Post-Processing Design and Application of Inconel 718

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Abstract. Inconel 718 is a Ni-based superalloy, usually used for aircraft engine because of its high temperature properties and oxidation resistance. According to the current experiments, most experiments are done through the traditional manufacturing. Recently, the additive manufacturing, also called 3D printing, has been regarded as a new manufacturing that is used in the experiment. Different manufacturing causes the different orientation and segregation, and leads to different results with traditional manufacturing. Besides, the design for the heat treatment is always the point that researchers are looking for. The conventional method is homogenization and ageing, but some researchers have tried the direct ageing to find the differences. This paper focuses on the influence of temperature, time of the heat treatment and the effect of manufacturing method. It is concluded that the manufacturing method can influence the best choice of heat treatment. What is more, the additive manufacturing with high temperature homogenization and ageing is a good method in the experiment but it is hard to use in the industry now. Through the research of various factors, it is helpful to find a better method to improve the properties of Inconel 718 during the application.

1. Introduction
Inconel 718 has been studied extensively since the last century. With the development of technology, the Inconel 718 is usually used in industry and aircraft due to the high strength and good oxidation. Recently, the Inconel 718 is still studied by lots of researchers. They usually focus on the method of heat treatment to observe the expected phases which can strengthen the mechanical properties. Most researchers prefer to explore the homogenization and ageing part but few of them focus on the direct ageing, may get different results. Because of the new technology, the additive manufacturing is popular during recent year while few of them explore it. The disadvantage of the additive manufacturing now is that it could not be used in the industry. This paper explores the influences of heat treatment and manufacturing. The heat treatment method is always updated but usually researchers use high temperature with a short time in homogenization part and ageing a long time. Recently, some researchers try to use direct ageing to explore the formation of phases. The manufacturing, even the additive manufacturing, cannot be used in the industry but the prospect is good. By contrast, researchers can find a better recipe for the Inconel 718 and provide a reference to the industry.

2. Literature Review
Ni-based alloy is the material usually used in airspace because of its high strength and oxidation resistance at high temperature. The major precipitate γ″ could increase the strength, which is an approach that should be explored [1]. Niobium (Nb) is a very important element in the Inconel 718 because it can form γ″. In addition, it is also the influential element for detrimental Laves phase and δ phase. The formula and their feature could be seen in table 1.
Table 1 Major Phases of Inconel 718 [2]

| Phase | Formula       | Comments                          |
|-------|---------------|-----------------------------------|
| γ     | -             | Matrix                            |
| γ'    | (Ni)3(Al, Ti) | Strengthening                     |
| γ''   | Ni3Nb_D022    | Principal strengthening, metastable|
| δ     | Ni3Nb_D0a     | Detrimental                       |
| Laves | (Ni, Fe, Cr)2(Nb, Ti, Mo)1 | Detrimental                       |

The formation of Laves phase could consume a large amount of Nb, making less Nb left in the γ matrix [3]. The formation of γ” would be influenced with less Nb, decreasing the strength of the material [4]. What is more, δ phase also could consume some Nb to preferably form along the grain boundaries, which could decrease the grain size [5]. If the grain size is small, the hardness could be increased. Nevertheless, yield strength, toughness and some other mechanical properties would be affected. Therefore, δ phase is also detrimental that cannot remain too much in the material.

Micro-segregation is also an important part that would influence the growth of the Laves phase and δ phase, and both of them consume a lot of Nb. However, at elevated temperature for a long time, the size of Laves phase decreases [3]. Meanwhile, dissolution of most Laves phase into γ matrix accompanies with recrystallization that could cause the grain growth with annealing twins [3]. The elemental segregation could be reduced to avoid the formation of Laves phase [4]. Without high temperature homogenization, Laves phase is hard to remove and the segregation could not be reoriented. There would be more Laves phase that influences the strength of the material. δ phase is usually formed along grain boundaries [6]. δ phase with small size causes the pinning effect on grain boundaries, and the grain growth is restricted [7]. Ageing process with low temperature could not introduce recrystallization and the grain size is hard to change, which will cause more δ phase. The homogenization could reorient the grains and induce the recrystallization, providing driving force for dissolution of Laves phases and δ along grain boundaries [6].

For the laser additive manufacturing (LAM), after direct ageing, the irregular and long-striped Laves phase still exists, which lowers the tensile strength [8]. However, according to F. Theska, et al, as-forged Inconel 718 alloy has a lower δ phase fraction through the direct ageing process. The reason is that direct ageing (720 °C and 620°C) could avoid the formation of δ phase whose forming temperature is between 875 °C and 925 °C. More Nb could be left in γ matrix to form the γ”, and the temperature is not easy to make γ” transforms to δ, and then the strength could be increased [9].

