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Effect of Shot Peening on Improvement of Fatigue Strength for Metal Bellows

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1 Introduction

Generally metal bellows (it is hereafter described as a bellows) are known for a seal to defend a leak being elastic[1].Recently small size bore bellows are getting to expect to a seal of pump which was small and can use under the circumstances of high pressure.However, until now, it would be difficult to achieve the fatigue strength for required specifications in most cases. Meanwhile it was known for that shot peening had an effect on improving fatigue strength[2].It can be expected that it is difficult to obtain a large compressive residual stress on the inner surface of small bore size bellows by shot peening process.In order to obtain the effect of shot peening on the inner surface of bellows, a new shot peening processes by using a air peening machine and a reflective plate were developed.It was found that this method can apply the shots to the inner surface of bellows effectively, to improve the fatigue life of bellows, comparing with non-shot peening one.

It can be also noted that the measurements of residual stress by X-ray diffraction is not applicable to the material of bellow, SUS304 stainless steel. The measurement of residual stress is essential to determine shot peening conditions. Since the structure of SUS304 bellows is mixed with austenite and stress-induced martensite by cold forming the signal to noise ratio is too small to show the peak of X-ray diffraction. In order to solve these problems, the SUS631 stainless steel bellows was selected because it was a good workability and had a lot of martensite. The optimum shot peening conditions were decided by using residual stress of SUS631 bellows.

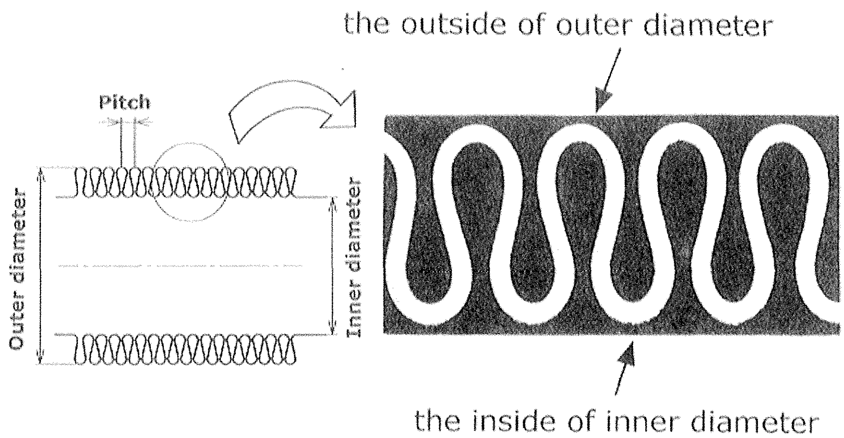

Figure 1: Cross section of bellows

2 Materials and Experimental Procedures

2.1 Materials

The specifications of U-shaped bellows are shown in Table 1. The radius of bent is about 0.5mm due to the small pitch as 1.5mm. The material is austenitic stainless steel SUS304. Fig.1 shows sectional shape cut in axis. Each section of bellows can be said as follows, outer diameter's area is the top, inner diameter' area is the bottom, outer diameter's direction is outside, inner diameter and centerline's direction is inside.

The manufacturing processes of bellows are to set the tube of which diameter is the same as inner diameter of bellows, to the mold divided into two. The interval of mold is contracted with giving internal pressure to the inside of the tube. It must be cautious that an explosion and buckling don't occur during the processes. This process of manufacturing can be well known as hydraulic bulge forming process. Fig. 2 shows the hardness distribution of bellows. The top is hard in comparison with bottom because of work hardening effect. Fig. 3 shows optical microstructure of bellows. It can be seen from the Fig. 3 that the top has a lot of martensite structure in comparison with the bottom.

