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Effect of Modified Ausforming on Fatigue Strength of Low Alloy Steel*

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The effect of modified ausforming on fatigue properties of Ni-Cr and Ni-Cr-Mo steels has been studied. These steels were rolled to reduce the thickness to 30, 54 and 72 % in the temperature range between 880°C and 700°C, and cooled to form martensite. Their fatigue properties under alternate bending stress were then compared with those of the conventionally treated specimen after tempering at 300°C or 600°C for 1 hour.

Fatigue limit increased approximately linearly with the reduction up to 54 % and the increase of fatigue limit amounted to about 0.17 - 0.22 kg/mm² per 1 % reduction. The maximum improvement of fatigue limit was 39 % and fatigue life was prolonged by the process. Endurance ratio was then improved by modified ausforming.

Moreover, modified ausforming restrained the intergranular fracture of these steels after low temperature tempering. Metallographic observations revealed that the modified-ausformed specimen kept refined subgrains even after higher temperature tempering. It was found that the refinement of subgrains was an important factor in the improvement of fatigue strength of these steels.

1. Introduction

Modified ausforming is deemed one of practical thermomechanical treatments because of its simple process schedule. In the previous paper,¹⁾ one of the authors investigated the effect of modified ausforming on tensile and impact properties of Ni-Cr and Ni-Cr-Mo machine structural alloy steels. As a result, a good combination of yield strength and ductility was obtained by modified ausforming whereby the processed specimen showed a higher yield strength than conventionally heat-treated one tempered at same conditions without a significant impairment of ductility. Metallographic examination revealed that martensite grains were refined by the process, and subgrains were kept very fine even when they were formed by recovery or polygonization at high temperature tempering. The relation between yield strength or impact toughness and grain size as examined on the specimens tempered at high temperature proved that strengthening and toughening of these steels by modified ausforming depended on the grain refinement.

However, the improvement of fatigue strength as well as yield strength or impact toughness is an essential problem in

machine structural steels. In this report, underlying reasons for the improvement of fatigue strength will be discussed on the basis of metallographic and electrofractographic observations, and then it will be proved that modified ausforming is an effective method for improving the fatigue strength of steel.

2. Experimental procedure

2.1. Test steel

Ni-Cr and Ni-Cr-Mo machine structural alloy steels (SNC2 and SNCM8) were used in this experiment. The chemical compositions of these steels are shown in Table 1. Steel bars of 32mm dia. were hot-rolled into strips of required thickness. These strips were annealed at 850°C for an hour in nitrogen gas atmosphere. Then, they were cut to necessary dimensions and machined into the shape like flat fatigue specimen beforehand.

2.2. Modified ausforming and tempering

Modified ausforming was carried out under the following conditions. Specimens were fully austenitized at 880°C for 30 min, rolled at the temperature and oil-quenched immediately thereafter. The rolling mill used in this experiment was a two-high single-stand mill equipped with 150 dia. rolls and working at a rolling speed of 10 m/min. Four rolling passes were needed for accomplishing the maximum reduction in thickness, and the temperature of specimens after the last pass was estimated to be approximately 700°C.

Conventionally-quenched specimens which were quenched immediately from aus-

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temitizing temperature of 880°C, were then prepared as a control to make clear the effect of modified ausforming.

Both the modified-ausformed and the conventionally-quenched specimens were tempered at 300°C and 600°C for an hour, followed by water-cooling. The tempering temperature of 300°C is a temperature within the range of low temper brittleness, and the temperature of 600°C is one within the range of standard tempering temperature (560 - 680°C) for these steels.

2.3. Test procedure

The shape and the dimensions of the fatigue test specimen are shown in Fig.1. The specimens were ground by nearly 0.5 mm from both faces and then polished with water-proof sand paper. Both the sides of R were also finished by the same procedures. The edges of the faces and the sides at R

Table 1. Chemical compositions of the steel tested (wt.%).

