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Heat-treatment of 2014 aluminium alloy forgings with intense strain①

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[Abstract] The triangular 2014 aluminium alloy forgings with intense strain were made by a variety of heat-treatment processes, and their mechanical properties were measured. The results showed that different solution and aging processes have very strong influence on the mechanical properties of the forgings. The forgings with intense strain from multidirectional deformation (deformation coefficient $\lambda = 12$), which were solutioned at 500 ℃ for 400 min and aged at 165 ℃ for 10 h, show advanced mechanical properties, and almost no anisotropies. The mechanical properties are $\sigma_b = 466$ MPa, $\sigma_{0.2} = 454$ MPa, $\delta = 10.5\%$ along LD; $\sigma_b = 457$ MPa, $\sigma_{0.2} = 444$ MPa, $\delta = 6.3\%$ along TD; $\sigma_b = 449$ MPa, $\sigma_{0.2} = 433$ MPa, $\delta = 4.2\%$ along HD. The yield strength of the forgings made by a new process was improved by 30% to 50%, the ultimate tensile strength by 15% to 30% and elongation by 100% to 200%, compared with the mechanical properties of the forgings made by the traditional process. The investigation indicated that the very fine grains (3 ~ 6 μm) and the sub-microphases(0.05 ~ 0.15 μm), and their homogeneous distribution have made the forgings have the high mechanical properties.

[Key words] 2014 aluminium alloy forgings; intense strain; solution; aging; mechanical properties
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1 INTRODUCTION

Strict requirements on aluminium alloy forgings are being put forward because of the development of modern aerospace technique. 2014 aluminium alloy with high mechanical properties is extensively used in aerospace industry[1~3]. However, the mechanical properties of the triangular 2014 aluminium alloy forgings made by the traditional process (unidirectional deformation, deformation coefficient $\lambda = 5.5$, solution at 500 ℃ for 105 min, aging at 150 ℃ for 4 h) can't meet the standard of American EL/53 Ml-94. So it is important to find a new process that can make the mechanical properties of the triangular forgings meet the standard of EL/53 Ml-94.

Refs.[4 ~ 8] concluded that heat treatment has obvious influence on the mechanical properties of the 2014 aluminium alloy. The research[9~11] showed that with the proper changes of solution and aging process the precipitates in the 2014 aluminium alloy become very fine. These dispersed phases ($CuAl_2$, Al_2CuMg) have made a contribution to the strength and elongation and have reduced the anisotropies as well.

This work involves a multidirectional large deformation ($\lambda = 12$), different heat treatment processes, and investigation of the mechanical properties in three different directions of the forgings. The mechanical properties are greatly improved compared with those of the forgings made by the traditional process. So a better heat treatment process is set up, the microstructure and mechanical properties of the forgings are examined and analyzed.

2 EXPERIMENTAL

The forgings were open die-forged, bored in the center, enlarged multidirectionally, intensely die-forged ($\lambda = 12$), solutioning and quenched in the water at 80 ℃, and aged at different temperatures for varied times, i.e.

1) solutioning at 500 ℃ for 105 min or 400 min;
2) aged at 150 ℃, 155 ℃, 160 ℃ and 165 ℃ for 2 h to 16 h.

The shape and dimension of the forgings are shown in Fig.1. The mechanical properties of the forgings were measured by Instron 8032. The microstructures of the forgings were examined and analyzed by TEM (Hitachi H-800).

3 RESULTS AND DISCUSSION

The mechanical properties of the forgings made by the new or the traditional process were compared with the standards of GB223-84 and American EL/

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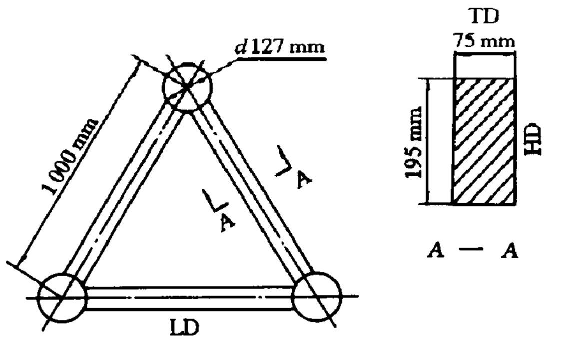

