Effect of Re-Nb on the strength and toughness of 3Cr2MoNiWV cast hot working die steel

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The effects of Re-Nb on the hardness, tensile strength, Charpy impact energy, and fracture toughness of 3Cr2MoNiWV cast hot working die steel have been investigated. It is shown that the tensile strengths at room temperature and at 600°C increased by 19% and 22% respectively while Charpy impact energy and fracture toughness increased to 109% and 70% respectively while the hardness remain unchanged by Re-Nb modification. The results showed that Re-Nb modification can refine the microstructure of the steel, increase the volume fraction of lath martensite and retained austenite in the tested steel and change the morphology of non-metallic inclusions from bar-like to a fine nodular type. The results are explained based on the modification of the microstructure due to Re–Nb modification.

1. Introduction

Die-casting die and forging die are made of hot working die steel through forging and machining. Large machining quantity and long cycle of machining lead to high manufacturing cost. Near net shape casting technology could manufacture almost final size of die, reduce mechanical cutting quantity, shorten the cycle of machining, and decrease the manufacturing cost of the die. It is well known that the properties of cast hot working die steel are lower than that of the forging die steel and brittle fracture often is occurred in its application [1, 2]. Therefore, it is important to improve the strength and toughness of cast hot-wrought die steel. Some new fashioned cast die steels, as 4Cr5MoVSiNi, 5CrNiMoNV, H13, Kh12M and Cr-Mo-Ni steel, are developed by improving toughness, raising hardness and wear resistance with alloying, modification and heat treatment. And they have been applied in Russian, Unite State, China and Japan [3–8].

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TABLE I. Chemical composition of the 3Cr2MoNiWV cast hot working die Steel

Elements	C	Si	Mn	Mo	Cr	Ni	W	V	Re	Nb	S, P
Before modification	0.32	0.43	0.39	1.21	2.23	1.24	0.62	0.41	–	–	≤0.03
After modification	0.32	0.43	0.39	1.21	2.23	1.24	0.62	0.41	0.06	0.096	

In this paper, a rare earth and niobium modifier was used to raise the strength and toughness of 3Cr2MoNiWV cast hot-work die steel. The strengthening mechanism was investigated with transmission electron microscopy (TEM), scanning electron microscopy (SEM) and X-ray diffraction (XRD).

2. Experimental procedure

The alloy is melted in 1000 Hz middle-frequency induction furnace of 250 Kg. The chemical composition of the 3Cr2MoNiWV cast hot-work die steel is given in Table I. Before the melt is tapped at 1620–1640°C, 0.1% Nb (with 66% Nb-iron alloy) is added in the furnace. And 0.15%Re modifier (with Si-Fe alloy containing 27% Re) is put on the bottom of a ladle and the liquid steel dashes down into the ladle to modify. At a temperature of 1540–1560°C the alloy melts were poured into sand moulds to be solidified as keel blocks. All the specimens were cut from the keel blocks. The heat treatments applied include austenizing at 1050°C for 1.5 h, oil quenching and the double temperature at 620°C. Fig. 1 shows the specimens for the impact, tensile and fracture toughness tests.

The tensile properties of the steel are measured on a AG-1 250KN tensile tester. The impact and hardness tests are carried out on a JB147/294A type impact tester and HR150D hardness tester respectively. And the

