Fatigue property of Shot peened Maraging Steel fabricated by Additive manufacturing

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Abstract
Shot peened maraging steel fabricated by additive manufacturing were evaluated the fatigue strength by rotating bending fatigue test. It is to investigate the influence of shot peening for the fatigue property of additive manufactured parts. The specimen was employed the surface which was as-built and the surface which was polished. As a result, shot peened specimens increased 2.5 times higher fatigue strength than As-built specimens. Fatigue fracture origin changed form surface to internal by shot peening. Furthermore, shot peened specimens were higher fatigue strength and longer fatigue life than Polished specimen. Fatigue fracture origin changed from surface to internal by shot peening. Therefore, shot peening drastically affects to increase the fatigue strength of additive manufactured material due to prevention of surface crack propagation by the inducing compressive residual stress.

Keywords Shot peening, Additive manufacturing, Fatigue strength, Maraging steel.

Introduction

Additive manufacturing has been researched by many researchers as new manufacturing method to fabricate complex parts which cannot fabricate conventional manufacturing methods such as grinding, forging, casting etc. [1-4].

Most of metal additive manufacturing are manufactured by melting material powder by thermal source such as laser beam, electron beam and stacking the molten metal. The surface roughness on additive manufactured parts is Ra > 4 [μm] [5]. This surface roughness affects the fatigue strength of additive manufactured parts. Consequently, additive manufactured parts were lower fatigue strength than parts which made by conventional manufacturing methods [6-7]. The surface roughness is generally removed by machining. However, it is difficult to access the machining the tool to parts due to complex geometry by the taking advantage of additive manufacturing. Therefore, surface enhancement method to be easy to process for the complex geometry is required.

Shot peening is one of the surface enhancement method by inducing the work hardening, compressive residual stress. This process is carried out the impact of peening media which has media diameter from 0.05[mm] to 2.0 [mm]. Hence, it is relatively easy to access the complex geometry and to enhance the parts. Many researchers studied the fatigue strength of shot peened specimen fabricated by additive manufacturing. However, the surface roughness of additive manufactured specimen in most of researches was machined [8-9].

In this study, we investigated the influence of shot peening on fatigue strength against the additive manufactured maraging specimen which retained the surface roughness of as-built condition.

Experimental Methods

Specimen

Maraging powder was employed. The powder was stacked in the direction of longitudinal direction of specimen by selective laser melting method. Polished surface and As-built surface were employed to investigate the influence of surface roughness on fatigue strength.

These specimens were carried out solution and aging treatment. Shapes and geometry of finished specimen is shown in Fig.1. Manufacturing procedure of both specimens were shown in Fig.2.

Three shot peening conditions which changed the mainly media diameter was employed to vary the residual stress distribution induced by shot peening. Kinds of specimens were shown in Table1.

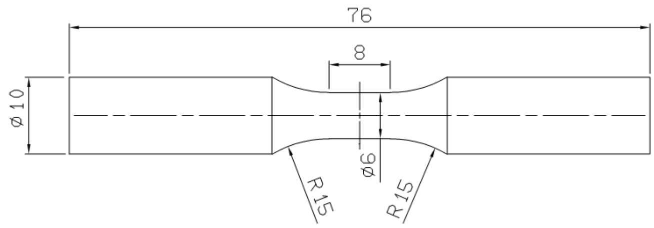


Fig.1 Shapes and geometry of specimen.

