COLD-WORKING AND HEAT-CRACKING IN Ni-Cu-BASE MONEL ALLOY K-500①

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ABSTRACT Cold-working and its effect on heat cracking of Monel alloy K-500 were investigated. The results showed that cold-working hardening is limited for its strong effect on heat cracking, although Monel alloy K-500 has good cold workability. It was revealed that the main reasons of heat cracking, which initiates on the surface of the specimens and propagates intergranularly into the inner during aging, are the residual stress due to cold working, the heat stress due to aging and the surface brittleness occuring in early aging stage. It was proved that mechanical straightening is a beneficial and economical method to prevent Monel alloy K-500 from heat cracking.

Key words Monel alloy K-500 cold-working heat cracking mechanical straightening

1 INTRODUCTION

Monel alloys based on Ni-base and containing about 30% Cu are characterized by their excellent resistance to corrosion in the wide range of environments. The strength of Monel alloys can be significantly enhanced by introducing certain precipitation-hardening elements. The addition of 2.30% ~ 3.15% Al and 0.35% ~ 0.85% Ti to Ni-Cu base produces an age-hardening Monel alloy K-500, which has excellent corrosion resistance with room-temperature mechanical properties comparable to some Ni-Cr-base alloys and low alloy precipitation-hardening steels[1, 2]. Monel alloy K-500 has been extensively applied in the field of sour oil service (pump shafts and impellers) for more than sixty years. This alloy can be hardened by cold-working plus precipitation of coherent Ni_3(Al, Ti) particles which are $L1_2$ structure[3-7]. The cold-worked alloy, however, has a strong tendency to heat cracking during further aging. The purpose of this paper is to study the cold workability and its effect on heat-cracking in Monel alloy K-500.

2 EXPERIMENTAL PROCEDURE

The elemental composition (mass fraction, %) of the experimental alloy was as follows:

Ni 64.14, C 0.15, Mn 1.42, Si 0.17, Fe 0.12, Cu 30.85, Al 2.65 and Ti 0.50.

The alloy was vacuum refined in a chrome-magnesite crucible through high-frequency induction heating a charge of carbonyl nickel pellet and cathode copper. Alloying additions of pure aluminum and titanium were made and casted into a steel mounds at 1 700 ℃. Subsequently, they were forged at 1 150 ℃ to 55 mm square bars and rolled to *d* 19.20 mm rods at 1 150 ℃ and drawn with various percent reductions. Some rods were mechanically straightened using a hyperbolic straightener.

Specimens were machined from rolled and drawn rods and aged at 480 ~ 640 ℃ for 6 h. The tensile tests were carried out at a strain rate of $10^{-5}s^{-1}$ at room temperature and the impact

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tests used the standard specimens with V-notch. The microstructures of cracks were observed after etching in C_2H_5OH(50 ml) + HCl(75 ml) + $CuSO_4$(10 g). The measurments of the residual stress in each specimen were carried out on DWX-RB X-ray diffraction machine (with Fe target and {220} planes).

3 RESULTS

3.1 Cold workability

After hot rolled and quenched by water, the microstructure of Monel alloy K-500 was austenic monophase and had small amount of dispersed nonmetallic inclusions such as metal-sulfides and silicates, as shown in Fig. 1(a). The moderate density of annealing twins illustrated that dynamic recrystallization would occur during hot rolling. The Monel alloy had good cold workability (elongation ratio more than 40%).

The cold-working curve is showed in Fig. 2. It can be seen that the strength increases remarkably but the plasticity and ductility decrease with increase of deformation degree. For example, as the percent reduction increasing from 20% to 25%, the increment of yield strength is only 30 MPa, but the elongation ratio decreases from 21% to 14% and impact ductility decreases from 1.88 MJ/m^2 to 1.26 MJ/m^2. The best percent reduction is about 20%, and further strengthening will be obtained by the aid of aging. It can be seen in Fig. 1(b) that the grains of cold-drawn rods have been elongated along drawing orientation.