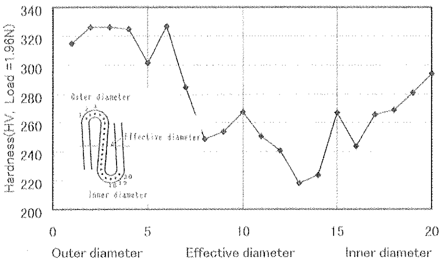

Figure 2: Hardness distribution of bellows

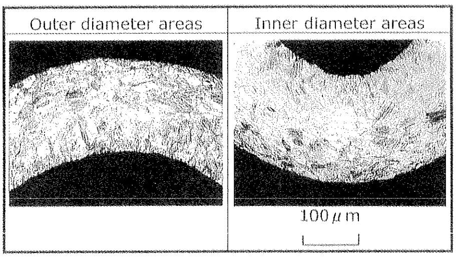

Figure 3: Optical microstructure of bellow

2.2 Shot Peening Processes

Bellows are usually used under compression. It occurs tension stress in outside of outer diameter and inside of inner diameter, where can be the origin of fatigue fracture in most cases. Therefore, the shot peening should be done in those area. The shot peening machine used here is suction peening machine in air peening machine. The reflection plate shown in Fig4 installed to the nozzle, in order to apply the shots effectively to the inside surface of bellows[3)]. Table 2 shows shot peening conditions. The pressure is from 0.1 MPa to 0.7 MPa. The nozzle diameter is 8 mm in the case of inner, 9 mm (normal size) in the case of outer. The shot materials used is glass beads (550 HV). The glass beads diameter used are from 38 μm to 215 μm. The shot peening processes were carried out under the condition that nozzle was fixed. The turning bellows can be moved from the top to the bottom four times within two minutes. After that, the direction of bellows is made up-down reverse, and it goes in the same action for two minutes. The total shot peening time is, therefore, four minutes. The outside of outer diameter was also shot peened for two minutes by using the standard nozzle without reflection plate.

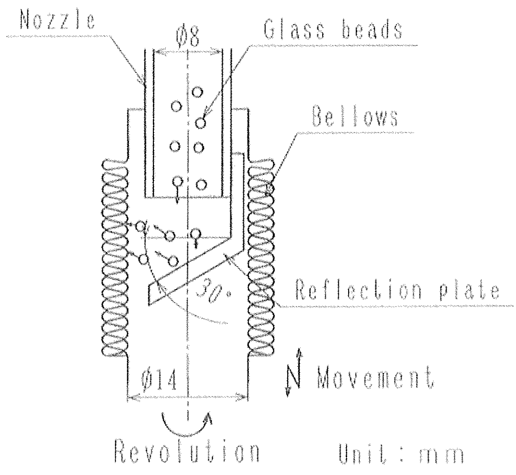

Figure 4: Reflection shot peening system

2.3 Residual Stress Measurement

It would be essential to measure residual stress, to decide shot peening conditions. Therefore, the residual stress measurement by X-ray stress measurement device, was made under the conditions shown in Table 3. The colimeter diameter is 0.5mm since bellows is small pitch. The measurements were made on the outside surface of outer diameter in the circumferential direction. The measurements were done at both $(311)_{\gamma}$ and $(211)_{\alpha}$ because SUS304 steel was mixed with austenite and martensite by cold forming. However, in both cases it was not found the peak value to decide the residual stress. In order to solve these problems, the SUS631 stainless steel bellows was chozen because it was a good workability and had a lot of martensite. The residual stress measurement under the conditions shown in Table 3, became possible by the SUS631 bellows. This means that the SUS631 bellows used for the purpose of deciding the optimum conditions of shot peening, and the SUS304 bellows applied by the optimum shot peening conditions were carried out in the fatigue tests.

2.4 Fatigue Tests

The fatigue test machine of the crank type where the displacement can be adjustable, was used. The frequency is 4 Hz. The fatigue test condition is pulsating stress.

3 Experimental Results

3.1 Relationship Between Residual Stress and Pressure

The relationship between residual stress and pressure in glass beads size 58 μm was studied. Fig. 5 shows the results. While the residual stress is –80 MPa in non-shot peened bellows, it can be seen from the Fig. 5 that the residual stress in shot peened bellows is over –700 MPa. The compressive residual stress tends to increase in proportion with increasing the pressure. It was measured –957 MPa in 0.7 MPa pressure.

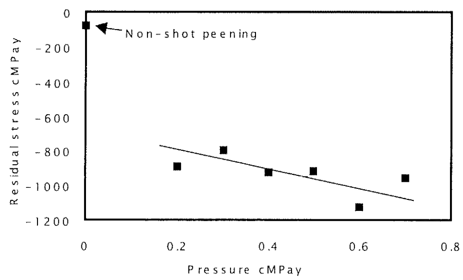

Figure 5: Relationship between residual stress and pressure, glass beads size, 58 μm

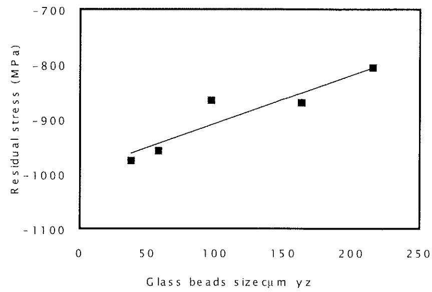

Figure 6: Relationship between residual stress and glass beads size, pressure 0.7 MPa

3.2 Relationship Between Residual Stress and Glass Beads Size

Fig. 6 shows the relationship between residual stresses and glass beads size in pressure 0.7 MPa. It can be seen from the Fig. 6 that the compressive residual stress tends to increase in proportion with the smaller glass beads size.

