RESIDUAL STRESS AND FATIGUE STRENGTH OF SURFACE HARDENED COMPONENTS

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ABSTRACT

The strengthening effect due to surface hardening can be estimated by high dependency of the fatigue strength of hardened material on the residual stress that is equivalent to mean stress. However, the residual stress sometimes decays with plastic strain repeated in unhardened material under the hardened layer inducted by cyclic loading. In induction hardened gears, the hardening must be thick enough not to cause cyclic plastic strain under the hardened layer.
Similary, in welded joints, the strengthening is not always expected by peening. This is due to the plastic deformation or fatigue failure of the internal unhardened material.

KEYWORDS

Surface hardening, fatigue strength, residual stress, relaxation, cyclic plastic strain, induction hardening, wire peening.

INTRODUCTION

High fatigue strength can be obtained by hardening the surface of a machine component with various methods such as induction hardening and peening. As a result, these two methods will be the main focus of discussion in this paper. Generally, when surface hardening is carried out, the overall effect is a strengthening of the machine component. However, there are cases when the effect is very little or none at all. This mechanism of strengthening can be further explained by the high dependency of fatigue strength of hardened material on residual stress.
But this residual stress easily experiences decay with cyclic stress or high mean stress, which yields plastic strain in unhardened material under the hardened layer. Examples are introduced so as to present induction hardening on specimens and gears as well as wire peening on welded joints.

RESIDUAL STRESS AND FATIGUE STRENGTH

When metallic material is subjected to cyclic stress with mean stress σ_m, the fatigue limit σ'_w is expressed as follows;

$$\sigma'_w = \sigma_w - m\sigma_m \qquad (1)$$

Where σ_w is the fatigue limit of a completely reversed loading. The residual stress σ_r is known to be equivalent to mean stress σ_m in the criterion. That is,

$$\sigma'_w = \sigma_w - m\,(\sigma_m + \sigma_r) \qquad (2)$$

The constant m, which describes the dependency of fatigue strength on mean stress, increases from 0.2 to 0.6 with the hardness of material as is shown in Fig. 1. Thus, it is clear that the residual stress is more effective for harder material.

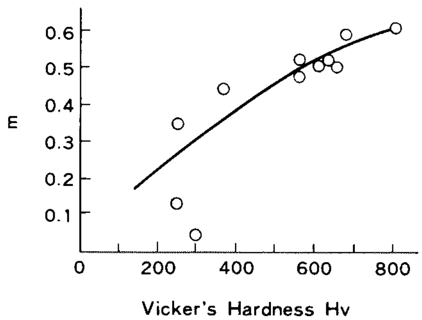


Fig. 1. Constant m describes the dependency of fatigue strength on mean stress

The strengthening effect of compressive residual stress on the surface was investigated by conducting fatigue tests using induction hardened notched specimens shown in Fig. 2 and those of hardened layers only.
The hardness distribution of a specimen is shown at the notch cross section in Fig. 3. In the specimens, a 10 mm hole was drilled out leaving a hardened surface layer (Hayama, 1975). The residual stress was measured by strain gauges bonded on the notch roots. The specimens were machined off mechanically and electrochemically to leave thin layers of bonding strain gauges, which indicates the residual strain released at the notch root after removing the surrounding