Inconel 718 is generally used in airspace, power plants and some manufacturing because of its high strength and oxidation resistance at high temperature. The current industrial procedure is homogenization at high temperature, followed by water quench, and then ageing for a long time followed by the water quench to get the high strength. However, the heat treatment is possible to be optimized due to the properties of the material and the important element niobium, 1180 °C for the homogenization is a possibility that makes the homogeneity of Nb [10]. Compared with different post processing treatment, it is clear for the latter researcher to explore the expected properties.
3. Experimental Procedure

3.1. Heat treatment
As for the homogenization, the temperature should be high but cannot make it to the liquid phase. Usually it is higher than 900 °C even 1000 °C but no more than 1200 °C followed by the water quench. After that, ageing needs to be designed that the temperature and time are important. It is often between 600 °C and 900 °C followed by water quench, but the time has the large differences due to researcher’s expectation. The direct ageing is also done by some researchers like F. Theska, and the purpose is to compare the phase and mechanical properties with homogenization and ageing.

3.2. Characterization
Samples are usually observed by scanning electron microscope (SEM). In addition, secondary electron (SE) was used to observe the morphology. Backscattered electron (BSE) was used to observe the phases. Laves phase and δ phase were studied under SEM. After etching, the γ' and γ" can also be found under SEM. Energy-dispersive X-ray spectroscopy (EDS) was used to find the distribution of each element. Transmission electron microscopy (TEM) is also good to find γ’ and γ". Besides, this method is better to explore the anisotropy of the phase, showing the properties is good or not.

4. Results and Discussion
The different manufacturing causes the different distribution of original phases and the isotropy. The new method additive manufacturing is built layer by layer and it introduces anisotropic structure. Therefore, the segregation for the additive manufacturing materials is more serious than other traditional method. The segregation of Nb can move Laves phase to the γ matrix in a much easier way. Due to the high temperature, the Laves phase and δ phase would disappear, which releases the Nb into the γ matrix. But the high temperature is good to make the phase homogenized and then after ageing, the Nb introduces γ", which increases the strength. However, for the traditional method, it is isotropic, and the homogenization cannot have such big differences like additive manufacturing. Under this condition, for the direct ageing, the additive manufacturing sample is better because of the anisotropic
structure. Nevertheless, the F. Theska’s experiment shows his results that direct ageing is better because it increases the two strengthening phases $\gamma'$ and $\gamma''$. In addition, the strength is also increasing, compared with homogenization and ageing. Hence, the manufacturing is a factor that can influence the results. The additive manufacturing is anisotropic that can be dissolved by the homogenization. While for the traditional method, the direct ageing can help increase phases $\gamma'$ and $\gamma''$, as well as the strength. When comparing the cast and additive manufacturing sample, additive manufacturing has much more precipitation than cast sample. And also, the additive manufacturing has higher density, and the higher strength. These factors cause different results when using the similar heat treatment. Through the precipitation of $\gamma'$ and $\gamma''$ in the experiment, the additive manufacturing is better than the traditional manufacturing. Even though it shows that the additive manufacturing has more advantages than cast, but this kind of sample is hard to be produced largely in the industry, remaining still a long way to explore.

As for the difference of heat treatment, the homogenization is to remove the Laves phase and make the Nb move into the $\gamma$ matrix. The high temperature is to make the phases homogenization, the temperature should be high but cannot be reached high enough to transform it into the liquid phase. Several researchers and industrials have realized it at the homogenized temperature between $970 \text{ °C}$ to $1065 \text{ °C}$. Recently, there is a new research that has done at $1180 \text{ °C}$ for the homogenization, especially for the additive manufacturing sample. With homogenization time increases, the Laves phases begins to dissolve while the carbides exist. The results for the homogenization time do not have much differences between 1 hour and 12 hours. After the ageing, the $\gamma'$ and $\gamma''$ has been produced and do not have too much differences. After compared with the industrial results, the new method for homogenization at $1180 \text{ °C}$ has higher strength and good mechanical properties, which is a good approach for the post-processing design. The problem is that it may be hard to get the high temperature in the industry, but it still a good approach for the design.

Inconel 718 is nickel based alloy that is usually used in airspace, power plants and some industries, but the importance of the strength and mechanical properties in these aspects cannot be neglected. Although for decades, researchers have explored the post-processing design for the Inconel 718, the best method has not been found and they are still exploring it.

5. Conclusion
The manufacturing method is very important in the experiment that it could introduce different results. Therefore, further experiment should be done to find the differences. Through the results of the comparison, the direct ageing may be better for the traditional manufacturing like forged sample but the homogenization and ageing is better for the additive manufacturing. Besides, the temperature and time for the heat treatment are still the important factors in the post-processing design. Although it is hard to find the best recipe, researchers are trying their best to make it better. Inconel 718 has many utilities such as its application in the airspace, and therefore it has the high requirement for the material. The importance in the industry and airspace cannot be neglected. It has a good prospect to do some research on it.

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