3.3 Relationship Among Pressure, Glass Beads Size and Fatigue Strength

Fig. 7 shows the relationship between the pressure, glass beads size and fatigue strength. It can be seen from the Fig. 7 that the fatigue strength tends to increase in proportion with increasing the pressure. This tendency is more remarkable in the case of a larger glass beads. The optimum conditions of shot peening can be said to be the pressure 0.7 MPa, glass beads size 97 μm in these results. Although it is a large compressive residual stress in glass beads size 38 μm, the fatigue life is low. This reason can be thought to be due to the depth of residual stress that can be discussed later.

3.4 S-N Diagram

Under the optimum conditions of shot peening experimentally decided (the pressure 0.7 MPa and glass beads size 97 μm), the S-N diagram of SUS304 bellows about shot peening and non-

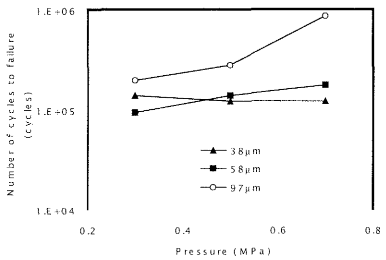

Figure 7: Relationship between number of cycles and pressure (Stress amplitude: 485 MPa)

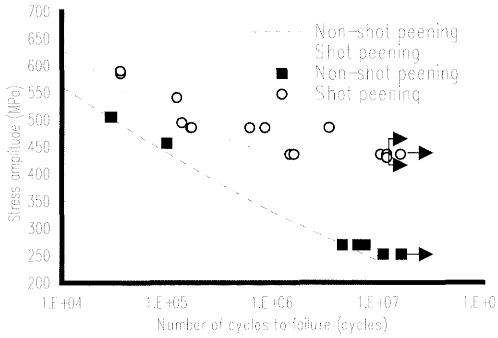

Figure 8: SUS304 S-N diagram Pressure 0.7 MPa, Glass beads size 97 μm

shot peening can be shown in Fig. 8. While fatigue limit of 10^7 cycles is 240 MPa in non-shot peened bellows that is 420 MPa in shot peened bellows. It can be realized that fatigue strength be improved about 75 % by shot peening in the optimum conditions.

4 Discussion

4.1 The Effect of Residual Stress

It has been normally discussed that the residual stress, work hardening and surface roughness can be the major factors on improvement of the fatigue strength by shot peening.

The fatigue test condition is pulsating stress in this time. In order to realize any change of residual stress before and after fatigue tests, fatigue tests and residual stress measurements by using SUS631 bellows, were carried out[4]. The fatigue test condition is the same as SUS304 bellows. The compressive residual stress before and after fatigue tests was measured. It was -957 MPa before fatigue tests and was –833 MPa after fatigue tests. This result can say that while the small amount of compressive residual stress can be released by fatigue tests, most can be remained after fatigue tests. Therefore, the reason why the fatigue strength was improved by shot peening is, obtaining a larger compressive residual stress – being remained the compressive residual stress during fatigue tests.

4.2 The Effect of Work Hardening

The surface hardness before and after fatigue tests were measured, in order to know whether there has the effect of work hardening for the reason why the fatigue strength was improved by shot peeping. The measuring point was the inside of inner diameter where can be the origin of fatigue fracture in this case. The measurements were carried out from the surface to inside at intervals of 5 μm, total 10 point by micro vickers hardness (load 49mN). Fig. 9 shows the results. Remarking the results of 0.7 MPa/97 μm condition in the Fig.9, which is the optimum shot peening condition, it can be seen that although the bellows before fatigue tests is work-hardened to show higher hardness, it becomes soft after fatigue tests. This can say that the bellows has already been hardened by cold forming and be hardened further by shot peening. Therefore, the work hardening can be one reason why the fatigue strength be improved by shot peening.