Material	C	Si	Mn	P	S	Ni	Cr	Cu	Mo
SNC 2	0.27	0.22	0.52	0.028	0.015	2.84	0.85	0.13	—
SNCM 8	0.43	0.26	0.71	0.016	0.019	1.90	0.74	0.18	0.17

Fig.1. Fatigue test specimen.

positions were rounded to a radius of approximately 0.5 mm. These specimens were dealt with as smooth ones, having a stress concentration factor of about 1.04 for plane bending stress.²⁾

Fatigue testing was carried out by loading a completely reversed plane bending stress, using a torsion-bending tester (Shimazu TB-10) which has a repeating speed of 2000 cpm and a capacity of 10 kg.m. The stress levels near fatigue limit were adjusted with an increment of 1 kg/mm² in fatigue testing, and the maximum stress amplitude at which the test specimen did not fracture after 10⁷ cycles was adopted as the fatigue limit.

Small tension specimens with 1.5 mm thickness, 2 mm width and 10 mm gage length were machined from these fatigue specimens, and yield and tensile strengths were determined from them.

Microstructures were examined on the transverse section of the fatigue specimens. The etchant used for revealing the microstructures was 2 % nital modified with a small surface active-agent (sodium dodecylbenzenesulfonate). Replicas were prepared by means of a two-step method of plastic and carbon, and the observation on microstructures was carried out by an electron microscope (JEM-30B). The micro-morphologies of fatigue-fractured surface were characterized under a scanning electron microscope (MSM-4).

3. Experimental results and discussion

3.1. Fatigue strength

S - N diagrams for the specimens tempered at 300°C are shown in Figs.2 and 3. The symbol CHT in the figures means the

Fig.2. S - N diagrams (SNC2, 300°C x 1 hr. temper).

Fig.3. S - N diagrams (SNCM8, 300°C x 1 hr. temper).

conventionally quenched and tempered specimen (hereafter called conventionally heat-treated specimen). The fatigue limit of the conventionally heat-treated Ni-Cr steel was 23 kg/mm². The fatigue limits of the modified-ausformed steel were raised up to the levels from 25 to 32 kg/mm², and therefore, an improvement of 9 to 39 % in the fatigue limit was obtained over the conventionally heat-treated specimen. The fatigue limits of the modified-ausformed Ni-Cr-Mo steel ranged from 42 to 52 kg/mm² against 39 kg/mm² of the conventionally heat-treated one, and this result showed an improvement of about 8 to 33 % in the fatigue limit. As shown in these results, the fatigue strength can be improved by modified ausforming even at tempering within the temperature range, resulting in a low temper brittleness.

S - N diagrams for the specimens tempered at 600°C are shown in Figs.4 and 5. In this case, the fatigue limit of modified-ausformed Ni-Cr steel increased by 20 to 37 %, and the Ni-Cr-Mo steel was improved by 20 to 27 %. Since the improvements of yield strength by modified ausforming ranged from about 13 to 19 % for the Ni-Cr steel and from about 7 to 15 % for the Ni-Cr-Mo steel respectively, it may be safely said that the improvements of the fatigue limit are a little greater than those of the yield strength.

Fatigue lives for higher stress amplitudes than the fatigue limit can be also improved by modified ausforming. Let's illustrate the fatigue lives of Ni-Cr steel for a stress amplitude of 50 kg/mm² on these S - N diagrams. In the case of 300°C temper, the fatigue life of the conventionally heat-treated specimen was about 4.8×10^4 cycles, whereas the minimum life of the modified-ausformed steel was about 1.4×10^5 cycles in 30 % reduction, the maximum being 1.8×10^5 cycles in 72 % reduction, and therefore the improvement of the fatigue life over the conventionally heat-treated specimen amounted to from 92 to 257 %. In 600°C temper, the fatigue life of the conventionally heat-treated specimen was about 5.8×10^4 cycles, while that of the modified-ausformed steel rose from the minimum 1.1×10^5 cycles in the 30 % reduction to the maximum 1.3×10^5 cycles in 54 % reduction, and thereby the improvement of the fatigue life extended from 90 to 124 %.

Fig.6 shows the relation between the fatigue limit and the reduction in thickness in these test results. The fatigue limit increases with the reduction, reaching a maximum value at 54 % reduction and then falling down at 72 % reduction below the value at 54 % reduction. Although a linear relation is not preserved between the fatigue limit and the reduction all through the reduction, its linearity is almost ensured up to 54 % reduction in 600°C temper. Then, the increment of the fatigue limit per 1 % reduction within those rounds amounted to the values from 0.17 to 0.22 kg/mm².