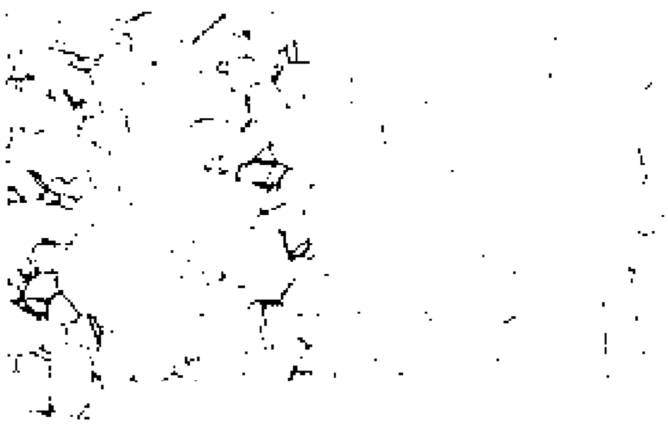

Fig. 1 Typical microstructures of Monel K-500 (20% reduction)

(a) —Solution-treated; (b) —Cold-drawn

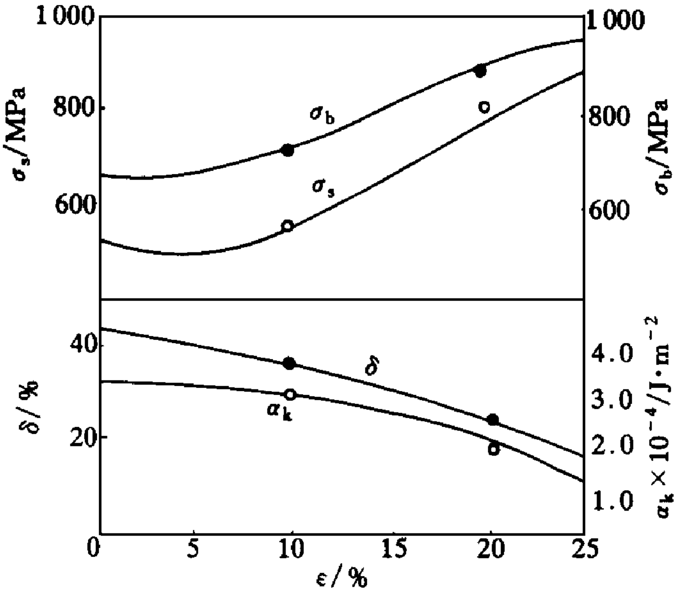

Fig. 2 Cold-working curves of Monel alloy K-500 at different reduction (ε)

3.2 Observation and analysis of heat cracks

The aging results of cold-worked specimen are listed in Table 1. It can be found that heat-cracking in the hot-rolled specimens didn't occur at all aging temperatures. For the smaller percent reduction (lower than 10%) specimens, heat-cracking didn't occur at low aging temperature but occurred at high aging temperature. For higher percent reduction (more than 20%) specimens, heat-cracking occurred at all aging temperatures, which suggested that the cold deformation and aging temperature strongly affected heat-cracking of Monel alloy K-500.

Table 1 Aging response of Monel alloy K-500 with various cold-drawn percent reductions at different temperatures for 6 h

Percent reduction	480 ℃	520 ℃	560 ℃	600 ℃	640 ℃
0	N	N	N	N	N
10%	N	N	N	C	C
20%	C	C	C	C	C
25%	C	C	C	C	C

* N —No cracking; C —Cracking

It was observed that the cracks initiated in early aging stage and propagated rapidly into the inner of specimen (as shown in Fig. 3). Micro-examination showed that the cracks brought into the branching, which have sawtooth morphology, and were intergranular in the process of propagation (see Fig. 4).

Fig. 3 A heat-crack propagating into the inner of the specimen aged at 520 ℃ for 6 h in Monel alloy K-500

3.3 Measurement of the residual stress

The residual stresses in the surface film of the specimen with several cold-working reductions are listed in Table 2. It is found that the circumferential stress was tensile but the axial and radial stresses were compressive. With the reduction increasing, the circumferential stress was enhanced remarkably.

