

# STRENGTH AND DUCTILITY OF Ni-Cu-BASE

## ALLOY MONEL K-500<sup>①</sup>

Wang, Zhixing Xie, Shishu Liu, Shigui Yuan, Chao Yang, Hongcai

*Department of Materials Science and Engineering*

*Northeastern University, Shenyang 110006*

**ABSTRACT** Characteristics of work hardening and age hardening of Monel K-500 have been investigated. Results revealed that, under aging conditions (below 600 °C), work hardening is dominant; besides,  $\gamma'$  precipitation induced volume expansion can decrease the plasticity and ductility of the alloy, but optimization of the amount and the size of  $\gamma'$  phase can improve the plasticity and ductility of the alloy. Then, the optimum age-treating procedure was determined.

**key words:** monel work hardening age hardening ductility

### 1 INTRODUCTION

Monel K-500 is a structural material with high strength and corrosion resistance. It has been extensively applied in fields of metallurgical industry, petrochemical industry, ocean exploitation and so on. Especially, it can be used for components such as pump shafts, impellers working under extremely aggressive environments<sup>[1,2]</sup>.

This alloy is a kind of alloy of work hardening and Ni<sub>3</sub>(Al, Ti) phase precipitation hardening produced by adding Al and Ti to Ni-Cu solid solution. It has not only excellent corrosion resistance like Monel K-400 but also characteristics of high strength like precipitation hardening Ni-base alloy. However, the plasticity and ductility usually drops with increasing strengths. Cracking often occurs due to improper processing in the course of production, i. e. Monel K-500 has a tendency towards cracking when aged. Consequently, improvements of the plasticity and ductility of the alloy have been one of focal points for study. Although many studies have been carried out on processing, microstructures and properties of Monel K-500, studies on strengthening and ductility of the alloy which

is the main subject of this paper are still not enough.

In this paper, mechanisms of strengthening and the ductility of Monel K-500 have been studied thoroughly so as to provide a theoretical basis for practical production

### 2 EXPERIMENTAL METHODS

The experimental alloys, made by vacuum refining, forging and hot rolling, are cold drawn to rods with various degrees of cold work respectively. The composition of the alloy is given in Table 1.

**Table 1 The composition of Monel K-500 (wt.-%)**

Element	Ni	C	Mn	Si
Composition range	63/70	≤0.02	≤1.5	≤1.5
Analysed composition	bal.	0.25	1.42	0.17
Element	Fe	Cu	Al	Ti
Composition range	≤2.00	27/33	2.00/4.00	0.25/1.00
Analysed composition	0.12	30.85	2.65	0.50

① Received July 25, 1994; accepted in revised form Sept 5, 1994.

For investigating the effects of cold work on the strengths, the plasticity and the ductility of the alloy, 10%, 20%, and 25% cold drawn were carried on the hot-rolled alloy respectively, then tensile strengths and impact-ductilities were examined after straightening. The effects of aging on properties have also been investigated.

Both optical and electronic (TEM) microscopes have been used for observing the microstructure of the alloy. The metallographic etching agent is 50 mL C<sub>2</sub>H<sub>5</sub>OH + 75 mL HCl + 10g CuSO<sub>4</sub>. Measurements of the volume fraction and the size of  $\gamma'$  phase were carried out by the quantitative metallography technique, and the specimens for TEM were prepared by electropolishing technique; temperature: -30 C ~ -40 C; electrolyte: 33 Vol.-% HNO<sub>3</sub> + 67 Vol.-% CH<sub>3</sub>OH

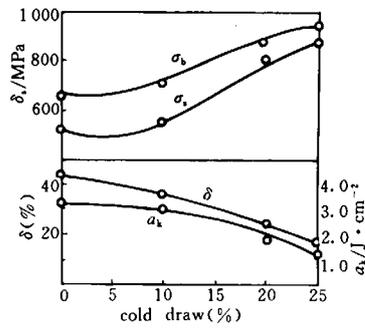
**3 EXPERIMENTAL RESULTS**

**3.1 Effects of Cold-Work on Mechanical Properties**

Monel K-500 has a microstructure of austenite monophase after hot rolled plus water quenched (Fig. 1). Grains will be elongated axial orientation after cold drawn. Fig. 2 is the cold-work curve which is a parabola-shaped one, and over 20% cold-work the hard-