Fig.1 Shape and dimension of studied forgings

53 Ml-94. The results are listed in Table 1.

From Table 1, it is obvious that the strength of GB223-84 is much lower than EL/53 Ml-94, although the mechanical properties of the forgings made by the traditional process have come to the standard of GB223-84. However the mechanical properties of the forgings made by the new process are much higher than the standard of GB223-84, also higher than the standard of American EL/53 Ml-94.

3.1 Influences of hot-deformation and solution time on mechanical properties of forgings

The influences of hot-deformation and solution time on the mechanical properties of the triangular 2014 aluminium alloy forgings are listed in Table 2. The strength and elongation of the forgings deformed by the multidirectional intense strain, solutioning at 500 ℃ for 400 min and aged at 150 ℃ for 4 h are also higher than those of the forgings deformed by the unidirectional deformation ($\lambda = 5.5$), solutioning at 500 ℃ for 105 min and aged at 150 ℃ for 4 h. This phenomenon can be explained by Fig.2. The density of the dislocations of the forgings made by the traditional process is lower, and the recrystallized grains are in a size range on the order of 5 ~ 10 μm. However the density of the dislocations of the forgings made by the new process is much higher, and the recrystallized grains are in a size range on the order of 3 ~ 6 μm.

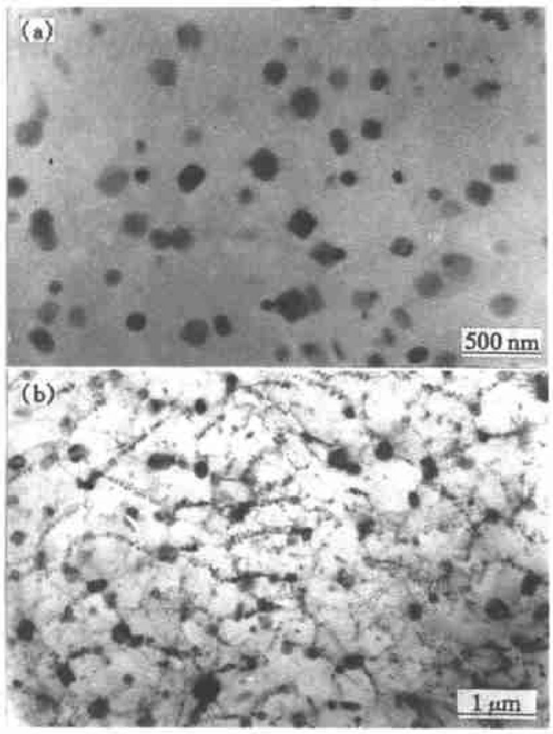

Fig.2 TEM images of forgings with different deformation coefficients and solutioned at 500 ℃ for different times
(a) — $\lambda = 5.5$, solutioned for 105 min, aged 4 h at 150 ℃;
(b) — $\lambda = 12$, solutioned for 400 min, aged 4 h at 150 ℃

Because the hot deformation ($\lambda = 12$) is severe and homogeneous, millions of tiny subgrains of slightly different crystallographic orientations separated by cell walls composed of condensed dislocation

Table 1 Comparison of mechanical properties of studied forgings with standards

Process	Along LD			Along TD			Along ND		
	σ_b / MPa	$\sigma_{0.2}$ / MPa	δ_5 / %	σ_b / MPa	$\sigma_{0.2}$ / MPa	δ_5 / %	σ_b / MPa	$\sigma_{0.2}$ / MPa	δ_5 / %
Traditional process	403	348	6.5	362	308	2.6	321	276	1.2
New process	466	454	10.5	457	444	6.3	449	433	4.2
Standard of GB223-84	382	-	6.0	353	-	4.0	333	-	2.0
Standard of EL/53 Ml-94	435	380	7.0	435	380	2.0	420	370	1.0

