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Warm shot peening is well-known as the shot peening process within a warm temperature range. However, the effect of warm shot peening on fatigue strength was not certain, and no substantial study had been made.

There are increasing demands for coil springs with higher fatigue strength, resistance to permanent set and lighter weight. While several new spring materials have been developed in recent years, the essence of those developments were to make the strength of the spring higher (the so-called "high-strength spring"). As for high-strength springs, the shot peening process becomes further essential to relieve the increased notch sensitivity due to higher strength. However, to shot peen high-strength springs, shot with higher hardness is required. This can decrease the life of both the shot and shot-peening equipment.

Warm shot peening under the tempering temperature may become one solution to those problems because the hardness of springs can be temporarily reduced only during the shot peening process. In this article, the following experimental results concerning the effect of warm shot peening are summarized:

1. Warm shot peening does increase the fatigue life of high-strength springs. It is especially effective when the spring hardness is greater than the shot hardness.
2. The appropriate temperature of warm shot peening is from 250° to 325°C.
3. The main reasons that warm shot peening is effective in improving fatigue life are:
    a. The increase of compressive residual stress distribution and higher coverage, which can be caused by more effective deformation under warm temperature.
    b. The increase of surface hardness by warm shot peening could be another reason for the improvement of fatigue life.

1. Introduction

Warm shot peening is a shot peening (SP) process conducted within a warm temperature range to increase material strength through the Cottrell effect and thus improve fatigue strength. As evidenced by a patent application filed by Gokyu in 1965 [1], this technique has been known for a relatively long time. However, follow-up tests conducted at that time did not demonstrate the apparent advantages of warm SP, and few study reports have been released on it since then, as far as we know.

On the other hand, with the increasing demand for the weight reduction of springs since the oil crisis, the need for higher fatigue strength and resistance to permanent set has also been increasing. To satisfy the demand, the development of new spring steels has become very prevalent, all leading to higher spring hardness.

The improvement of spring hardness is very effective in countering permanent sets and is said to also improve fatigue strength in general. However, since the notch sensitivity of the materials increases as well, the strictness of defect control must be raised. In addition, if the spring's hardness is higher than the hardness of the shot itself, the difficulty of shot peening will result in difficulty in ensuring fatigue strength. One way to make the SP process easier is by making the shot harder, but the harder shot has a shorter life, which is an essential shortcoming and does not appear economically advantageous.

If the SP process is conducted at a warm temperature that is lower than the tempering temperature, it should be possible to reduce the spring's resistance to deformation only during the process, thus enabling appropriate SP without sacrificing the hardness of the spring. This is how warm SP has newly come into focus. This paper covers the following issues:

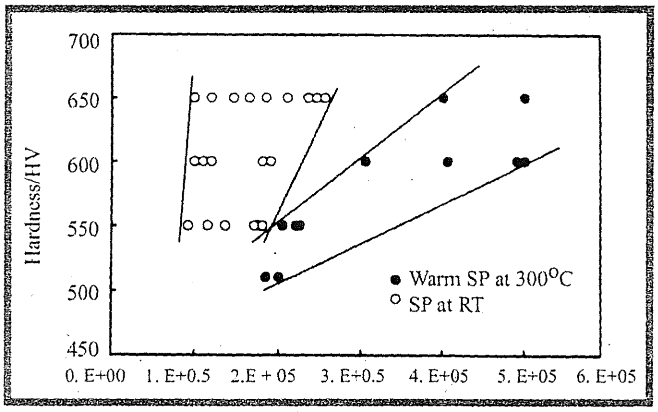

Figure 1: Relationship between spring hardness and fatigue life. Stress condition: Mean stress 637 Mpa, Stress Amplitude 539Mpa.

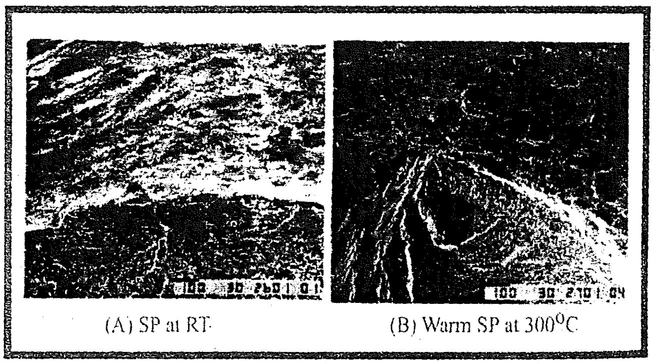
(A) SP at RT (B) Warm SP at 300°C

Figure 2: Comparison of fatigue-fractured surface and outside surface in HV 600 springs subjected to: (A) RT SP and (B) Warm SP at 300°C.