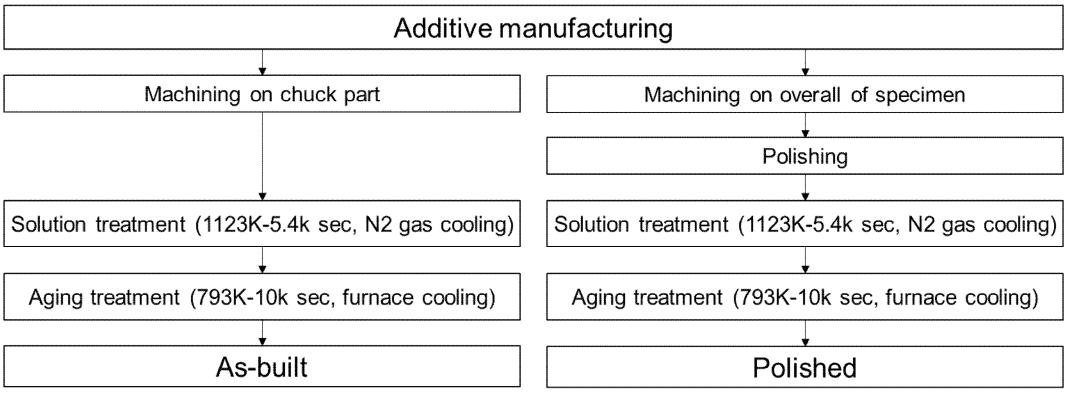


Fig.2 Manufacturing procedure of specimen.

Table1 Kinds of Specimens.

Symbol	Surface condition	Shot Peening Conditions					
		Media	Media diameter [mm]	Media Hardness [HV]	Peening Method	Air Pressure [MPa]	Arc height
As-built	As-built	-	-	-	-	-	-
Polished	Polished	-	-	-	-	-	-
FSP	As-built + Shot Peening	Cast steel	0.1	800	Direct Pressure	0.2	0.286 [mmN]
SP		CCW	0.6	600		0.3	0.430 [mmA]
HSP		CCW	1.2	600		0.3	0.901 [mmA]
Polished + FSP	Polished + Shot Peening	Cast steel	0.1	800	Direct Pressure	0.2	0.286 [mmN]
Polished + HSP		CCW	0.6	600		0.3	0.430 [mmA]

Evaluation Methods

Microstructure surface roughness, hardness distribution and residual stress measurement were evaluated to investigate the characteristics of each specimens. Furthermore, cross section of minimum diameter part in specimen was carried out to investigate the defect due to additive manufacturing in specimen.

Cross section observation was carried out by laser microscope. The specimen was mirror polished sample which was cut at minimum diameter part in transverse direction. This sample was mounted by hot set resin before mirror polishing.

Microstructure was observed by laser microscope after etching against sample which used in cross section observation.

Surface roughness was measured by stylus-based profiler. Roughness measurement standard was JIS B 0601-2001. Roughness measurement direction was longitudinal direction of specimen.

Hardness distribution was measured by micro Vickers hardness tester. Measurement load was 2.94[N].

Residual stress was measured by X-ray diffraction method. Analyzing method of residual stress by X-ray diffraction was $\sin^2\psi$ method. X-ray constant was -318[MPa/deg.]. Measurement angle was selected the 5 angles that $\sin^2\psi$ value of measurement angles was equal interval from 0 to 0.5. Oscillation angle was 5[deg.]. Depth direction measurement of residual stress was carried out by removing the layer to optional depth by electropolishing.

Fatigue test Method

Fatigue test was carried out under room temperature and atmosphere by Ono-type rotating bending fatigue testing machine. Number of run-out was 2.0 X 10^7 [cycles]. Stress ratio was R=-1. Fractured surface was observed by optical microscope and scanning electron microscope to evaluate the crack initiation point.

Experimental Results and Discussions

Cross-section and Microstructure observations

Representative cross-section and microstructure observation results are shown in Fig.3.

In the cross-section observation, many defects were observed from surface to center of specimen. These defects are uniformly distributed in specimen. This trend was observed in all conditions.

Microstructure of all specimens was martensite by solution and aging treatment. Unmelted particles were observed on As-built surface. On the other hands, unmelted particles were not observed on surface of shot peened specimens which had As-built surface due to removing it by the impact of peening media.