Fig.4. S - N diagrams
(SNC2, 600°C × 1 hr. temper).

Fig.5. S - N diagrams
(SNCM8, 600°C × 1 hr. temper).

Fig.6. Relation between fatigue limit
and reduction in thickness.

3.2. Fatigue ratio

It is well known that fatigue limit generally increases with yield strength or ultimate tensile strength except at their extremely high levels.³⁾ However, fatigue ratio, i.e. the ratio of fatigue limit to ultimate tensile strength, is usually lowered by an increased tensile strength. That is, fatigue limit does not always rise in proportion to the increase of ultimate tensile strength. Fig.7 shows the variation of the fatigue ratio by modified ausforming. In both steels, the fatigue ratios increase with the reduction in thickness up to 54 % reduction, but tend to fall at 72 % reduction. The specimens tempered at 600°C generally have higher fatigue ratios than ones tempered at 300°C.

Now, Borik et al.⁴⁾ showed that an ausformed H-11 steel maintained high levels of fatigue ratios from 0.4 to 0.45 for tensile strengths between 200 to 260 kg/mm². One of the authors⁵⁾ also showed that the fatigue ratios of Mn-Cr type spring steel were improved by ausforming (modified ausforming) up to the levels of 0.32 to 0.42 against the tensile strength levels ranging from 120 to 160 kg/mm² against at the values of 0.25 to 0.31 for the conventionally heat-treated specimens. Fig.8 shows the relation between the fatigue ratio and the tensile strength in this experiment. In Ni-Cr steel tempered at 300°C, the conventionally treated steel had a tensile strength of 155 kg/mm² and a fatigue ratio of 0.15, whereas the modified-ausformed one showed fatigue ratios from 0.16 to 0.19 at the tensile strength levels ranging from 160 to 169 kg/mm². In 600°C temper, the conventionally heat-treated steel had a fatigue ratio of 0.33 for the tensile strength of 90 kg/mm², whereas the modified-ausformed one showed an improved fatigue ratio of 0.38 to 0.44 at the tensile strength levels ranging from 94 to 96 kg/mm². The SNCM8 steel always had a higher tensile strength and a little higher fatigue ratio than the SNC2 in the case of 300°C temper, but both steels showed nearly equal fatigue ratios in 600°C temper.

Thus, increasing the tensile strength by low temperature tempering does not necessarily result in an improvement of the fatigue ratio. These results suggest that the fatigue strength cannot be estimated only from the tensile strength, and that fatigue properties may be closely associated with the internal microstructures of steel.

3.3. Observation of fracture morphology

The microscopic morphologies of frac-

ture surfaces were examined in order to clarify how modified ausforming affects the

Fig.7. Variation of fatigue ratio with reduction in thickness.

Fig.8. Relation between fatigue ratio and tensile strength.

(a) SNC 2
l = 0.1, h = 1.3
σ_a = 50 kg/mm²
N_f = 4.8 × 10⁴

(b) SNCM 8
l = 0.3, h = 0.3
σ_a = 55 kg/mm²
N_f = 1.2 × 10⁵

(c) Observation position.

Fig.9. Fractographs of conventionally heat-treated specimen (300°C × 1 hr. temper).

fatigue fracture process. We will adduce some examples of fractographs helpful in grasping the qualitative relationship with the improvement of fatigue life, and examine their characteristic morphologies below.

Firstly, the observations on the specimens tempered at 300°C will be described. Fig.9 shows examples of the fractographs of conventionally heat-treated specimens. The observation position determined from a crack nucleation point is also illustrated in the figure. As shown in the figures, the greater part of the fracture surface is occupied with intergranular fracture patterns, and a few striation-like patterns are observed inside the intergranular fracture. It may be inferred from the grain size that this intergranular fracture originates from prior austenite boundaries. Similar intergranular fractures were predominant even at the positions where cracks fairly grew. Fig.10 shows examples of the fractographs of 54 % and 72 % reduced Ni-Cr specimens. As shown in these examples, no intergranular fracture can be observed in the modified-ausformed steel. These fracture surfaces are covered with striation-like patterns. These results show that modified ausforming has an effect⁶⁾ of restraining intergranular fractures.