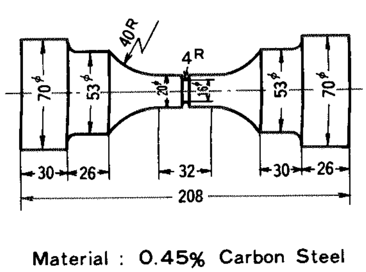


Fig. 2. Induction hardened notched specimen

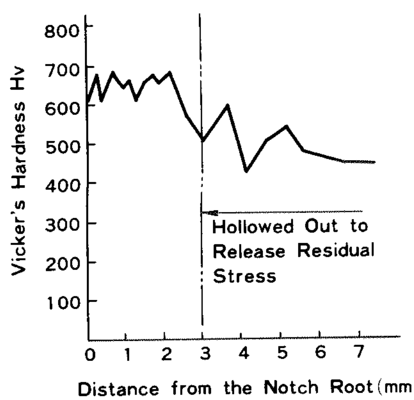


Fig. 3. Hardness distribution of the notch cross section

material.
The residual stress was measured initially as high enough, i.e., -830 MPa at the notch root of the induction hardened specimen and was decreased to -20 MPa at the notch root of the hardened layer only after being released. However, high compressive residual stress by induction hardening was observed to decay. Then it stabilized at the fatigue limit with cyclic loading. In other words, it measured -460 MPa in the completely reversed loading and -510 MPa in the repeated loading. In the edurance diagram, Fig. 4., the fatigue test results of induction hardened specimens coincide almost with those of the shifted results of induction hardened layers by stabilized compressive residual stress at -450∼-500 MPa to a negative direction along the mean stress axis. This fact verifies Eq. 2. In order to study the relaxation mechanism of compressive residual stress, the deformation behavior of specimens was investigated in detail using induction hardened unnotched specimens of 16 mm in diameter and those of surface layers with 12 mm drilling holes only. A small amount of plastic deformation was observed during the repeating load using a circuit that amplified the nonlinear strain signal by subtracting the linear part from the total strain signal which was then measured by the strain gauges on the surface of the specimen. When the amplitude is increased gradually in the completely reversed loading method, an induction hardened specimen shows hysteresis loops that shift toward the tensile side in the stress-nonlenear strain diagram in Fig. 5.

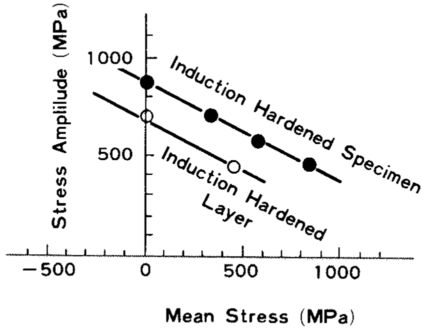


Fig. 4. Endurance diagram of induction hardened specimens

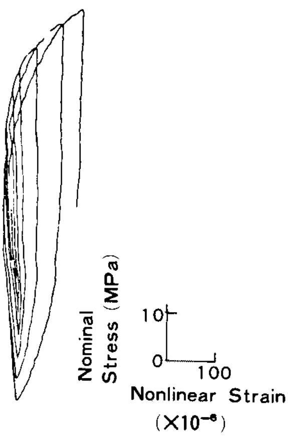


Fig. 5. Stress-nonlinear strain curve

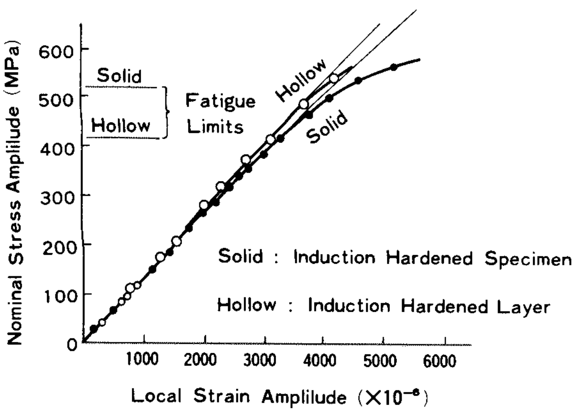


Fig. 6. Stress amplitude-strain amplitude diagram

On the other hand, the stress-nonlinear strain curve of the hardened layer is quite stable and did not show any shift due to plastic strain above 700 MPa. It is concluded in surface hardened components that compressive residual stress beneficial to high fatigue strength is capable of being relaxed during load repetition. This is due to plastic strain repeated in the unhardened material below the hardened layer. Fig. 6 shows the nominal stress amplitude-local strain amplitude diagram of induction hardened notched specimens shown in Fig. 2 in a completely reversed condition. In the induction hardened specimen, cyclic plastic strain is observed even below the fatigue limit but tends to increase rapidly above it. Conversely, in the surface layer, cyclic plastic strain is not observed even above the fatigue limit. It can also be confirmed from this fact that cyclic plastic strain in the unhardened core material induces the relaxation of compressive residual stress at the surface and leads to the elimination of its strengthening effect.