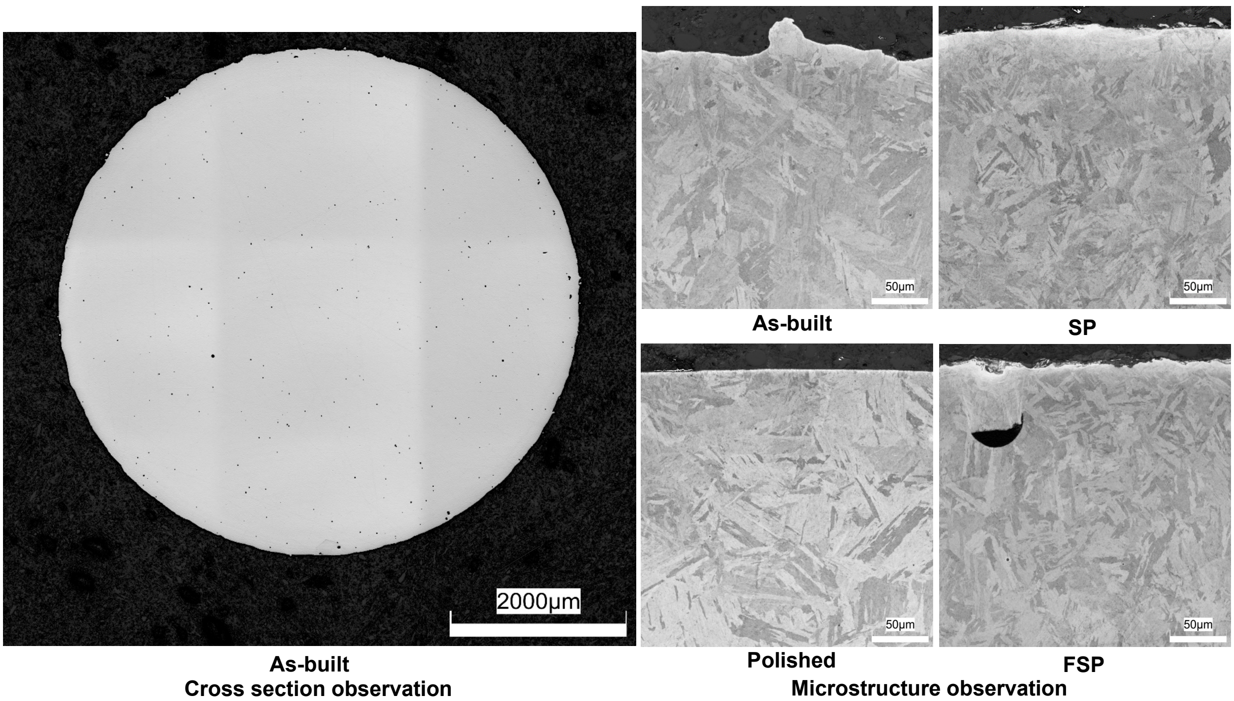


Fig.3 Cross section and Microstructure observation results.

Surface roughness

Average surface roughness measurement results are shown in Fig.4.

Average surface roughness of As-built was approximately 7.25 [μm]. All shot peened specimen which had As-built surface decreased the surface roughness due to smoothing the surface roughness and removing the unmelted particles by the impact of peening media. In the case of same hardness of peening media, surface roughness decreased with increasing the media diameter. The larger media diameter is, the higher media impact energy obtains.

Therefore, HSP condition can smooth the high surface roughness of As-built surface due to higher impact energy of peening media. In this study, even though media diameter of FSP was the smallest, FSP condition was the most effective condition to reduce the surface roughness of all shot peening conditions. The result indicates that the ablation generated in FSP condition due to higher media hardness than that of SP and HSP conditions.

Average surface roughness of Polished was approximately 0.27 [μm]. All shot peened specimen which had Polished surface increased the surface roughness. The surface roughness increased with increasing media diameter in these conditions.

Hardness distributions

Hardness distributions are shown in Fig.5.

Hardness of this specimen was approximately 630 [HV] from surface to internal.

Work-hardening of all shot peened specimen were not obtain in these conditions. These results imply that the work-hardening coefficient of this material was low.