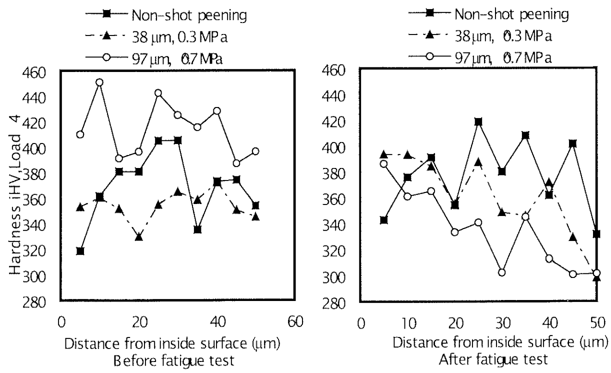

Figure 9: Comparison of hardness distributions

Figure 10: SEM observation of bellows surface before shot peening

4.3 Surface Roughness

The surface of bellows cold formed is usually getting rough by the hydraulic bulge forming processes. It can be seen from the Fig. 10 that there are micro cracks of about 2 μm round the grain boundary when observed with scanning electron microscope (SEM). In order to know the influence of the surface roughness to the fatigue strength, the surface roughness before fatigue tests was measured. The measuring point is the outside of outer diameter. Fig. 11 shows the relationship between the pressure, glass beads size and surface roughness. It can be seen that the surface roughness is improved by shot peening, comparing with non-shot peened bellows. It can be also realized that the surface roughness has no correlation with glass beads size, and tends to be improved in proportion with increasing pressure.

It can be considered that the surface of bellows becomes smooth by being struck repeatedly with the particles of glass bead. Therefore, the reduced depth of micro crack and improved surface roughness by shot peening can be one reason why the fatigue strength was improved.

4.4 The Effect of Residual Stress Depth

The residual stress mentioned above is the residual stress value on the surface of bellows. The distributions of residual stress against the thickness of bellows were obtained, as shown in Fig. 12. In the Fig. 12, the residual stress measurements were made at the outside of outer diameter before fatigue tests. It can be seen from the Fig. 12, that the residual stress distributions of which the fatigue strength is low, is shallow and those of which the fatigue strength is high, is deep. It can be concluded that the deeper and larger compressive residual stress can delay the development of micro-crack caused by the bulge forming processes[5].

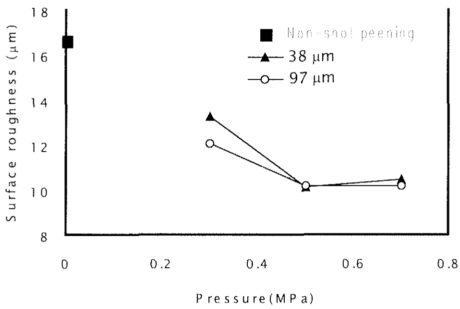

Figure 11: Relationship between surface roughness and pressure

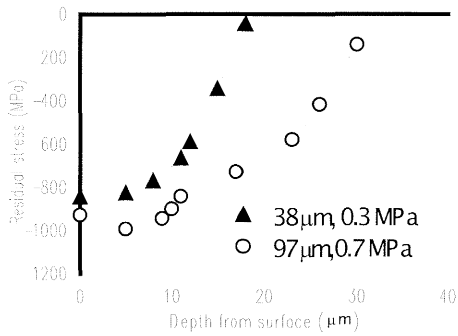

Figure 12: Distributions of residual stress of bellows before fatigue test

5 Conclusions

1. It becomes possible to make shot peening to the inside of small bore by developing the special nozzle which is set up a reflection plate to the inside of small bore size bellows.
2. It can be noted that the greater compressive residual stress (-957 MPa) on the inner surface of bellows can be obtained by shot peening. Since the residual stress is not released much during fatigue tests, the fatigue limit of 10^7 cycles shows 420 MPa in shot peened bellows, comparing with 240 MPa in non-shot peened bellows. It is realized that fatigue strength is improved about 75 % by shot peening.
3. The fatigue strength is improved in proportion with increasing the pressure as for the relationship between pressure, glass beads size and fatigue strength. Specifically, the tendency is recognized remarkably as much as a glass beads size is larger. It can be said that the pressure 0.7 MPa and glass beads size 97 μm be the optimum shot peening condition in these experimental result.
4. It can be thought that deeper and larger compressive residual stress, higher work-hardening(hardness), and smaller surface roughness can be the reason why the fatigue strength of shot peening condition of (3) is the highest.

6 References

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