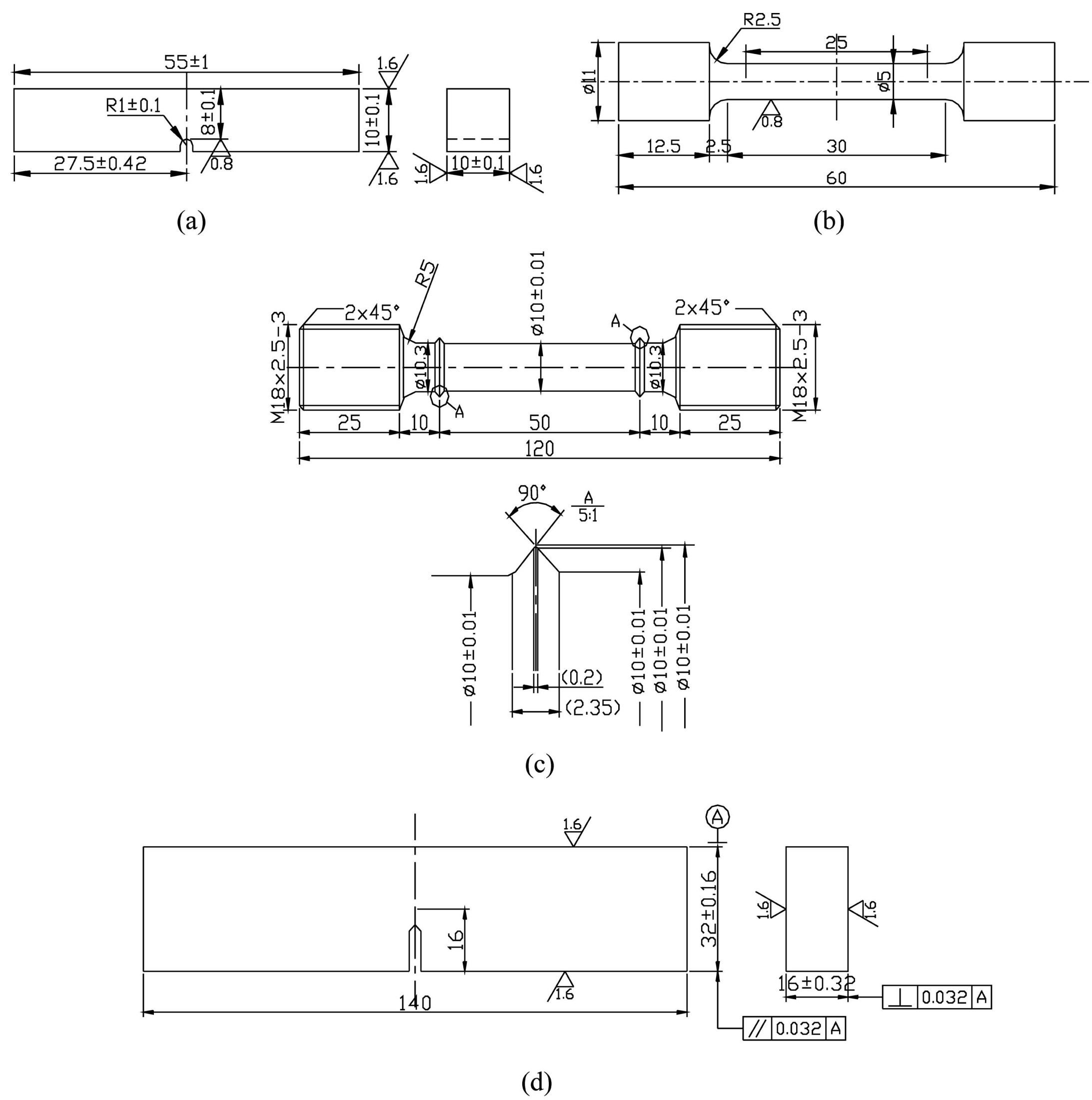

Figure 1 Specimens of (a) Charpy, (b) tensile at room temperature, (c) tensile at 600°C, (d) fracture toughness.

TABLE II. Tensile properties and impact toughness of the tested steels

Re-Nb modifier	Hardness (HRC)	Impact toughness (J/cm^2)	Tensile strength (MPa) (at room temperature)	(at 600°C)	Fracture toughness K_{IC} ($MPa\ m^{1/2}$)
Before adding	43.0	25.0	1234.0	815.0	34.1
After adding	42.0	52.2	1468.0	994.4	58.0

precracking procedure and fracture toughness test of the samples are carried out on MTS810 type material fatigue tester according to ASTM E 1304-97 (Chinese standard GB4161-84).

The microstructures and the fracture surfaces of the modified and non-modified steels are analyzed with H-800 transmission electron microscopy (TEM), JSM-56E scanning electron microscopy (SEM) and Ricon-2 X-ray diffraction (XRD). The thin foil for TEM are cut to 0.3 mm thickness foil from the above heat-treated steel, then normally ground to about 50 μm, and electropolished in perchloric acid-methanol solution.

