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Defect analysis and fatigue design basis for Ni-based superalloy 718 manufactured by selective laser melting

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A R T I C L E I N F O

Keywords:
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Statistics of extremes

A B S T R A C T

It is well known that high strength metallic materials with Vickers hardness $HV > 400$ are very sensitive to small defects. This paper discusses fatigue properties of a Ni-based Superalloy 718 with $HV = \sim 470$ manufactured by additive manufacturing (AM). The advantage of AM has been emphasized as the potential application to high strength or hard steels which are difficult to manufacture by traditional machining to complex shapes. However, the disadvantage or challenge of AM has been pointed out due to defects which are inevitably contained in the manufacturing process.

Defects of the material investigated in this study were mostly gas porosity and those made by lack of fusion. The successful application of the $\sqrt{area}$ parameter model was confirmed. Although the statistics of extremes analysis is useful for the quality control of AM, the particular surface effect on the effective value of defect size must be carefully considered. Since the orientations of defects in AM materials are random, a defect in contact with specimen surface has higher influence on fatigue strength than an internal defect and has the effective larger size termed as $\sqrt{area}$eff than the real size, $\sqrt{area}$, of the defect from the viewpoint of fracture mechanics. The guide for the fatigue design and development of higher quality Ni-based Superalloy 718 by AM processing based on the combination of the statistics of extremes on defects and the $\sqrt{area}$ parameter model is proposed.

1. Introduction

The advantage of AM has been emphasized as the potential application to high strength or hard steels which are difficult and costly to manufacture by traditional machining to complex shapes. However, the disadvantage or challenge of AM has been pointed out due to defects which are inevitably contained in the manufacturing process and detrimental to fatigue strength.

Many literature on fatigue properties of AM materials have been published in recent years as seen in the review papers [1–6]. The review paper by Berreta and Romano [1] gives a detailed and thorough analysis on the fundamental problems to be studied on AM materials. Günther et al. [6] carried out precise experimental observations on Ti-6Al-4V in high cycle fatigue and very high cycle fatigue and based on the observation they discussed the problem from the viewpoint of statistical scatter of defect size. They pointed out the problem raised by the interaction between defects and specimen surface. Application of AM to Ni-based super alloy 718, Inconel 626 and Hasteloyx-X is expected for aerospace engine components and gas turbines under high temperature use. Although there is some investigations on long crack growth properties on Ni-based superalloy [7], the current most important problem of AM to be solved is how to cope with surface roughness and defects which are inevitably contained in AM materials.

This paper discusses fatigue properties of a Ni-based Superalloy 718 manufactured by AM in terms of the effect of defects. The guide for the fatigue design and development of high quality Ni-based Superalloy 718 by AM processing will be presented based on the combination of the statistics of extremes on defects and the $\sqrt{area}$ parameter model [8,9].

2. Material, specimen and experimental method

The materials were made by AM processes, Selective Laser Melting (SLM) method. The materials denoted by Material A and Material B produced by SLM used in this study were exposed to heat treatments for stress relief, solution heat treatments and precipitation heat treatments in accordance with AMS5663 basically. Therefore residual stress was reduced sufficiently and major residual stress states can be avoided.

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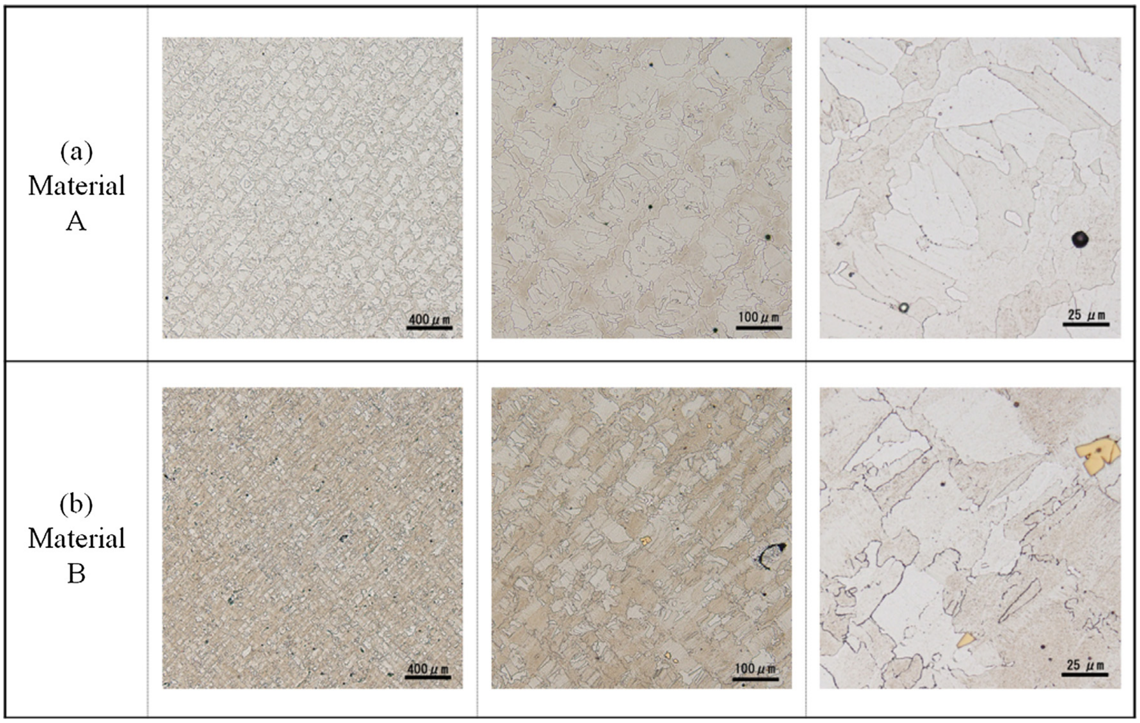

