CALCULATION ON THE YIELD STRENGTH OF A PRECIPITATION STRENGTHENING Ni-BASE ALLOYS①

Li Bo, Wang Zhixing, Yang Hongcai
P. O. Box 326, Northeastern University, Shenyang 110006

ABSTRACT On the base of experimental research on a group of Ni-base alloys designed, the yield strength of the alloys was quantitatively calculated. The calculation was dependent on the composition of structure and parameters of microstructure. The result accorded with the measured values very well.
Key words Ni-base alloys precipitation strengthening calculation strength

1 INTRODUCTION

Presently, it still can't be achieved that composition and structure of alloys are designed according to the requirement on properties. The main problem is that there isn't a quantitative formula which can directly relate properties to composition and structure of alloys. Because properties of materials, especially strength, are affected by many factors such as chemical constituent and kinds of technological parameters; it is difficult for them to be analysed and calculated validly in theory.

The calculation on the yield strength of the microalloying steel of V, Nb and Ti has been reported[1], that of heat-resisting alloys was researched less. In this article, it was tried that the yield strength of a precipitation strengthening Ni-base alloy was calculated with the theory of physical metallurgy. A valuable result was expected.

2 TESTED ALLOYS AND THE STRUCTURE

Designing chemical constitution of the tested alloys was based on Rene'41 Alloys developed internationally. The content (in weight) of element Mo was reduced from 10% to 8%, and element W was added in percentage of 2% to 5%. Four alloys containing W were obtained. It was expected that fairly good properties emerged among the four W contents.

The alloys were all smelt in vacuum induction furnace, and then forged, rolled and heat treated in the same processes.

According to the chemical component, the alloys belong to the group of precipitation hardening ones and their organism is solid solution matrix and precipitation. The precipitation are primarily γ' phase and carbonide phase. Due to the small quantity the later makes less contribution, which can be neglected, to the conventional yield strength of Ni-base alloys. The parameters of the matrix and the microstructure were measured experimentally which included grain size d and the quantity f_w, particle radius r and the antiphase domain boundary energy γ_0 of the phase γ'. The measurig conformed to the standard procedure, and the method commonly used was adopted to those without standard one. The result is shown in Table 1.

3 CALCULATION METHOD

The same processes of forming and heat treament were employed to the series of alloys to eliminate the effect of process factors on

① Received Jan. 23, 1995

Table 1 The matrix composition and microstructure parameters of alloys

alloys	Conc. of solute element i C_i /%							d /μm	f_w /%	r /nm	γ_0 /J·m^{-2}
	Ni	Co	Cr	Mo	W	Al	Ti				
1	50.72	13.81	22.74	9.56	2.00	0.56	0.60	95.5(A_w=0.2) 23.0(A_t=0.8)	22.65	16.00	0.1827
2	49.46	14.00	23.19	9.46	2.77	0.44	0.56	1.91	23.18	17.45	0.1853
3	46.67	14.36	24.36	9.56	3.97	0.47	0.61	15.8	23.56	18.73	0.1872
4	44.47	13.63	23.22	9.27	5.06	0.43	0.65	18.8	23.14	19.55	0.1883

properties. Strength of alloys is chiefly caused by chemical component and microstructure. The factors such as the solution alloying elements, grain size and precipitation should be considered according to the theory of strengthening.

3.1 *Solution Strengthening of Matrix*

Because Ni can hold a large amount of alloying elements, Co, Fe, Cr, Mo, W, V, Ti, Al and so on, and new phase will not form, the solid solution constituted by these element and Ni should be concentrated. The following formula was applied to calculate the strength increment

$$\Delta\sigma_s = \sum_i K_i C_i^{2/3} \qquad (1)$$

where C_i expresses the concentration of the solute element i, K_i corresponds to the solution strengthening coefficient of the element. The theoretic value of K_i still hasn't given up till now, can be determined with the experimental data of Decker[2]. As a result of calculation, K_i (MPa/%) for various elements are: Co0.88, Cr7.86, Mo41.71, W43.96, Al32.75, Ti39.23

3.2 *Grain Boundary Strengthening*

The effect of grain size on strength has been given in Hall-Petch relation.

The authors believe that nonhomogeneous contribution of grain size commonly exists in Ni-base superalloys which are compound with all size of grians. The small grain or the fine crystal band can be consider as strengthening fibre. Therefore, $\Delta\tau_g$, the increment of the critical shear stress for grain boundary strengthening, can be expressed using the following formula.

$$\Delta\tau_g = M(A_w K_y d_w^{-1/2} + A_t K_y d_t^{-1/2}) \qquad (2)$$

where A_w and A_t indicate the percentage that the coarse and fine grain account for, respectively; d_w and d_t are the diameters of the coarse and fine grain, separately; $K_y = 7.34$ MPa · mm$^{-1/2}$. Taylor factor $M = 2.75$[3].

3.3 *Precipitation Strengthening*

Literatures provided lots of theoretic formulas. But when they were applied to the same alloy, it was found that the difference between the results was obvious and even up to orders of magnitude. Electron microscopic observation showed that there were two mechanisms in Ni-base alloy.