FATIGUE STRENGTH OF SURFACE HARDENED MACHINE COMPONENTS

In complicated machine components, it is sometimes not easy to control the surface hardening process to give sufficient hardened depth and stable compressive residual stress to the surface. Induction hardening is a rather difficult method to be applied to the roots of gear teeth.
Fig. 7 shows some examples of residual stress with a wide distribution.
These examples were measured at each tooth of induction hardened locomotive gear which were made from 0.43 % of carbon steel. The fatigue strength of the teeth in the repeated bending method also shows a wide scattering pattern compared with that of tempered teeth, when plotted against surface hardness together with the results of other authors (Seabrook and Dudley, 1964; Aida and Oda, 1968).
The hardening depth of teeth of the higher strength was thick enough to keep the compressive residual stress around -500 MPa after initial decay of 100~150 MPa during the cyclic loading. However, that of the lower strength is so thin that the residual stress can be easily decreased to zero. The fatigue strength of each case was proven to be estimated by Eq. 2 using the settled value of the residual stress.

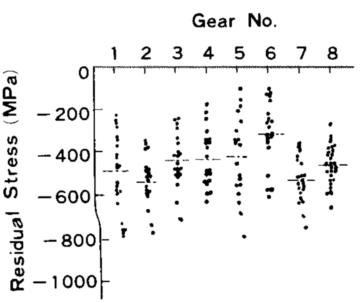


Fig. 7. Residual stress of gear teeth at the roots

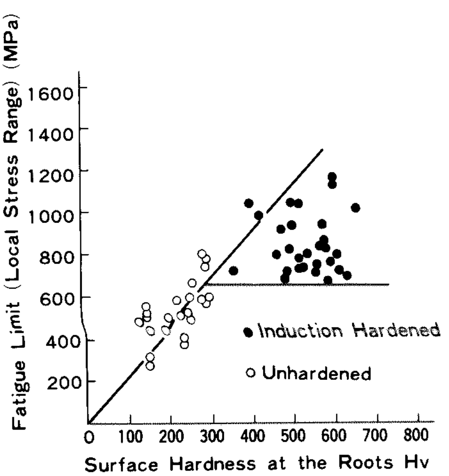
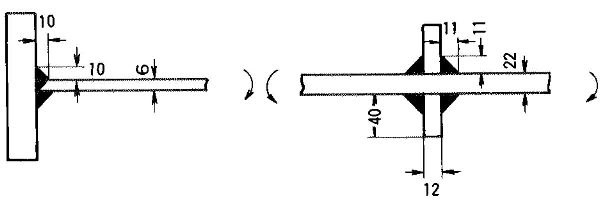