The specimens with larger reduction were mechanically straightened in a hyperbolic straightener and aged similar to Table 1. It was found that no cracking occured, which suggested that the mechanical straightening had beneficial effect on the heat-cracking, which is confirmed by Table 3.

Table 2 Residual stresses in surface film of cold-drawn specimens of Monel alloy K-500 (MPa)

Percent reduction	Residual stress		
	Axial	Radial	Circumferential
0	- 109.17 ±41.85	- 305.76 ±36.65	113.68 ±64.29
10%	- 100.84 ±28.81	- 52.82 ±8.82	173.17 ±35.87
20%	- 84.08 ±21.95	- 396.02 ±22.54	352.11 ±18.23
25%	- 155.23 ±34.69	- 47.24 ±31.75	459.03 ±33.42

4 DISCUSSION

The solution-treated (hot rolled and quenched by water) Monel alloy K-500 exhibited good workability. With the percent reduction increasing, the strength was remarkably enhanced but the plasticity and the ductility would become bad. The cold-working could also bring in circumferentially residual tensile stress in the surface film of the drawn rods, which strongly affected the heat-cracking. So it is concluded that cold-working hardening is limited and the optimum percent reduction is about 20%.

During aging, the surface of the specimen was firstly heated and its natural size would be

Fig. 4 Microstructures of heat-cracks of Monel alloy K-500

(a) —Tow branches with sawtooth morphology;

(b) —Intergranular cracks

Table 3 Effect of mechanical straightening (MS) on residual stress in surface film of cold-drawn specimens of Monel alloy K-500(MPa)

Reduction	Residual stress		
	Axial	Radial	Circumferential
20% + MS	− 84.08 ±21.95	− 396,02 ±22.54	352.11 ±18.23
20% + MS	− 101.72 ±26.75	− 165.42 ±21.95	138.47 ±64.68
25%	− 155.23 ±34.69	− 47.24 ±31.75	459.03 ±33.42
25% + MS	− 65.07 ±12.54	− 19.70 ±43.22	249.31 ±27.44

enlarged. This enlarging, however, would be bound by the inner and produce "Bulgy Effect"[8], and the circumference tensile stress was formed in the surface film of the aging specimen. This tensile stress would increase with the increment of aging temperature. It was predicted that this tensile stress plus the residual stress resulted from cold working would produce a very higher circumferential tensile stress in the surface film of the specimen. Additionally, during the early aging stage, the surface of the specimen firstly became brittle due to precipitation. It was studied that the effect of the aging time on the impact ductility of Monel alloy K-500 solution treated at 600 ℃, and the results revealed that the impact ductility almost decreased linearly with the increment of aging time from 3.1 MJ/m^2(before aging) to 1.25 MJ/m^2(aged for 2 h)[9]. Consequently, the cracks would be initiated in the surface film under the higher circumferential tensile stress and the brittleness of the surface, the initiated cracks would play a role of notch to enhance the propagation rate and led to intergranular failure gradually.

In the course of mechanical straightening, the repeated deformation of drawn rods among the drum-rollers of the straightener would lead to remarkable descent of the circumferential tensile stress and adjustment of the axial and radial stresses, so mechanical straightening would reduce the sensitivity of Monel alloy K-500 to heat-cracking.

5 CONCLUSIONS

(1) The Monel alloy K-500 has good cold-workability, but the cold-working hardening is limited because the larger percent reduction (more than 20%) will strongly affect heat-cracking at subseqent aging.

(2) During the early aging stage, heat cracks initiate on the surface and propagate intergranularly into the inner.

(3) Monel alloy K-500 with larger cold-drawn reduction exhibit a strong tendency to heat-cracking during aging, which is mainly caused by the higher circumferential tensile stress from residual stress due to cold working, heat stress and the surface brittleness in the early stage of aging.

(4) The mechanical straightening for the cold-worked rods before ageing is an effective and economical method to avoid the heat-cracking in Monel alloy K-500.

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