The Effect of Warm Shot Peening on the Fatigue Strength of Springs

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1. The relationship between spring hardness and fatigue life when the warm SP temperature is constant
2. The relationship between SP temperature and fatigue life when the spring hardness is constant.

It also discusses warm SP's effect on fatigue from the following angles:

1. The dependency of spring steel's resistance to warm deformation on the temperature
2. Residual stress distribution
3. Coverage
4. The strengthening of materials through warm working.

2. Experimental Conditions

2.1. Springs

The spring material used in our experiments is the JIS (Japanese Industrial Standard) SUP7 grade spring steel, with a chemical composition of 0.59% carbon, 0.85% manganese, 2.05% silicon, and 0.15% chromium. The specifications for the springs are as follows: 9.0 mm in wire diameter, 84.9 mm in mean coil diameter, number of active coils = 5.5, and spring constant = 19.1 N/mm. In the experiment for determining the relationship between spring hardness and fatigue life, quenching temperature was set to 920°C while tempering temperature was varied between 300°C and 450°C, to provide the spring hardnesses of HV 510, 550, 600, and 650. The hardnesses HV 600 and HV 650 exceed the shot hardnesses HV 520–570. In the experiment for determining the relationship between SP temperature and fatigue life, tempering was conducted at 350°C for 60 minutes of heating time to provide the fixed spring hardness of HV 600.

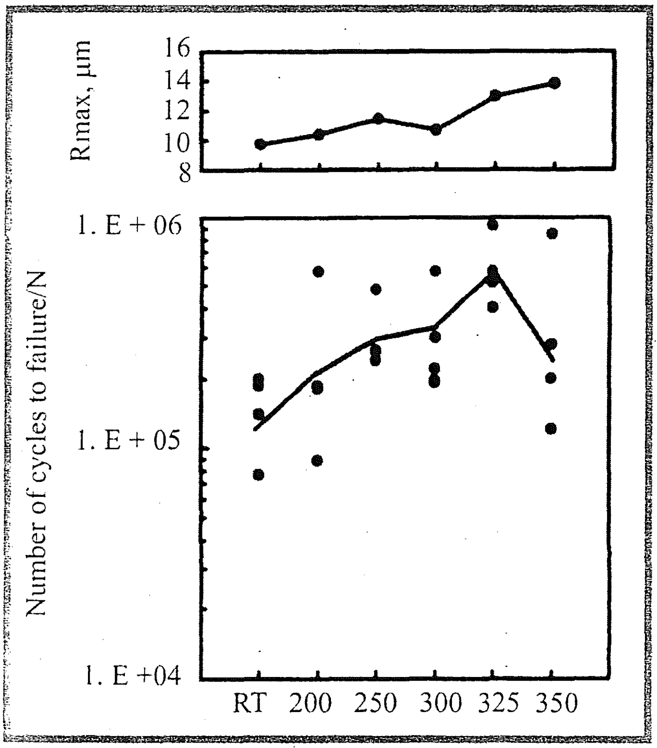

Figure 3: Relationship between SP temperature, surface roughness, and fatigue life. Stress condition: Mean Stress 637 MPa, Stress Amplitude 539 Mpa5. Hardness: HV 600.

2.2 Shot peening process

Each spring was allowed to stand at 200°C–400°C for 20 minutes to heat it to the approximate ambient temperature with a hot-air circulation furnace. Immediately after this, warm SP was conducted. For the purpose of comparison, SP was also conducted at room temperature ("room temperature SP" or "RT SP"), without heating the springs. SP conditions were as follows: 0.87 mm in shot diameter, the shot made of cut wire with the hardnesses of HV 520–570, shot projection speed = 66 m/s, and arc height = 0.42 mmA.