Fig. 8. Results of repeated bending fatigue test of gear teeth

The peening effect on fatigue strength was investigated using T-shaped and cruciformed welded joints shown in Fig. 9 made from three kinds of structural steels SS41, HT60 and HT80. The welded joints of each material were prepared as 1) welded 2) ground to bigger radius more than 2 mm, 3) peened with wires of 2mm in diameter and 4) ground and peened. Bending fatigue tests were made and the results are shown as one of S-N curves in Fig. 10 and as endurance diagrams in Fig. 11. From the comparison of the three endurance diagrams, it may be concluded that high tensile steel can raise its static strength but cannot always improve its fatigue strength when it is welded. It is also clear from Fig. 10.that grinding or peening cannot always be expected to improve the fatigue strength, when it is applied independently. This is probably due to undercuts which are irremovable by grinding or due to unpeened welded toes which are too sharp for wires. Therefore, peening must be done on the ground surface at the same time in order to get higher reliability on welded joints. The hardness distributions of these specimens are shown on the left side of Fig. 11 before and after the peening. Hardness increases from 140 to 210 in Vicker's hardness in the SS41 but only from 190 to 200 in the HT60. In the HT80, no change in hardness was observed. The residual stress σ_r at the surface had been measured at intervals during the fatigue test using a computer controlled X-ray stress measuring system. The residual stress was observed to be settled down to -300 MPa for the SS41, HT60 and down to -400 MPa for the HT80 after a short decay from the initial values at the fatigue limit in the repeated stress condition. However, it was easy to decay almost to zero, when maximum stress in the cyclic loading



a) SS41,HT60　　b) HT80

	Sy	SB	ϕ
SS41	277	471	53
HT60	559	671	59
HT80	742	808	70

SB : Tensile strength(MPa)
Sy : Yield stress(MPa),
ϕ : Reduction of area (%)

Fig. 9. Specimens and materials

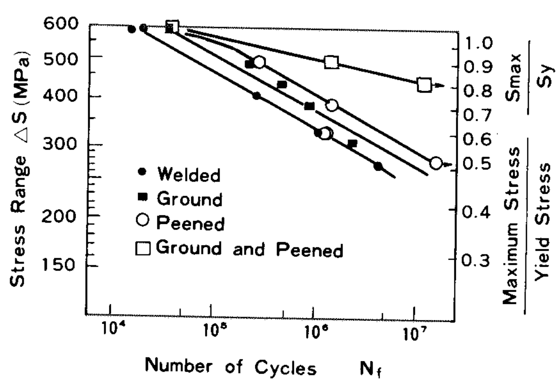


Fig. 10. S-N curves (HT60, Smin=5 MPa)

reached yield stress. Extending Eq.2 to the notched specimen in the repeated stress condition

$$S'_{wo} = \frac{\sigma'_{wo}}{K_f} = \frac{\sigma_{wo} + m\sigma_r}{K_f} \cong S_{wo} - \frac{m\sigma_r}{K_t} \qquad (3)$$

is obtained, where K_f is notch factor apporoximated by the theoretical stress concentration factor K_t and σ_{wo} is the fatigue limit of the material in the repeated stress condition. S_{wo} and S'_{wo} are fatigue limits in repeated bending of the welded joints of the ground specimens before and after peening. In Table 1, the fatigue limit of ground and peened welded joints was estimated from Eq. 3 for each material. This was based on the experimental fatigue limit S_{wo} of the ground welded joints and was compared with the experimental fatigue limits of