Table 2 Mechanical properties of forgings deformed by $\lambda = 5.5$ or 12, solutioned at 500 ℃ for 105 or 400 min and aged at 150 ℃ for 4 h

Process parameter	Along LD			Along TD			Along ND		
	σ_b / MPa	$\sigma_{0.2}$ / MPa	δ_5 / %	σ_b / MPa	$\sigma_{0.2}$ / MPa	δ_5 / %	σ_b / MPa	$\sigma_{0.2}$ / MPa	δ_5 / %
$\lambda = 5.5$ soluting 105 min	403	348	6.5	362	308	2.6	321	276	1.2
$\lambda = 12$ soluting 400 min	426	363	12.9	396	329	8.9	381	309	6.6

tangles can be observed, and are in a size range on the order of 3 ~ 6 μm, the recovery is complete. The high density of the dislocations in the forgings made by the new process and the high stored energy make the rate of the nucleation very high during the solution. Even though solutioning at 500 ℃ for 400 min, the grains don't obviously become bigger. The fine grains make the forgings have high strength and elongation. Furthermore, the multidirectional deformation and the solution at high temperature for a long time are able to provide relatively good conditions for the precipitated phases. So the precipitation is much more complete than those in the forgings made by the unidirectional deformation ($\lambda = 5.5$), and the size of the precipitated phases is much smaller and their distribution is much more homogeneous. Ref.[11] pointed out that the precipitate phases are the main reason for strengthening of the aluminium alloy. So the increase of the number of the precipitated phases and their homogeneous distribution improved the mechanical properties of the forgings. However the mechanical properties of the forgings aged at 150 ℃ for 4 h can't meet those of the standard of American EL/53 Ml-94.

3.2 Influence of aging temperature on mechanical properties

The experiments used multidirectional deformation ($\lambda = 12$), solution at 500 ℃ for 400 min, aging for 4 h. Aging temperatures were from 150 ℃ to 165 ℃ and the properties were measured in every 5 ℃. The influence of aging temperature on the mechanical properties of the triangular 2014 aluminium alloy is shown in Fig.3.

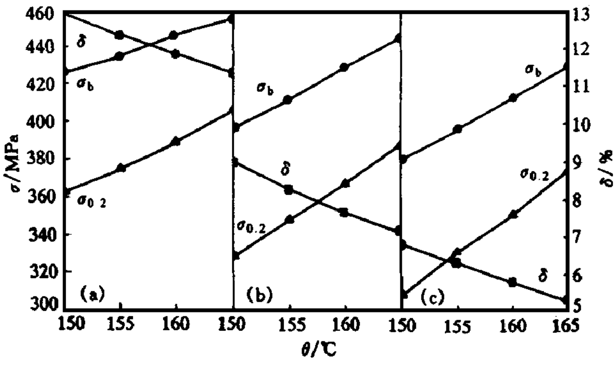

Fig.3 Mechanical properties of 2014 alloy forgings versus aging temperature
(a) —Along LD; (b) —Along TD; (c) —Along HD

It shows that the strength is improved and elongation is reduced with enhanced temperature. The mechanical properties of the forgings along LD have reached the standard of EL/53 Ml-94, however those along RD and TD need further improvment. It can be seen from Fig. 4 that the precipitated phases were much more and smaller, which results in higher strength of forgings aged at 165 ℃ for 1 h.