3. Results and discussion

3.1. Strength and toughness

The tensile properties and impact toughness of both modified and non-modified 3Cr2MoNiWV cast hot-work die steel are shown in Table II. It is known from Table II that with little change in hardness, the impact toughness at room-temperature had been raised from 25.0 Jcm^{-2} of non-modified steel to 52.2 Jcm^{-2}, and the tensile strengths at room-temperature and elevated temperature (600°C) have been improved from 1234.0 MPa to 1468.0 MPa and 815.0 MPa to 994.4 MPa respectively. The Re-Nb modifier is effective in increasing the mechanical properties of the steel.

Fracture toughness indicates the resistance of the material to crack propagation. In Table II, there is a comparison of the fracture toughness between the modified and non-modified steels. The Fracture toughnesses of the steel were calculated to conform to the following.

$$P_{max}/P_Q < 1.1 \quad (1)$$

$$a, B, (W - a) \geq 2.5 \left(\frac{K_Q}{\sigma_s}\right)^2 \quad (2)$$

where P_{max} is maximal load applied, P_Q is determined according to $P - V$ curve of the specimen, B and W are the thickness and width of the sample respectively, a is precracking length, i.e. $\frac{a}{W} = 0.503$, σ_s is yield strength, K_Q is given by

$$K_Q = \frac{P_Q S}{B W^{3/2}} f\left(\frac{a}{W}\right) \quad (3)$$

where S is the span of 3-ponit bend test specimen, i.e. $\frac{S}{W} = 4$,

$$f\left(\frac{a}{W}\right) = 2.9\left(\frac{a}{W}\right)^{1/2} - 4.6\left(\frac{a}{W}\right)^{3/2} + 21.8\left(\frac{a}{W}\right)^{5/2} - 37.6\left(\frac{a}{W}\right)^{7/2} + 38.7\left(\frac{a}{W}\right)^{9/2}$$

It is also known from Table II that the fracture toughness of modified steel is raised to 58.0 MPa $m^{1/2}$ from 34.1 MPa $m^{1/2}$ without modification. It is about 70.4% more than that of the un-modified steel.

3.2. Transformation of martensite

The martensite microstructures of the tested steel are given in Figs 2 and 3. As seen, the microstructure of 3Cr2MoNiWV cast hot-work die steel includes lath and plate martensites. The proportion of the plate martensite in the steel is decreased at Re-Nb modification, and the volume fraction of lath martensite is increased to about

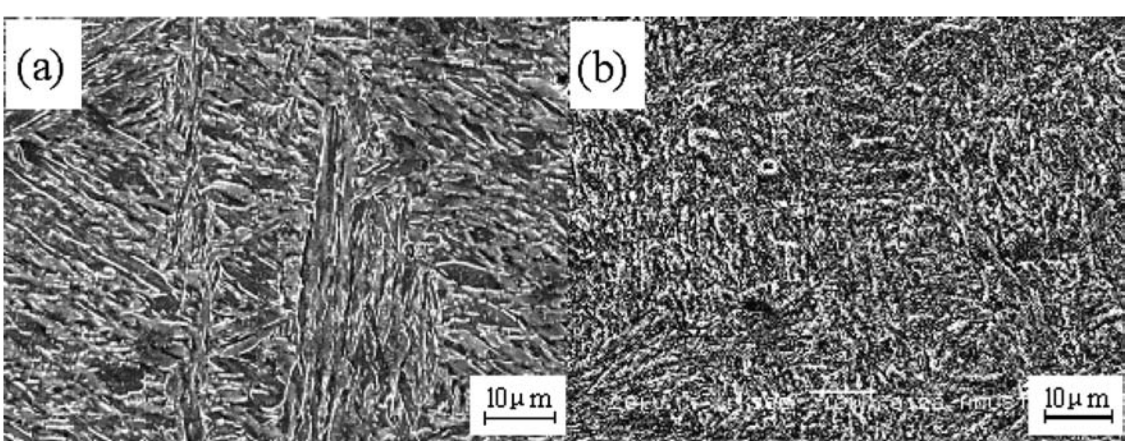

Figure 2 morphology of martensite in the tested steel (SEM): (a) Un-modified, (b) modified.