**Fig. 1 Microstructures of the alloy hot rolled W.Q (section perpendicular to axial orientation)**



**Fig. 2 Effects of cold-work on properties of Monel K-500**

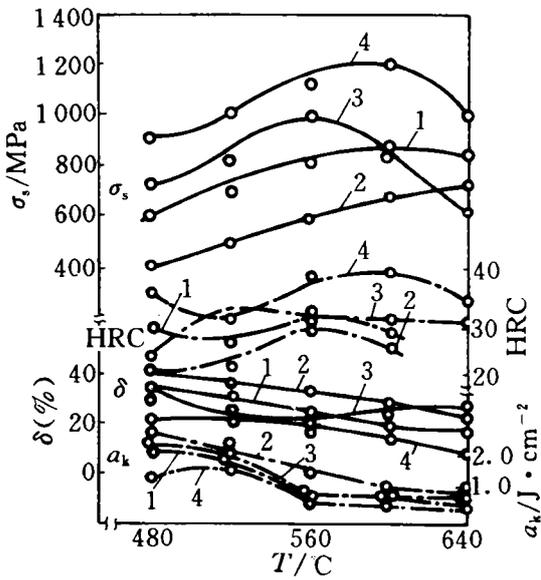
dening rate of the alloy decreases and the plasticity and ductility drop obviously.

**3.2 Effects of Aging on Mechanical Properties of the Alloys With Various Cold-Work**

For getting high strengths, the alloy usually can be used after aging. Therefore, mechanical properties of the alloys with various cold-work aged at various temperatures have been tested. The results shown in Fig. 3 reveal that, first, aged at the same temperature, the alloy with 10% cold-work has the lowest strengths and then the strengths rise with cold work; second, the alloys with various cold-work have their strengths peaks when aged in the range of 560~600 C, for instances, the alloy with 20% cold-work has its strength peak when aged at 560 C, so does 25% cold-worked one at 600 C. It is evident that cold-work has influences on the aged temperature for strength-peak.

**3.3 Laws of  $\gamma'$  phase precipitation**

The strengthening phase in Monel K-500 is  $\gamma'$  phase (Ni<sub>3</sub>Al), and the amount of  $\gamma'$  is about 10 wt.-%. Its lattice constant determined by X-ray testing is given in Table 2, (the mismatch between  $\gamma$  and  $\gamma'$ )  $\delta < 3\%$ .



**Fig. 3 Effects of aged temperature on properties of Monel K-500 at room temperature**

1—As solution; 2—10% cold work;  
3—20% cold work; 4—25% cold work

The quantitative measurement results of volume fraction and size of  $\gamma'$  phase are shown in Fig. 4. In the range of experimental temperature  $\gamma'$  volume fraction increase with temperature, the higher the temperature is, the sooner the  $\gamma'$  precipitation will be, and the sooner equilibrium state will be reached. The law of  $\gamma'$  coarsening in this alloy is the same as that of  $\gamma'$  phase in other Ni-base alloy, the relationship between the average diameter of  $\gamma'$  phase  $d$  and the time  $t$  fits the equation of  $d = kt^{1/3}$ [3].

**Table 2 Lattice constants of  $\gamma$  and  $\gamma'$**

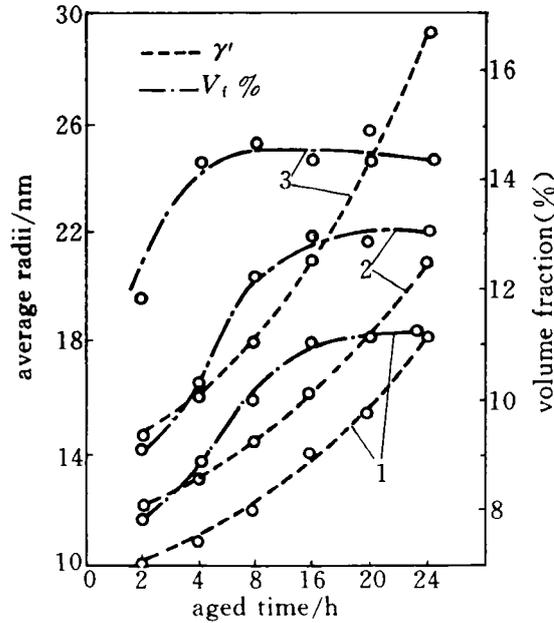
phase	lattice constant/nm
$\gamma$ matrix	0.3565
$\gamma'$ phase	0.3568