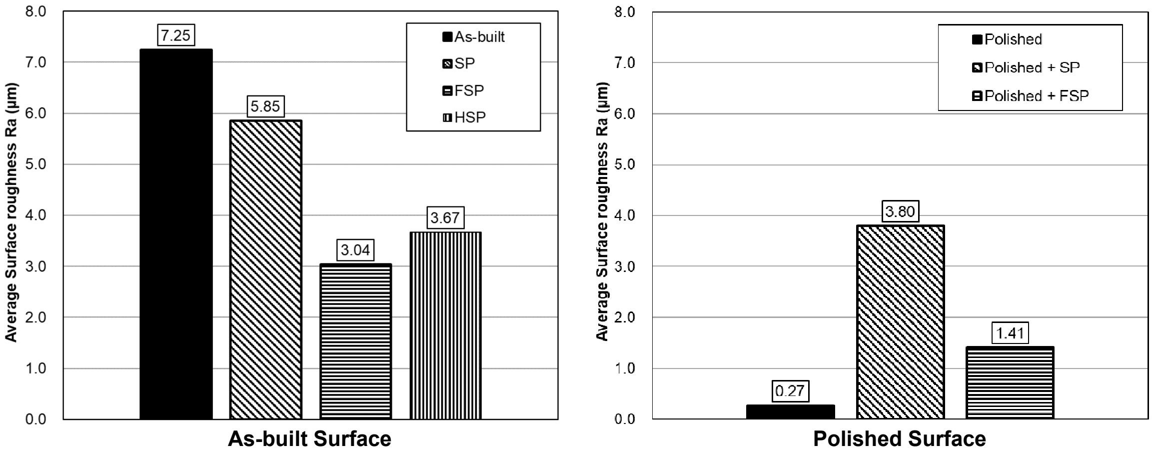


Fig.4 Surface roughness results.

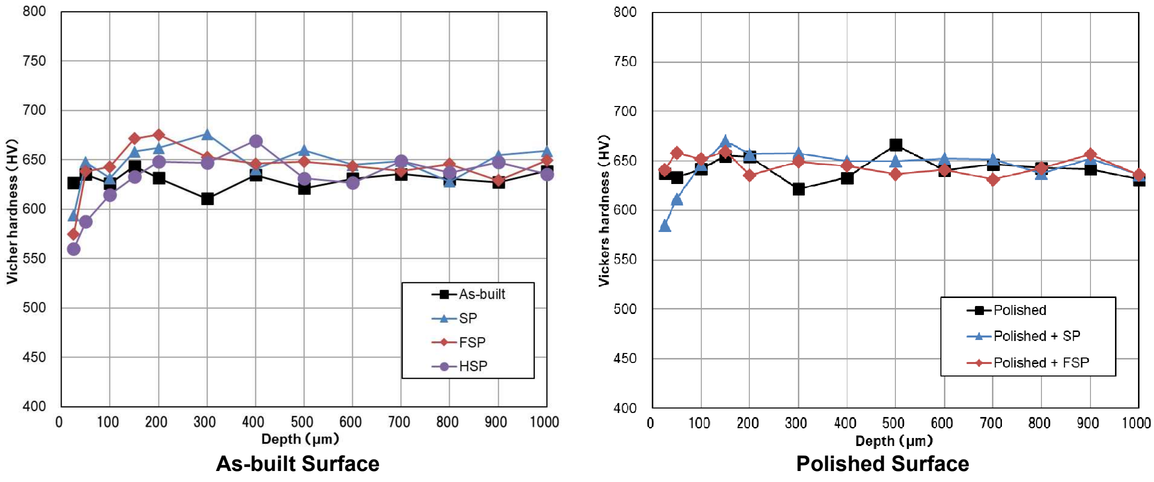


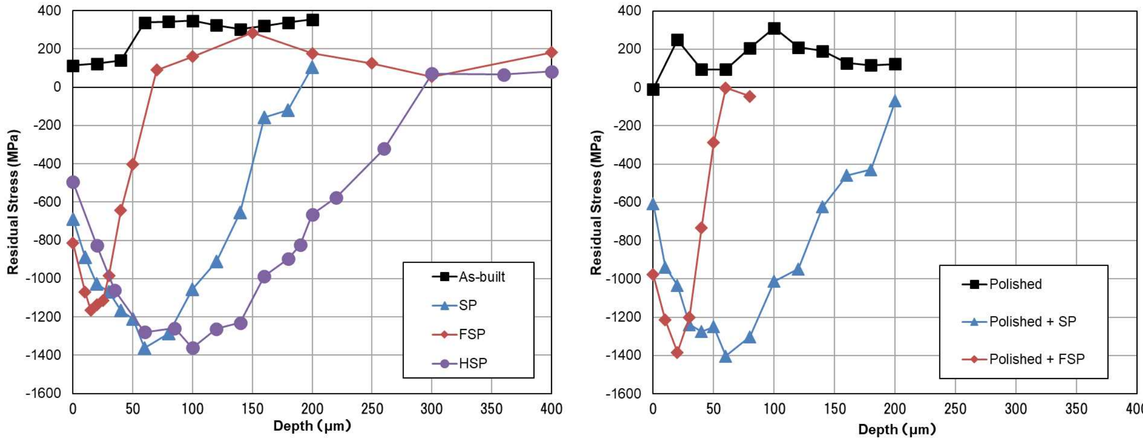
Fig.5 Hardness distributions.