Secondly, the observations on the fracture surface of the specimens tempered at 600°C will be described. Fig.11 shows examples of the fractographs of the conventionally heat-treated specimens. Fig.(a) shows the part where a few striations can be observed, and (b) shows another part consisting of tire track patterns. The similar fracture patterns were observed at other positions. Fig.12 shows examples of the fractographs of the 54 % modified-ausformed specimen. Fig.(a) shows the part consisting of regular striation patterns, while (b) shows another part consisting of striation-like patterns. Both the spacings between the striations and the striation-like patterns tended to become narrower in the modified-ausformed specimens. Then, some secondary cracks penetrating into the fracture surface appeared partially at the stages where cracks fairly grew. These secondary cracks usually occur in parallel with the rolling plane. Justusson et al.⁷⁾ attributed the im-

provement of fatigue life by modified ausforming to the occurrence of secondary cracks, which momentarily interrupted the propagation of main cracks.

As above, these fractographs of the modified-ausformed steel have shown some characteristic patterns closely related to the improvement of the fatigue life instead of shortening the life. However, since the whole fatigue life consists of crack nucleation and its propagation lives, the characteristic fracture patterns in the

Fig.10. Fractographs of modified-ausformed specimens (SNC 2, 300°C x 1 hr. temper).

Fig.11. Fractographs of conventionally heat-treated specimen (SNC 2, 600°C x 1 hr. temper).

Fig.12. Fractographs of modified-ausformed specimen (SNC 2, 54 % reduction, 600°C x 1 hr. temper).

fractographs will not give enough information on the improvement of fatigue life. The effect of modified ausforming on the whole fatigue life cannot be clarified until its effects on the fatigue crack nucleation and propagation processes have been elucidated. These will be problems to be solved in the future.

3.4. Microstructure and fatigue limit

As stated above, the intergranular fracture being restrained, the fatigue limit is improved by modified ausforming. Some underlying reasons for these results will be discussed here on the basis of observations of microstructures.

The microstructures of the specimens tempered at 300 °C will be shown firstly. Fig. 13 shows examples of the micrographs of the conventionally heat-treated specimens. Martensite grains show comparatively long platelets, while needle-shaped carbides tend to precipitate in a line along the martensite grain boundaries. A small number of carbides precipitate inside the martensite plates. Then, the prior austenite grain boundaries of the conventionally heat-treated specimens tended to be easily etched by 2 % nital added with the surface active-agent. Fig. 14 shows examples of the micrographs of 54 % reduced specimens. These microstructures consist of refined martensite grains. Needle-shaped carbides can be never seen even along the interfaces between martensite plates, most of carbides being spheroidized. The microstructures of the 72 % reduced specimens also showed similar characteristics to those of the 54 % deformed one. As a result, the martensite grains are refined and carbides spheroidally precipitated by modified ausforming. This precipitation tendency of carbides will be beneficial for restraining intergranular fractures.⁸⁾ Moreover, the prior austenite grain boundaries were hard to reveal by etching in the modified-ausformed steel. This fact may imply that the segregation of certain impurities along the prior austenite grain boundaries is lowered by this process. Thus, grain boundary fractures may be unlikely to occur in the modified-ausformed steel, since the boundaries are strengthened by the composite effects of the fine-grained martensite, the

refinement of carbide and the diminution of grain boundary impurities. Consequently, the fatigue limit and the fatigue life of

Fig.13. Microphotographs of conventionally heat-treated specimen (300°C×1 hr. temper).

Fig.14. Microphotographs of modified-ausformed specimen (54 % reduction, 300°C×1 hr. temper).

Fig.15. Comparison of microstructures between modified-ausformed specimen and conventionally heat-treated one (SNCM 8, 600°C×1 hr. temper).

the modified-ausformed steel are improved even in the case of tempering within the temperature range of low temper brittleness.