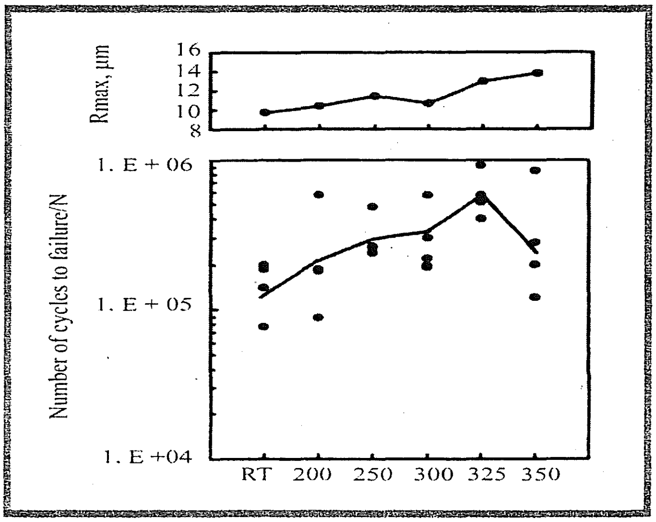

Figure 4: Relationship between SP temperature and 0.2% proof stress on SUP7 HV 600 springs.

3. Experimental Results and Discussion

3.1 Relationship between spring hardness and fatigue life

Figure 1 shows the relationship between spring hardness and fatigue life measured on the springs subjected to SP at room temperature and 300°C. The average life of the springs subjected to room temperature SP improves slightly as the hardness increases, but the minimum life remains unchanged. Also, the dispersion of fatigue life tends to become wider and notch sensitivity to increase. The springs subjected to warm SP, if the hardness is lower at HV 500 and HV 550, have slightly longer life than the springs subjected to room temperature SP, while the HV 600 and HV 650 springs, harder than the shot, are found to have remarkably longer life as the hardness increases. This indicates that the effect of warm SP is greater on harder springs. From this finding, one can presume that the main reason why a significant advantageous effect was not found in warm SP in the past was because of the relatively low spring hardness at that time.

Figure 2 shows the fatigue-fractured surface near the fatigue-crack origin point as well as the outside surface of the HV 600 springs subjected to RT SP and warm SP. The cracks started from the surface in both cases, but there were remarkable differences in the size of the indentations created by the shot and left on the springs' surfaces, as well as in the peening coverage. The spring subjected to RT SP had unclear indentations and insufficient coverage, while the spring subjected to warm SP had clear indentations and sufficient coverage. Thus, the difference in fatigue life between the harder springs subjected to RT SP and those subjected to warm SP appears to have come mostly from the insufficiency of shot-peening for the former and its sufficiency for the latter. The fact that harder springs subjected to warm SP demonstrate a greater effect implies that warm SP can be a very effective technique for improving both resistance to permanent set and fatigue strength.

3.2 Relationship between shot peening temperature and fatigue life

Figure 3 shows the relationship between SP temperature and fatigue life of the HV 600 springs, along with the maximum surface roughness of the springs after SP. The average fatigue life of the springs subjected to warm SP exceeds that of the springs subjected to RT SP within the entire SP temperature range of 200–350°C. The temperature range with the highest fatigue life is found between 250 and 325°C, and a temperature lower (200°C) or higher (350°C) than that tends to result in shorter life. The maximum surface roughness steadily increases from approximately 10 μm when subjected to RT SP, to 14 μm when subjected to SP at 350°C.

The increase in surface roughness appeared to have been caused by the shot's increased workability on the springs because the springs' resistance to deformation decreases as the SP temperature to which the springs are subjected becomes higher. Therefore, we conducted a tensile test on specimens (5 mm in diameter, 50 mm gage length) made of the SUP7 grade spring steel and heat-treated to the hardness of HV 600, at a relatively high strain rate of 10/min. at a designated temperature from room temperature to 400°C, to determine the temperature dependence of 0.2% proof stress. The test results, shown in Figure 4, indicate that the 0.2% proof stress at room temperature is approximately 1,920 Mpa, while those at 200°C and 350°C are 1,650 Mpa and 1,350 Mpa, respectively. These findings support the fact that thorough SP can be carried out on the springs harder than the shot by selecting a warm SP temperature.

However, since the spring hardness must not be lowered by heating, the temperature for warm SP must be lower than the tempering temperature.