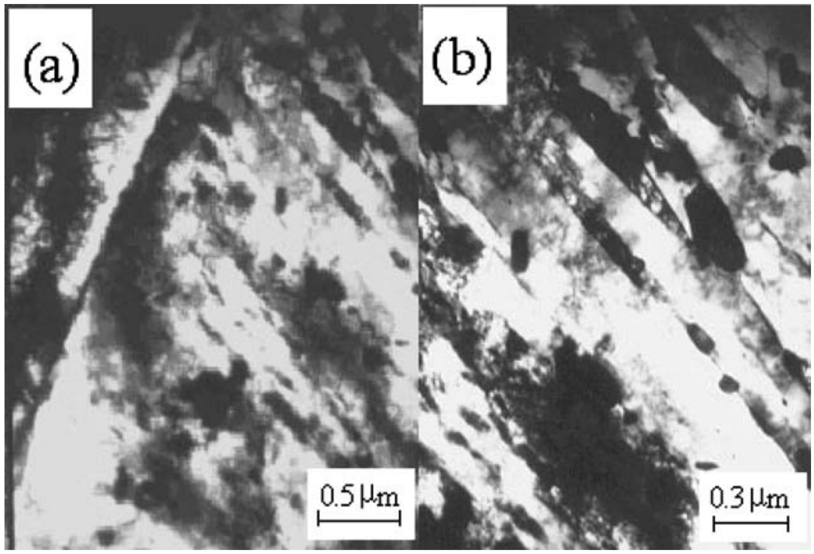

Figure 3 TEM morphology of martensite in the tested steel: (a) Un-modified, (b) Modified.

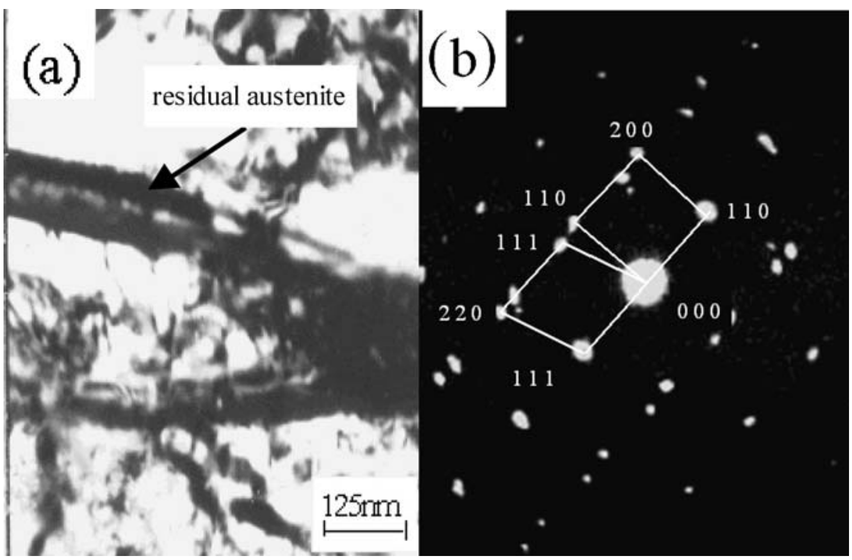

Figure 4 TEM micrographs of retained austenite and its diffraction in modified steel: (a) Retained austenite between martensites, (b) Diffraction patterns of retained austenite and martensite.

86.7 vol.% from 62.5 vol.% without modification. It also makes the martensite laths narrower and shorter.

As it is well known, the toughness of the cast hot-work die steel depends mainly on both the substructure and grain size of martensite. In other words, the microstructure with the fine lath martensite is the superior to coarse one. When the internal micro-cracks exist in the coarse plate martensites, the cracks are easy to initiate from them. The initiated cracks can propagate through and cross the plate martensites in the microstructure.

With Re-Nb modification, the fine lath martensite grains are obtained. As a result, because of existence of a lot of grain boundary more energy is necessary for the propagating and crossing of the initiated cracks through the lath martensites. Thus the propagation of initiated crack requires higher stress values. This is why the toughness of the modified with Re-Nb steel is improved.