Examples of the microphotographs of the specimens tempered at 600°C are shown in Fig.15. Platelet-like or lenticular martensite grains survive and a retarded recovery in martensite is observed in the microstructures of the conventionally heat-treated steel even at such high temperature tempering. Although a few platelet-like martensites can be seen in the 30 % reduced specimen, most of them are polygonized. These grains seem to be subgrains as yet. Most carbides precipitate spheroidally along the martensite or the subgrain boundaries. These subgrains were more refined in 54 % reduced specimen, and the carbides which precipitated along their boundaries seemed to restrict the movement of subgrain boundaries. Needless to say, carbides precipitated even inside the subgrains. The microstructures of 72 % reduced specimen were about similar to those of 54 % deformed one. Thus, the modified-ausformed steel maintains refined grains up to the stage of higher temperature tempering. Not only a large number of dislocations may be introduced into the martensite grains by modified ausforming, but also cell structures may be formed by dynamic recovery or polygonization during deformation.⁹⁾ Carbides may preferentially precipitate along the cell walls when these martensites containing such substructures are tempered. Since such carbides may restrain the movement of the grain boundaries, finer grains seem to be kept even when clear subboundaries are formed by high temperature tempering.

Polygonized boundaries being clearly revealed in the specimens tempered at 600°C, the variations of the subgrain size by modified ausforming were determined. The results are shown in Fig.16. Mean intercept lengths $\bar{l}$ crossing grains being measured on microphotographs by lineal analysis, the grain size d was calculated from an equation of $d = 1.68 \bar{l}$.¹⁰⁾ As shown in the figure, although the grain sizes decrease abruptly at first with the increase of reduction, their further refinement ceases above 54 % reduction owing to their saturation phenomena.

Now, it has been shown in many investigations that yield strength σ_y and fatigue limit σ_w can be related to the grain size d in the following equations^{11) -13)}

$$\sigma_y = \sigma_{y0} + k_y \cdot d^{-1/2} \quad (1)$$

$$\sigma_w = \sigma_{w0} + k_w \cdot d^{-1/2} \quad (2)$$

where σ_{y0} , σ_{w0} are stresses and k_y , k_w are constants independent of the grain size respectively. Fig.17 shows the relation between yield strengths or fatigue limits and grain sizes in the present results. Although there is a certain amount of scatter in results, equations (1) and (2) hold for these data. The values of $\sigma_{y0} = 29.8 \text{ kg/mm}^2$, $\sigma_{w0} = 8.2 \text{ kg/mm}^2$, $k_y = 2.1 \text{ kg/mm}^2$, and $k_w =$

Fig.16. Relation between grain size and reduction in thickness.

Fig.17. Relation between yield strength or fatigue limit and grain size.

1.0 kg/mm^2 were obtained for the straight lines drawn in the figure. Inequalities; $k_y > k_w$ and $\sigma_{y0} > \sigma_{w0}$ are then confirmed¹⁴⁾ from these experimental results. Namely, the dependency of the yield strength on grain size is a little greater than that of the fatigue limit. However, needless to say, the grain refinement by modified ausforming is an important factor to the improvement of fatigue strength as shown in these results. Thus, it has been shown that the improvement of fatigue strength in the case of high temperature tempering depends largely on the grain refinement through modified ausforming. Although the effect of microstructures on fatigue ratio could not be investigated this time, the authors would like to examine this interesting problem in the future.

4. Conclusions

The effect of modified ausforming on fatigue properties of Ni-Cr and Ni-Cr-Mo machine structural alloy steels has been investigated with the following results.

(1). Fatigue limit can be improved by modified ausforming. The improvements of

fatigue limits ranged from 8 to 39 % in the case of 300°C × 1 hr. temper and from 20 to 37 % in the case of 600°C × 1 hr. temper.

(2). Although a saturation phenomenon in improvement of fatigue strength was seen in the range of high reduction, yet the increment of fatigue limit per 1 % reduction varied from about 0.17 to 0.22 kg/mm².

(3). Fatigue ratios were also improved by modified ausforming. In the case of 600°C × 1 hr. temper, the fatigue ratios of the modified-ausformed steel increased to the levels of 0.38 to 0.44 against 0.33 of the conventionally heat-treated one.

(4). Modified ausforming was an effective process for restraining intergranular fracture.

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