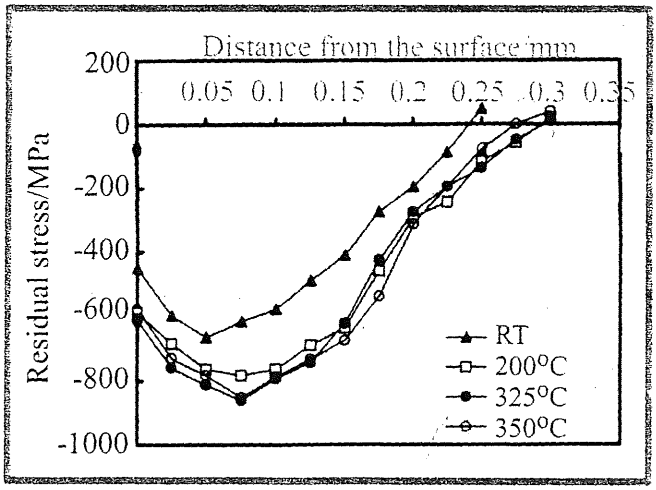

Figure 5: Relationship between SP temperature and residual stress distribution.

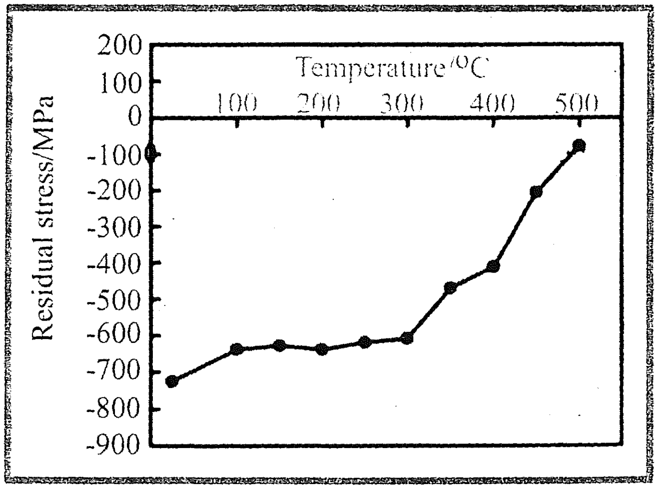

Figure 6: Relationship between SP temperature and the relief of residual stress

Figure 5 shows the residual stress distribution in the direction parallel to the wire axis on springs obtained through RT SP and warm SP at 200°C, 325°C and 350°C. It indicates that, when compared with those subjected to RT SP, the springs subjected to warm SP have higher surface residual stress and peak values. The peak value locations and crossing points are found to be deeper as well. When we made more detailed comparisons on the residual stress distribution from the surface to the points with peak values, which would affect fatigue life most significantly, the largest distribution was found in the case of 325°C, followed by the cases of 350°C and then 200°C, though the differences were small. In consideration of the fact that the residual stress distribution in the area between the surface and the points with peak values affects fatigue crack propagation life most significantly [5], it can be explained that the fatigue strength is highest when subjected to an SP temperature of 325°C. SP at 350°C resulted in the highest surface roughness. In warm SP, the application of residual stress through SP and the relief of the residual stress through the heating appears to progress at the same time.

Referring to Figure 6, as reported by Ō–no et al. [6], in their findings of the residual stress relieved by heating, the reduction in compressive residual stress is insignificant up to 300°C. However, the residual stress reduction becomes more aggressive once the temperature exceeds that. In our experiments, the compressive residual stress was highest at 325°C, contradicting Ō–no et al.'s findings, but when considering the possibility that the springs may be cooled rapidly by the impeller once the SP machine is switched ON, we can presume that the relief level of the residual stress is lower at 325°C than at 350°C. It seems that the relief of residual stress also explains the reduction of spring fatigue life through heating above 350°C .

3.3 Strengthening the Material through Warm Working

So far, we have discussed the improvement of fatigue life achieved with springs subjected to warm SP from the aspects of the coverage improved by warm temperatures, as well as surface roughness and residual stress distribution. We also examined warm working's effect on material strength. Figure 7 shows the examination conducted on SUP6 grade plates (thickness = 6 mm) with hardnesses of HV 380, 450, 500, and 580, subjected to SP at room temperature, 100°C, 200°C, 300°C, and 350°C. The hardness distribution near the surface was checked using the chord method [7]. When focusing on HV 380 and HV 580 plates, it can be determined that the hardness of the plates subjected to RT, 100°C, and 200°C SP has a slight increase near the surface, while the increment is significantly higher in the range from the surface to the point approximately 0.25 mm below the surface at 300°C and 350°C, which appears to correspond with the shot-peened depth. The increase level was about HV 500 (measured at the surface) on the plate with a lesser hardness of HV 380, versus HV 150 on the harder plate of HV 580, the latter of which is significantly higher. A similar trend was found on the plates with medium hardnesses of HV 450 and HV 500, where the increase level was medium. The increase in hardness appears to come from the Cottrell effect, or the effect of dynamic strain aging as free carbon and nitrogen stick to dislocation during the warm SP process [8]. A possible reason why the harder materials increase in hardness more significantly appears to be that harder materials, which require a lower tempering temperature, contain more C and N, which have been super-