The observations with TEM show that there is nearly no austenite phase in the un-modified steel, but a small proportion of the retained austenite phases as narrow films is distributed among the lath martansite grains in the modified steel, as shown in Fig. 4. Table III gives the volume fraction of the retained austenite phases

TABLE III. Residual austenite volume fraction of the tested steels

Specimen	Modification	Fraction of residual austenite (%)
A	Unmodified	0.96
B	Re-Nb-modified	2.37

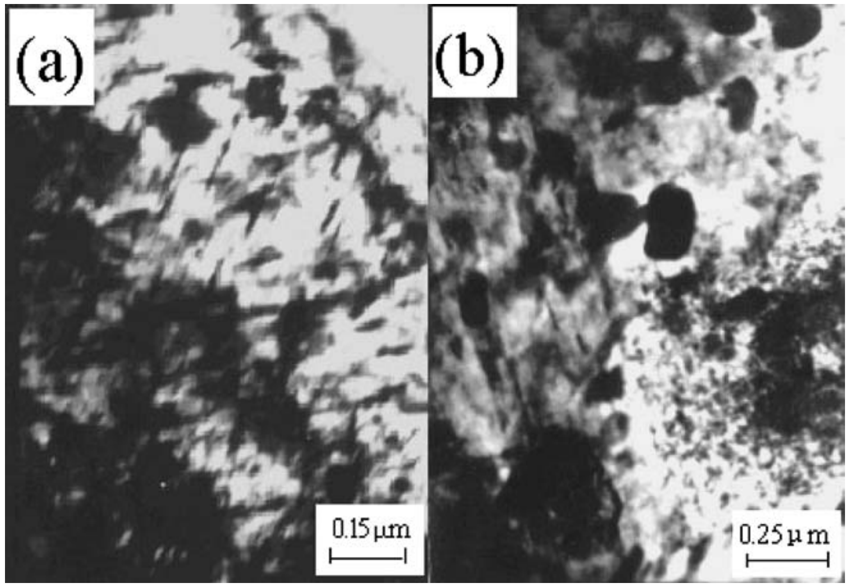

Figure 5 Tempered carbides in the tested steel: (a) Un-modified, (b) Modified.

