alloy after creep age forming, and found that after aging treatment, the fatigue life of material has increased than the original, and also found that after aging treatment, the fatigue performance of the low stress are better than others.

In summary, we are behind in the foreign about the research about the creep age forming technology, especially, the studies about the influence of the age forming process parameters on the fatigue performance of materials are just beginning. In order to meet the requirement of Chinese “large aircraft” project development, it is urgent to reveal the mapping rules that the creep age forming process parameters to the fatigue performance of the materials.

3.3. Life Prediction Model of Creep Age Forming

In 1962, Taita S [18] first predicted the fatigue life of structure, which take into account the creep rupture and cyclic strain. In the 1980s, in the promotion of the United States of America NASA HOST plan, creep fatigue life prediction model of high temperature materials has made a spurt of development. In 1991, Halford G [19] divided the creep-fatigue life prediction models into 13 categories, but only the three of which were applied, that are the time-cycle fraction method, damage mechanics method and the strain range partitioning method. In recent years, many scholars have proposed some new creep-fatigue life prediction model. In 2003, Tarun G [20] proposed a creep-fatigue life prediction model which suitable for the common alloy, the fatigue prediction results were consistent with the experimental results; In 2007, Chang Y J [21] presented a new creep-fatigue life prediction model which based on the creep stress release of the process of aging, this model is applicable high-temperature materials those have any crack geometry; In 2008, Valentin R [22] proposed a creep-fatigue life prediction model which based on the elastic stress release of via hole structures, this model makes creep-fatigue life prediction calculation faster; In 2006, Chen L [23], who comes from the Domestic Zhejiang University, based on the laws that conservation of energy and momentum conservation, proposed a new creep-fatigue life prediction model, and which is very simple and presentation clear; In 2012, Zhang G B [24], who comes from Beijing Institute of Technology, improved the Saxena model and applied it to carry out nickel-base superalloy creep-fatigue life prediction, and the results are consistent with the experiment results. Overall, there are a variety of creep-fatigue life prediction models, however, many of them no longer been studied deeply, additionally, because of the complexity of the mechanism of fatigue damage, some life prediction model is not sufficient to consider the impact of factors, especially, it is not sufficient to be verified and be revised by fatigue testing so that many models can only be restricted in the laboratory but not be applied in practical engineering structure design.

4. Conclusions

Most scholars have focused on the relationship between the creep/stress relaxation mechanism and the deformation of materials, from which we can precisely control the deformation during the process of creep age forming treatment, and focused on how the creep/stress relaxation mechanism affects the material microstructure, from which we can improve the material’s performance. In China, the studies
of creep age forming technology, although, with the strong support of the country and the hard work of research institutes, obtained some valuable results, is at the very beginning. There were still many problems to be solved: (1) During aging, the processes that strengthening phase formation and precipitation have not been explained clearly, the relationship between the strengthening phase and the fatigue performance are not yet clear; (2) The relationship between the parameters of creep age forming process and the material fatigue performance has not been studied comprehensively and systematically, the relationship between theoretical and actual has not been established yet; (3) Especially, in complex environment, the fatigue performance based on the creep age forming technology has not been studied deeply.

View from home and abroad, the development trend of aging forming technology are as follows: (1) The development should transform from the static mechanical performance (yield strength, plastic, etc) to the dynamic mechanical performance (fatigue, fracture toughness, et al) after aging treatment; (2) The development should transform from the experimental analysis of aging precipitation behavior under the single stress aging condition to the mapping rules that age forming mechanism and the component’s fatigue performance under the complex thermal/mechanical conditions (different age forming process parameters); (3) Based on the available creep-fatigue life prediction models, new creep-fatigue life prediction model which is suitable for multi-factor coupling conditions should be developed.

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