## 4 ANALYSIS AND DISCUSSION

### 4.1 Analysis of Hardening Factors

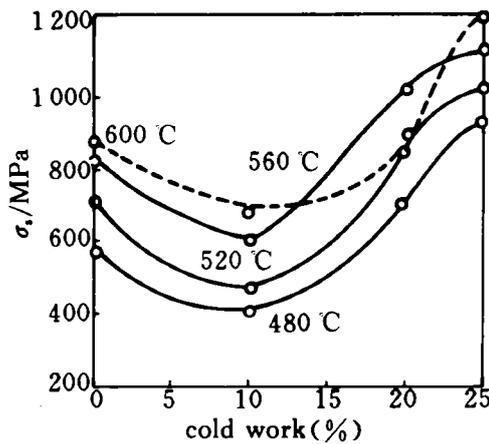
Monel K-500 is a kind of alloy with complex hardening factors. Its high strength results from combination of solution hardening, age hardening, work hardening and so on.

Cu, Si and Mn are solution hardeners which improve strengths and stabilities of  $\gamma$  solid solution. Supposing the yield strength of the alloy is  $\tau$ , it should mainly consists of three parts, i. e.  $\tau = \tau_1 + \tau_2 + \tau_3$ , where  $\tau_1$  is the strength of solid solution,  $\tau_2$  is the strength increased by cold-work,  $\tau_3$  is the strength-incr-



**Fig. 4 Relationships between  $\gamma'$  precipitation and aged time**

1 600 C; 2—650 C; 3—700 C



**Fig. 5 Effects of cold drawn on yield strength**

eased by  $\gamma'$  precipitation. As an approximate result under the condition of the same compositions of alloy, it can be obtained that  $\tau_1 \approx 520$  MPa by testing the alloy hot-rolled plus water quenched. Effects of cold-work on the yield strength under various aged-temperatures are shown in Fig. 5 (hot rolled W.Q + various cold-drawn + aging). It is found that the alloy has the lowest value of  $\sigma_y$  when treated by 10% cold-drawn + 480 ~ 600 C aging. Obviously it is due to small amount of cold work induced dislocation's breaking away from pinning, and work hardening being in the stage of easy slipping.

Variations in the yield strengths of alloys with various cold-work display the same regular pattern when aged in the range of 480 ~ 560 C. Over 10% cold work, the yield strength  $\tau_2$  increases about 40 MPa with one percent increase in cold-work, while the yield strength  $\tau_3$  increases only 2.5 ~ 4 MPa with 1 C increase in aged-temperature. Consequently, work hardening play a leading role in strengthening of the agehardenable alloy Monel K-500.

#### 4.2 Age Hardening

Aged in the range of 480 ~ 560 C, the yield strength increases constantly with cold work and temperature. The strength of precipitation hardening Ni-base alloy is related to the size and amount of  $\gamma'$  phase in the alloy.



Fig. 6  $\gamma'$  particles in Monel K-500  
(20% cold drawn, 600 C x 6 h aged)

From Fig. 4, it can be found that the amount of  $\gamma'$  phase has reached its maximum precipitation limit after 6 ~ 8 h aged in the range of 600 ~ 650 C, if the aged temperature increased, or the aged time still prolonged, the amount of  $\gamma'$  phase increases very slightly but the coarsening rate of  $\gamma'$  phase increases. Shown as Fig. 6,  $\gamma'$  particles in Monel K-500 are very small, even if they are coarsened.

Increments of  $\sigma_y$  of Monel K-500 under various cold work and aging are presented in Table 3. It can be seen that more cold work be done, the stronger strengthening effects will be gotten. This implies that in the age temperature range used in this experiment complete-recrystallization does not occur, the complete-recrystallization temperature should be around 600 C, and the optimum effect of aging should be obtained at 560 C. In fact, the temperature factor mainly exert its influences on strength by means of changing the size and the amount of  $\gamma'$  phase. Between the size and the amount, there is an optimum coordination by which maximum strengthening effects can be achieved.