Residual stress distributions

Residual stress distributions are shown in Fig.6.

Polished and As-built had tensile residual stress from surface to internal. In our past research [8], the additive manufactured maraging steel which was carried out solution treatment was lower tensile residual stress than the specimen in this study. Hence, this comparison indicates that the precepted particles due to aging treatment affects the residual stress.

Shot peened specimens were induced compressive residual stress up to approximately -1400 [MPa] by shot peening. Surface compressive residual stress was difference in each shot peening conditions. As a tendency, the smaller media diameter was, the higher surface compressive residual stress increased. The crossing point was approximately 60[μm] in FSP and Polished + FSP, approximately 200[μm] in SP and Polished + SP, approximately 300[μm] in HSP. In addition, the depth of maximum residual stress point was approximately 20[μm] in FSP and Polished + FSP, approximately 60[μm] in SP and Polished + SP, approximately 100[μm] in HSP. The depth of maximum residual stress point and the crossing point increased with increasing the arc height.



As-built Surface **Polished Surface**

Fig.6 Residual stress distributions.

Fatigue test results

1.As-built and Polished

Fatigue test results are shown in Fig.7. Fracture surface observation results are shown in Fig.8.

Fatigue fracture was generated surface and internal. Surface fatigue fracture was generated the valley of surface roughness, matrix crack of microstructure, and surface defect. Internal fatigue fracture was generated matrix crack of microstructure and internal defect.

Fatigue strength of As-built was 200[MPa], this result was the lowest fatigue strength of all conditions. On the other hand, it of Polished was 450[MPa]. As a result, Polished was 2.25 times higher fatigue strength than As-built. The fatigue life of Polished extended comparison with As-built. The residual stress and hardness distributions between As-built and Polished were almost same. Furthermore, fatigue fracture of As-built was generated from the valley of surface roughness, whereas it of Polished was generated from surface defect or matrix crack of microstructure. Because, stress concentration due to surface irregularity decreased to remove surface irregularity by shot peening. Therefore, surface roughness strongly affects fatigue fracture in this comparison.

2. As-built and FSP, SP, HSP

Fatigue strength of FSP, SP and HSP were 500[MPa]. There was not the difference of fatigue property in FSP, SP, and HSP. The fatigue strength of theses increased 2.5 times against As-built. The fatigue life of its extended in comparison with As-built. Surface roughness of all shot peened specimens decreased in comparison with As-built. From the comparison with As-built and Polished, the reduction of surface roughness affects to increase the fatigue strength. Therefore, the one of influence factor to increase the fatigue strength is to reduce the surface roughness by shot peening. Fatigue fracture origin of shot peened specimens changed from surface to internal. SP was the highest surface roughness of all shot peened conditions, however fatigue fracture generated from the internal. On the other hand, Polished which was the lowest surface roughness in this study failed from the surface.

Furthermore, the surface hardness has no relation to prevent the surface fatigue crack initiation, because the surface hardness of shot peened specimens was almost equivalent to Polished. Therefore, compressive residual stress strongly affected to increase the fatigue strength due to prevention of surface crack initiation and propagation.

3. Polished and Polished + FSP, Polished + SP

Fatigue strength of Polished + FSP, Polished + SP were 500[MPa]. The fatigue strength of these increased 1.1 times against Polished, however there were not the difference of fatigue property between shot peened specimens for As-built surface and shot peened specimens for Polished surface. The fatigue life of these extended in comparison with Polished. These fatigue fracture origins changed from surface to internal, even though these were higher surface roughness than Polished which was surface fatigue fracture from surface defect or the matrix crack of microstructure. In this comparison, the surface hardness of shot peened specimens slightly decreased, furthermore surface roughness of these increased in comparison with Polished. Therefore, compressive residual stress due to shot peening strongly affected to increase the fatigue strength due to prevention of surface crack initiation and propagation. In addition, the reduction of surface defect due to shot peening, which is employed large shot media occurred, because there were not fatigue fracture from the surface defect in SP condition.