Fig. 1. Microstructure of Ni-based Superalloy 718 produced by SLM.

Fig. 1 shows the microstructure of the both Materials A and B. It can be found that the granulometry of the powder particle of Material B is smaller than that of Material A from the microstructure observation. Also the Materials A and B were produced by different selective laser melting machine systems based on the recommended processing parameters of the machine fabricators.

Specimens were machined from the two kind of raw plate Materials A and B, produced by SLM. Specimens were cut in two directions, i.e. as-built direction (L direction) and perpendicular (T direction) to as-built direction as shown in Fig. 2 (Case for Material A and similarly for Material B). Fig. 3 shows the shape and dimension of specimen.

The mechanical properties were measured by using the fatigue specimens. Table 1 shows tensile test results. The 0.2% proof stress ranged from 1227 MPa to 1329 MPa and the ultimate tensile strength ranged from 1306 MPa to 1499 MPa. The elongation with 8 mm gauge length ranged from 13.6% to 31.8% and the reduction area from 8.6% to 30.7%. It was revealed by observation of fracture surfaces that the scatter of the mechanical properties was caused by various defects contained in specimens. Tensile tests show the low performance in elongation and reduction of area of Material B especially in L-direction. From the microstructure shown in Fig. 1 and also SEM observations of tensile fracture surfaces, Material B has more numbers of defects and inclusions than the number of defects in Material A. This is the cause of the decrease of the elongation and the reduction of area in Material B.

Specimen surface was polished by emery paper with #600. The remaining materials of Fig. 2 after cutting specimens were used to investigate the microstructure and statistical distribution of defects.

The analysis of statistics of extremes was applied to the largest defects observed on 9 sections with the observation area $S_0 = 80.97\ \mathrm{mm}^2$ for Material A and $S_0 = 116.49\ \mathrm{mm}^2$ for Material B. The largest defects were separately analysed on pores, linear defects and equivalent elliptical defects for interactive adjacent defects. The Vickers hardness HV ($P = 5$ kgf) was measured at 5 points. $HV = 465 \pm 1.7\%$ for Material A and $HV = 474 \pm 1.2\%$ for Material B. The averaged HV value was used in the fatigue assessment shown later. HV value cannot significantly depend on the specimen direction extracted from raw Material due to the low dependence of specimen direction in ultimate tensile strength as shown in Table 1. Tension compression fatigue tests at the stress ratio of $R = -1$ were carried out with hydraulic tension-compression testing machine at 30 Hz with strict specimen alignment within ± 5% for the values of 4 strain gauges attached to each specimen at $\pm 500\ \mu\varepsilon$ and $\pm 1000\ \mu\varepsilon$. The fatigue fracture origins were mostly at defects. The accurate specimen and testing machine alignment are very important to avoid obtaining wrong data related to non-uniform stress distribution, statistical size distribution of defects and spatial configurations of defects in specimens.

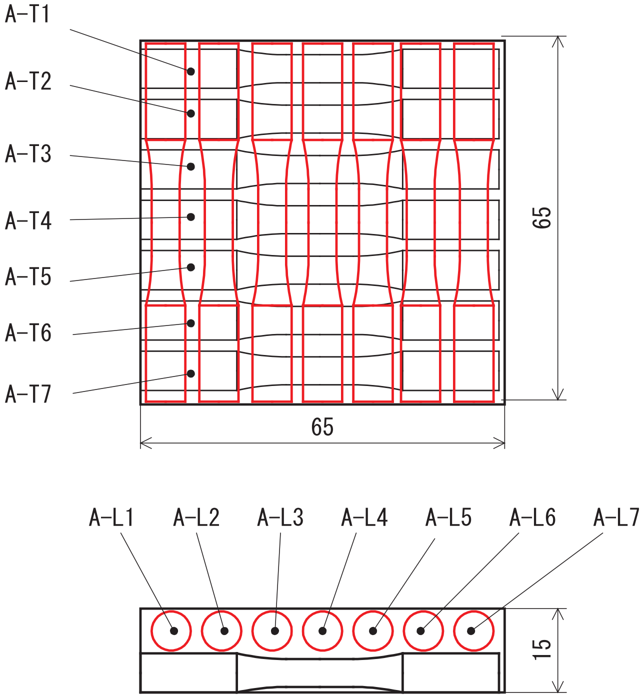

Fig. 2. Raw plate material (Material A) and cutting layout for specimens.