Bidislocation cutting mechanism and the strengthening relation given by Gieiter and Horn-bogen

$$\left.\begin{aligned}\Delta\tau_p &= \frac{\gamma_0}{2b}\left[\left(\frac{4\gamma_0 f_v r_s}{\pi T}\right)^{1/2} - f_v\right]\\ \Delta\sigma_p &= M\Delta\tau_p\\ &= \frac{M\gamma_0}{2b}\left[\left(\frac{4\gamma_0 f_v r_s}{\pi T}\right)^{1/2} - f_v\right]\end{aligned}\right\} \qquad (3)$$

where f_v, r_s and γ_0 represent the volume percentage, valid radius and antiphase domain boundary energy of the secondary phase particles, respectively.

The authors advanced a relation for the expanding dislocation rounding the particle[4]

$$\begin{aligned}\Delta\sigma_p &= M\Delta\tau_p\\ &= MGb/2(\pi/f_v)^{1/2} r_s\end{aligned} \qquad (4)$$

In the formulas (3) and (4), the shear modulus G takes value of 5.67×10^{10} Pa, Poisson vector b is 0.253 nm or 2.53×10^{-10} m, r_s =

$(2/3)^{1/2}r$ (r is the particle radius) and f_v %(in Volume) = 1.03 f_w%(in weight)[5].

3.4 *Yield Strength of the Alloys*

The yield strength of Ni-base, according to the principle of repeated addition, should be the sum of the strength σ_0 of the matrix Ni and kinds of the strengthening contribution above-mentioned

$$\sigma_y = \sigma_0 + \Delta\sigma_s + \Delta\sigma_g + \Delta\sigma_p \quad (5)$$

Leading the formula (1), (2) and (3) or (4) into formula (5), the following formulas are obtained.

$$\sigma_y = \sigma_0 + \sum_i K_i C_i^{2/3} + M(A_w K_y d_w^{-1/2} + A_t K_y d_t^{-1/2}) + \frac{M\gamma_0}{2b}\left[\left(\frac{4\gamma_0 f_v r_s}{\pi T}\right)^{1/2} - f_v\right] \quad (6)$$

or

$$\sigma_y = \sigma_0 + \sum_i K_i C_i^{2/3} + M(A_w K_y d_w^{-1/2} + A_t K_y d_t^{-1/2}) + \frac{MGb}{2(\pi/f_v)^{1/2} r_s} \quad (7)$$

4 RESULTS AND DISCUSSION

The yield strength of Ni in the matrix, σ_0, equals 196 MPa[6]. According with the cut mechanism for general Ni-base alloys σ_y of the alloys 1 and 2 can be calculated with the formula (6). Bidislocation rounding was observed in the alloys 3 and 4, so their σ_y should be counted with the formula (7). C_i, d, f_v, r and r_0 all take the value in Table 1, and T equals $Gb^2/2$ approximately.

Table 2 shows the division results and the total results from calculation and the results from measurement for the yield strength of the alloys. It can be seen that the difference between the calculated value and the measured value is all less than 5%, so a close fitting has been reached. Therefore, the way of calculating the individual terms of the strength and then adding them is feasible for getting the yield strength of the series of alloys by using the principle of physical metallurgy. The value of the individual terms represents the extent of contribution of every factor on the strength. The solution and secondary phase strengthening is bigger, and the effect of grain size is less.

Table 2 Comparision between the calculated value σ_y and the measured value $\sigma_{0.2}$

alloy	σ_0 /MPa	$\Delta\sigma_s$ /MPa	$\Delta\sigma_g$ /MPa	$\Delta\sigma_p$ /MPa	σ_y /MPa	$\sigma_{0.2}$ /MPa	δ /%
1	196.0	375.9	119.5	388.6	1080.0	1065	1.4
2	196.0	386.7	146.2	429.0	1157.9	1110	4.3
3	196.0	417.3	160.7	359.2	1133.2	1120	1.1
4	196.0	430.5	147.2	341.0	1114.7	1110	0.4

Apparently, varying structure parameters such as process parameters will influence the measured results and the calculated results simultaneously. The series of alloys changes primarily in content of W to get an appropriate W concentration expected. The calculated results indicates solution strengthening increases with addition of W, but so doesn't the total strength, which is highest while the alloys with 3%W.

REFERENCES

1 Gawne D T, Lewis G M H. Mater Sci Technol, 1985, 1(3): 183.

2 Sim C T, Hagel W C. The Superalloys. New York: Wiley, 1973: 83.

3 Lai Zuhan. Crystal Defect and Mechanical Properties of Metals (in Chinese). Beijing: Metallurgical Industry Press, 1988: 273.

4 Yang Hongcai, Wang Anchuan. J of University of Science and Technology Beijing (in Chinese), 1991, 13: 508.

5 Yang Hongcai. Acta Metallurgica Sinica, 1983, 19 (2): B90.

6 Ye Jun. American Ni-Base Superalloys (in Chinese). Beijing: Science Press, 1978: 55.

(Edited by Zhu Zhongguo)