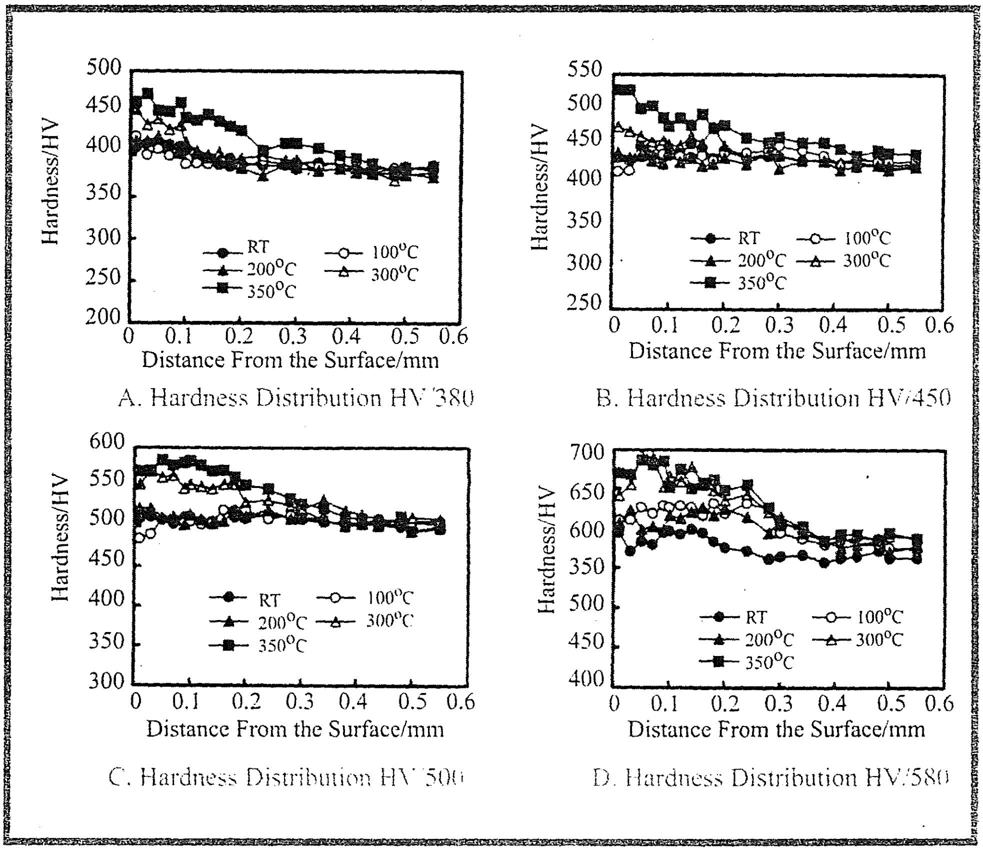

Figure 7: Hardness distribution around the surface, for SUP6 plates with the hardness of HV380, HV450, HV500 and HV580, shot peened at RT, 100°C, 200°C, 300°C and 350°C

saturated in a solid solution of ferrite, thus resulting in more aggressive strain aging than with softer materials.

The increase in the hardness through warm working also appears to contribute to the improved fatigue life of the springs subjected to warm SP. Our experiments show that this contribution is greater when subjected to warm SP at higher temperature, i.e. above 300°C.

4. Conclusion

The results through our study are as follows:

1. Warm SP's advantageous effect on fatigue life is larger for harder springs. It is especially effective when the spring hardness is over the shot hardness.
2. The appropriate temperature for warm SP is from 250 to 325°C.
3. Warm SP could become an SP technique that improves both resistance to permanent set and fatigue strength.
4. The main reasons why the warm SP is effective in improving fatigue life are the formation of the large, deep distribution of compressive residual stress on and near the surface of the spring, as well as higher peening coverage, which is caused by more effective deformation under warm temperatures. The increase of surface hardness by warm SP could be another reason for the improvement of fatigue life.

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