4.Relashitonship between Residual stress distribution and Internal fracture

Fig.9 shows relationship between Stress amplitude and Depth of internal fatigue fracture origin from the surface. The internal fatigue fracture origin was generated at location more than 70[μm] in FSP and Polished +FSP, at location more than 240[μm] in SP and Polished +SP, at location more than 400[μm] in HSP. These depths were deeper than crossing point of each shot peening conditions. Therefore, compressive residual stress by shot peening affects the internal fatigue crack initiation. Furthermore, it has possibility to achieve internal defect harmless due to additive manufacturing when the size of defect is not large enough to reach the threshold stress intensity factor including the residual stress.

Conclusions

(1) Additive manufactured specimens were induced compressive residual stress up to -1400[MPa] by shot peening. Furthermore, the surface roughness of As-built surface was decreased from 7.25[μm] to 3.04[μm] at maximum by shot peening.
(2) In comparison with As-built and Polished, Polished was higher fatigue strength than As-built due to the reduction of stress concentration to remove the surface irregularity.
(3) In comparison with As-built and SP, FSP, HSP, fatigue strength of shot peened specimens increased 2.5 times against As-built due to the prevention of the fatigue crack initiation and propagation by the inducing compressive residual stress and the reducing stress concentration to remove the surface irregularity.
(4) In comparison with Polished and Polished + FSP, Polished + SP, the fatigue strength of shot peened specimens increased 1.1 times against Polished due to the prevention of the fatigue crack propagation by the inducing compressive residual stress the reducing the surface defect size.
(5) Compressive residual stress distribution affects the depth of internal fatigue fracture origin. It has possibility to achieve internal defect harmless due to additive manufacturing when the size of defect is not large enough to reach the threshold stress intensity factor including the residual stress.

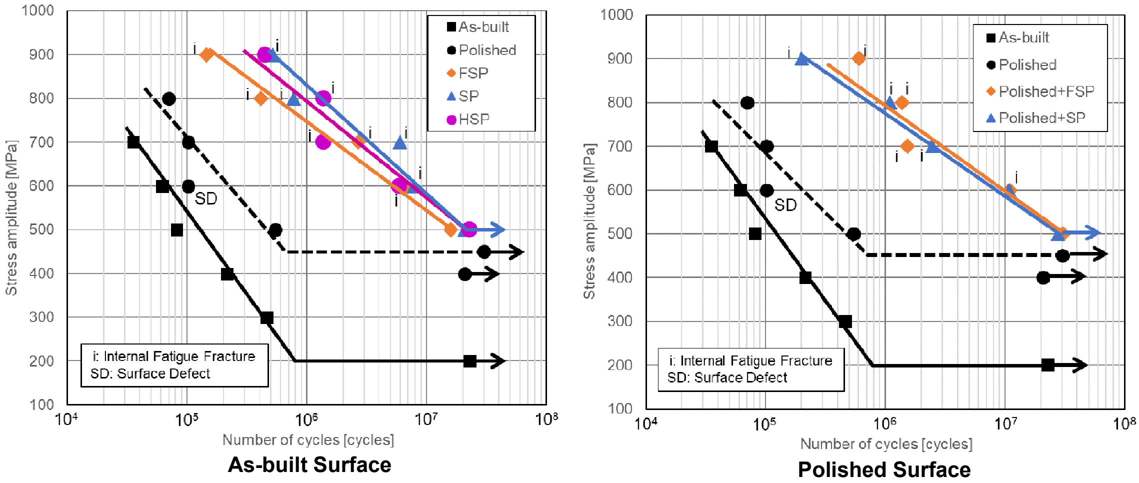


Fig.7 S-N curves.