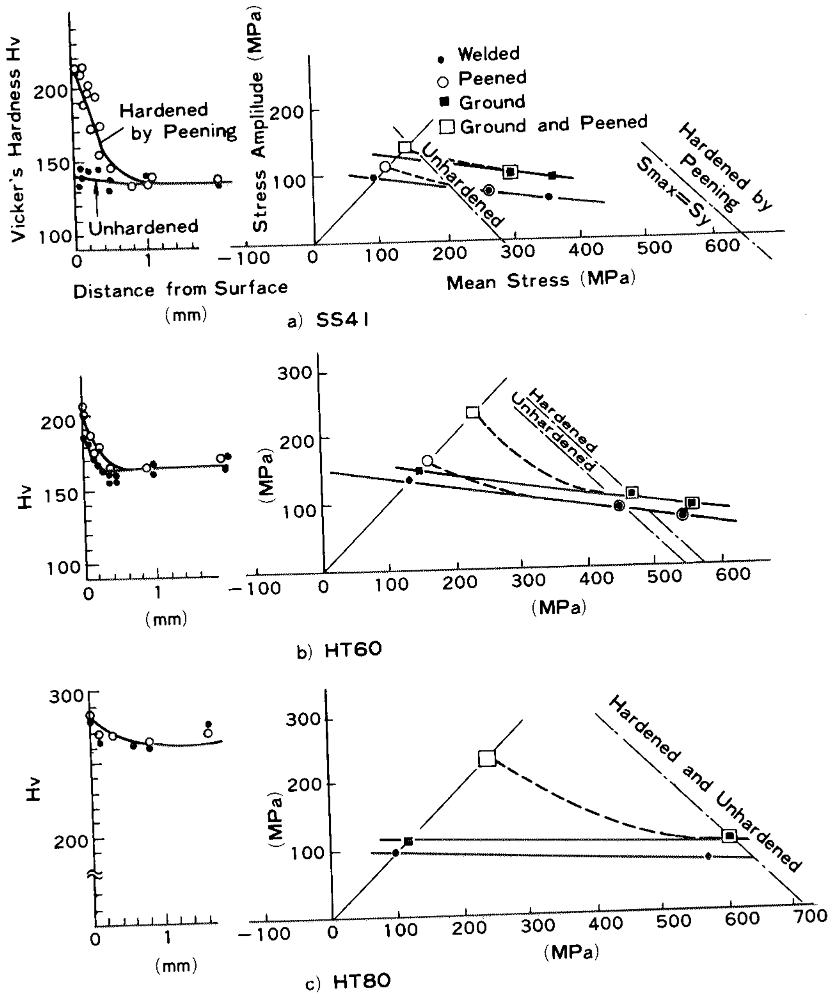


Fig. 11. Hardness distributions and endurance limit diagrams ($N=5 \times 10^6$)

ground and peened welded joints. In the case of SS41, the fatigue strength was improved experimentally only to 143 MPa from 136 MPa by peening, though the fatigue limit of the welded joints with a peened surface was estimated by Eq. 3 as too high, i.e., 262 MPa. This was due to an increase in hardness and stable compressive residual stress. It is supposed that the fatigue failure is initiated on the unhardened material on the inside of the specimen. As a result, the hardened layer can hardly improve the fatigue strength of the welded joints. Accordingly in case HT60, the fatigue strength was raised from 150 MPa to 240 MPa by peening. Additionally, the fatigue limit of the ground and peened welded joints was also estimated to be raised to 211 MPa. The compressive residual stress seems to have acted effectively in improving the fatigue strength of the welded joints. In case HT80, the improvement of fatigue strength is more notable in that it was raised from 117 MPa to 245 MPa as compared with that of the one estimated from 117 to 192. Thus, it is supposed that peening may contribute to the elimination of negative factors that deteriorate the fatigue properties of HT80 such as undercut and so on, in addition to beneficial compressive residual stress. However, futher investigation must be required on this point. For each material, it is clear in Fig. 11 that any peening effect cannot be expected after yielding occurs at the unhardened inside material and surface compressive residual stress is released. It must be remembered that high mean stress is sometimes experienced in a welded structure due to its own weight or its reaction stress at assembly. Therefore, peening shows little effect on the improvement of the fatigue strength.

TABLE 1 Experimental and Estimated Fatigue Limits

Materials		Surface Hardness	m	Specimen		Fatigue Limits(R=0)(MPa)	
				Kt	Residual Stress(MPa)	Experiment	Estimation
SS41	Before Peening	140	0.14	1.20	0	136	—
	After Peening	210	0.23		−300	143	262
HT60	Before Peening	190	0.20	1.25	0	150	—
	After Peening	200	0.22		−300	240	211
HT80	Before Peening	280	0.25	1.33	0	117	—
	After Peening	280	0.25		−400	245	192

CONCLUSION

The surface hardened components are treated as a structure composed of a hardened layer and a unhardened core. The strengthening mechanism is usually explained when considering the high hardness and compressive residual stress at the surface. However, the residual stress sometimes decays easily by cyclic stressing or high mean stress. In these experiments, the mechanisms were analysed as to induction hardening and wire peening.

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