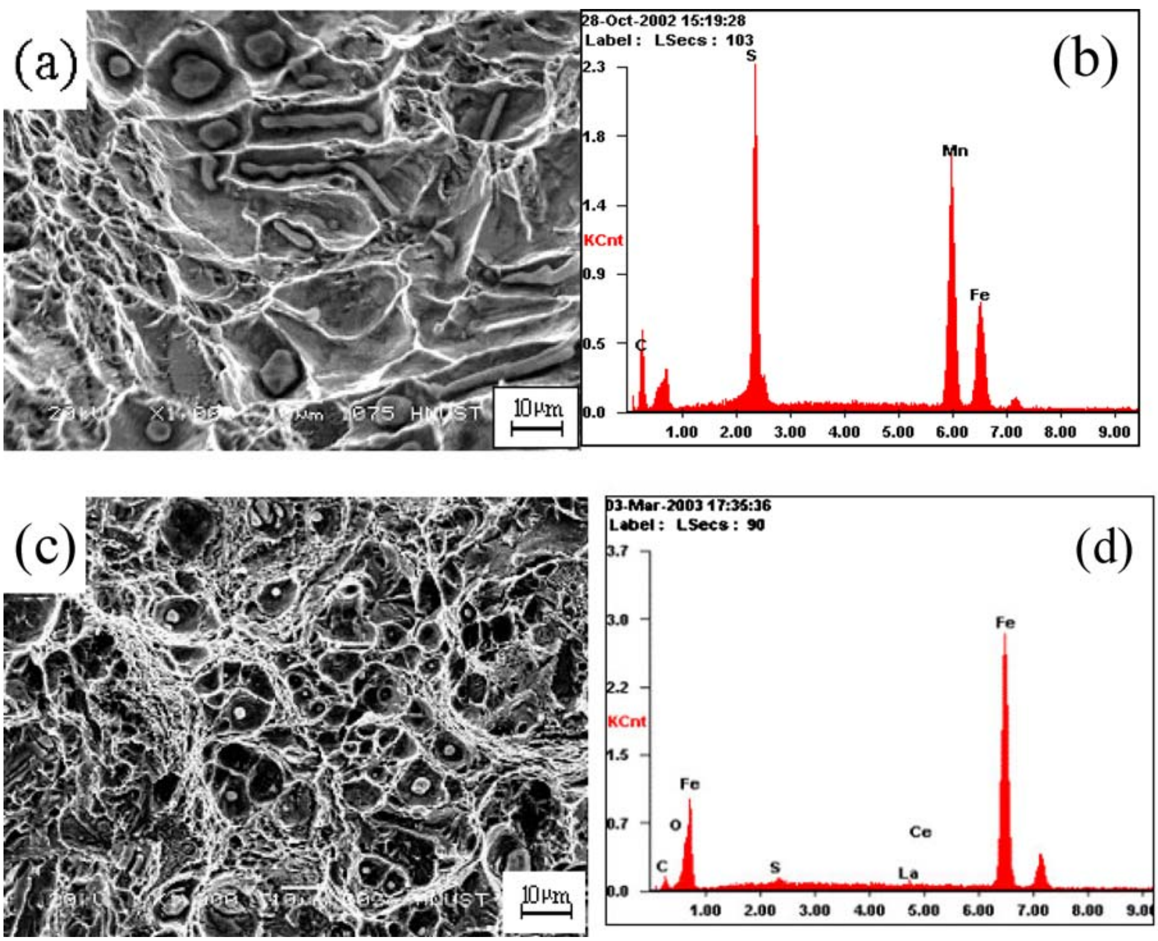

Figure 6 Fracture surface and inclusion pattern of the un-modified and modified steels: (a) SEM-photography of the inclusion and (b) EDS-analysis of bar-like inclusions in the un-modified steel; (c) SEM-photography of the inclusion and (d) EDS-analysis of nodular inclusions in the modified steel.

in the tested steels, which were quenched at 1050°C and then double tempering at 620°C, determined by XRD. The residual austenite has been increased by modification.

It is well known that the retained austenite, as a ductile phase in the cast hot working die steel, can reduce the stress concentration in the crack areas. When the cracks propagate through the retained austenite phases, it has to spend more energy in order to deform or tearing them [9]. So one of the reasons why the modification with Re-Nb raises the toughness of the tested steel is the increase of the volume fraction of the residual austenite in the modified steel.

3.3. Carbide participation in martensite grains

The strength and toughness of cast hot-working die steel are determined in some degree by the shape, size and contribution of dispersion-carbides. The TEM patterns of tempered carbides are presented in Fig. 5. In the tempered microstructure of the un-modified steel, coarse needle carbides precipitate along the twinned-crystal boundaries as shown in Fig. 5a. As a result, the boundaries become brittle faces for the cracks to propagate along. Compared with this, in the modified steel the tempered carbides as fine granules are dispersed over the lath martensites in fine granules, as shown in Fig. 5b. The lath martensites are then dispersion-strengthened with little loss of the toughness.

3.4. Non-metallic inclusions in the tested steels

Moreover, the modification changes the shapes of the non-metallic inclusions, which is one decisive factor for improving the strength and toughness of steel. Fig. 6 shows the fracture surface and inclusion pattern of the un-modified (a) and modified steels (b). As seen, the bar-like and particle inclusions in the un-modified steel are aggregated along the grain boundaries. And the inclusions of the modified steel have been transformed from a bar (Fig. 6a) into a nodular shape (Fig. 6c), and the bar-like inclusions are eliminated. EDS-analysis shows that the like-bar inclusions in the un-modified steel are sulphide inclusion, and the nodular inclusions in the modified steel are the oxide-sulfide inclusion containing Re. The worse effects of the bar-like inclusions in the tested steel are limited, so that the grain boundaries get to strengthen [10]. Therefore the mechanical properties, particularly the toughness, are improved for the cast hot working die steel with the Re-Nb modification.

4. Conclusions

(1) Under same heat treatment condition, the ultimate tensile strengths (UTS) of the modified 3Cr2MoNiWV cast hot working die steel, compared with the un-modified steel, are increased by 234 MPa and 179 MPa and at the room and elevated temperature (600°C) respectively. And the Charpy impact toughness and the fracture toughness are increased by 108.8% and 70.4% more than that of unmodified tested steel respectively, with the hardness maintained.

(2) Re-Nb modification can refine microstructures of the 3Cr2MoNiWV cast hot working steel, increase the volume fraction of lath martensite and retained austenite in the tested steel, and improve morphology of tempered carbide from coarse needle into fine particle shape.

(3) With the addition of Re-Nb modifier, the non-metallic inclusions in the tested steel are transformed from a bar and particle into a fine nodular shape, and the bar-like inclusions are eliminated.

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