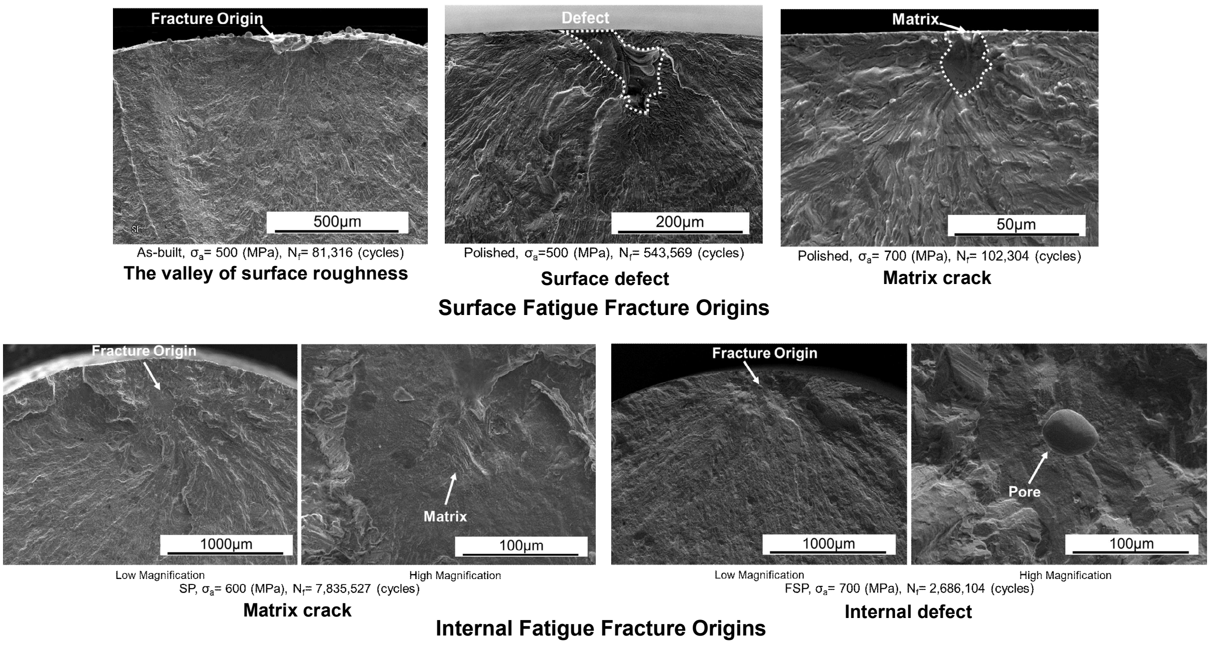


Fig.8 Fracture surface observation results.

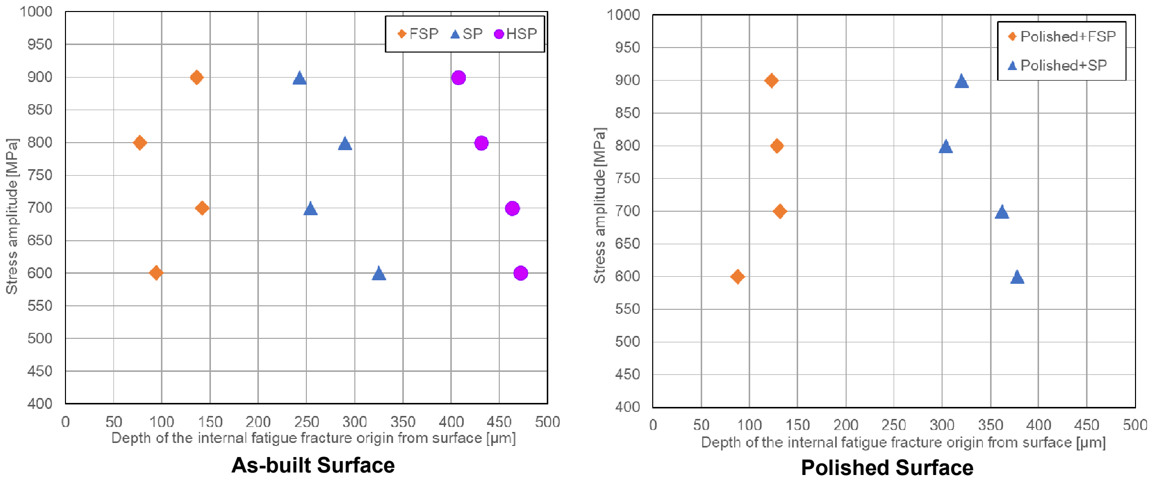


Fig.9. relationship between Stress amplitude and
Depth of internal fatigue fracture origin from the surface.

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