Table 3 Increments in  $\sigma_y$  of  
Monel K-500 under various cold  
work and aged temperature

cold work (%)	aged temperature (C)			
	480	520	560	600
hot rolled	80	180	300	340
10	-120	-60	60	140
20	180	380	480	420
25	400	570	600	530

#### 4.3 Strength and Ductility

In this experiment the plasticity  $\delta$  and the impact ductility  $a_k$  decrease with increasing deformation degrees. Cold work results in grains fined which lead to an increase in strength but a decrease in plasticity value  $\delta$  due to shortened space for dislocations slipping. meanwhile, cold work can cause internal stress increased which lead to easy initiation and propagation of crack, therefore, it lower the value of  $a_k$ .  $\gamma'$  precipitation in aging can also lead to plasticity and ductility loss. This is due to dif-

ference between lattice constants of  $\gamma$  and  $\gamma'$  induced volume expansion which can produce internal stress. In the reference [4], effects of  $\gamma'$  precipitation induced volume expansion on ductility of Ni-base alloy have been discussed in detail. Assuming  $\gamma'$  phases are spheroidal particles with diameter  $R$ , its volume fraction is  $f$ , the thickness of expansion layer around particle is  $d$ , where  $d$  only related to lattice mismatch, and has nothing to do with the size of particles, the volume expansion around a  $\gamma'$  particle can be expressed as

$$\begin{aligned}\Delta V &= [\pi/6(R+d)^3] - [(\pi/6)R^3] \\ &= (\pi/2)R^2d\end{aligned}$$

The number of particles in per volume is  $N_v = [f/(\pi/6)R^3]$ , then the expansion volume in per volume is  $\Delta V' = \Delta V N_v = 3dfR^{-1}$ . Here,  $d$  is a constant because the lattice mismatch of Monel K-500 is a constant. Substituting values of  $f$  and  $R$  of the alloy under 20% cold-drawn and various temperatures and time aged into the above equation leads to calculated results of effects of aged time and temperature on the volume expansion shown as Table 4. Results indicate that aged in 600~650 °C, volume expansion decrease with increasing temperatures, the elongation and  $a_k$  value should increase correspondingly, which conform to the experimental results (see Fig. 3). The optimum aging procedure is 560 °C  $\times$  4~8 h.

**Fig. 4** Calculated values of  $\Delta V$

Time/h	Aged temperature/ °C	
	600	650
2	$0.23 \times 10^2 d$	$0.23 \times 10^{-2} d$
4	$0.26 \times 10^{-2} d$	$0.24 \times 10^{-2} d$
8	$0.30 \times 10^{-2} d$	$0.24 \times 10^{-2} d$

## 5 CONCLUSIONS

(1) High strength of Monel K-500 alloy is obtained by work hardening and age hardening. Work hardening increases with increasing deformation degrees (cold work should be over 10%). The optimum cold-drawn is 20%, the yield strength of the alloy after 20% cold-drawn can increase about 300 MPa.

(2) In the range of 480~640 °C, aged below 600 °C, work hardening play a leading role because no complete recrystallization occurs. Under conditions of the same cold work, aged at 560 °C has the optimum hardening effect.

(3) Aging produced plasticity and ductility loss mainly results from  $\gamma'$  precipitation induced volume expansion which is related to the fraction and size of  $\gamma'$  phase. Large value of volume expansion makes lower ductility.

## REFERENCE

- 1 Thompson, J G. Nickel and its Alloy, National Bureau of Standards Circular, Feb. 5, 1958, 592.
- 2 Monel Weiding Electrol, Alloy Dig, Feb 1985, 190.
- 3 Dey, G K; Mukhopadyay, P. Materials Science and Engineering, 1988, 84: 177~189.
- 4 Yong, Qilong; Ma, mingtu; Wu, baorong. Microalloyed Steel-Physical and Mechanical Metallurgy. Beijing: Metallurgy Machine Industrial Press, 1989. 109.