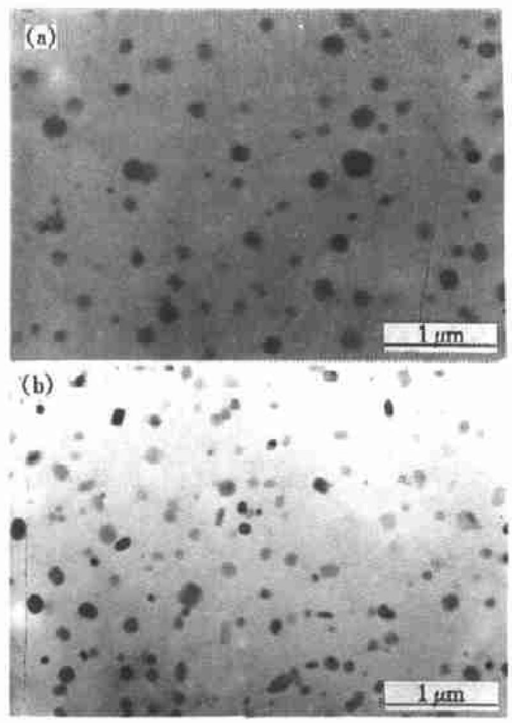

Fig.4 TEM images of forgings at different aging temperatures
(a) —150 ℃; (b) —165 ℃

The high temperature can accelerate the precipitation. Fig.3 showed that neither of the forgings at 150 ℃ or 165 ℃ for 4 h has reached the peak-aging.

3.3 Influence of aging time on mechanical properties

The experiments used multidirectional deformation ($\lambda = 12$), solution 500 ℃ for 400 min, The mechanical properties of the forgings aged at 165 ℃ were measured every 2 h. The influence of aging time on the mechanical properties was shown in Fig.5.

From Fig.5, the forgings underwent three typical stages including insufficient, peak and over-aging as the aging time increased. The strength of the forgings was on the peak when aged for 10 h, and the strength in three directions was almost the same and anisotropies were very small. Although the elongation decreased slightly, the mechanical properties in the three directions have come up to, some even surpassed the standard of EL/53 Ml-94.

From Fig.6(a) it can be seen when the forgings were aged for 2 h, the aging has not completed, and the precipitated phases is few. The strength of the forgings is very low, compared with that of the forgings aged for 10 h (Fig.6(b)). When aged for 16 h, some of the precipitate phases have become bigger (Fig.6(c)), thus the strength of the forgings become low. From Fig.6(d), the needle-like phases S' (Al_2CuMg) appeares in the matrix. The S' phases

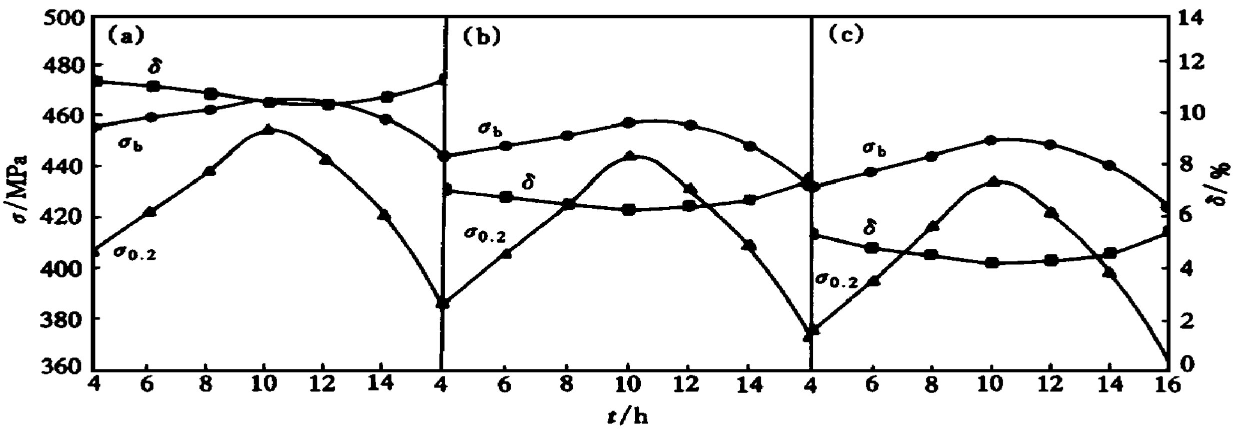

Fig.5 Mechanical properties of 2014 alloy forgings versus aging time
($\lambda=12$, $\theta_s=500$ ℃, 400 min; $\theta_A=165$ ℃)
(a) —Along LD; (b) —Along TD; (c) —Along HD

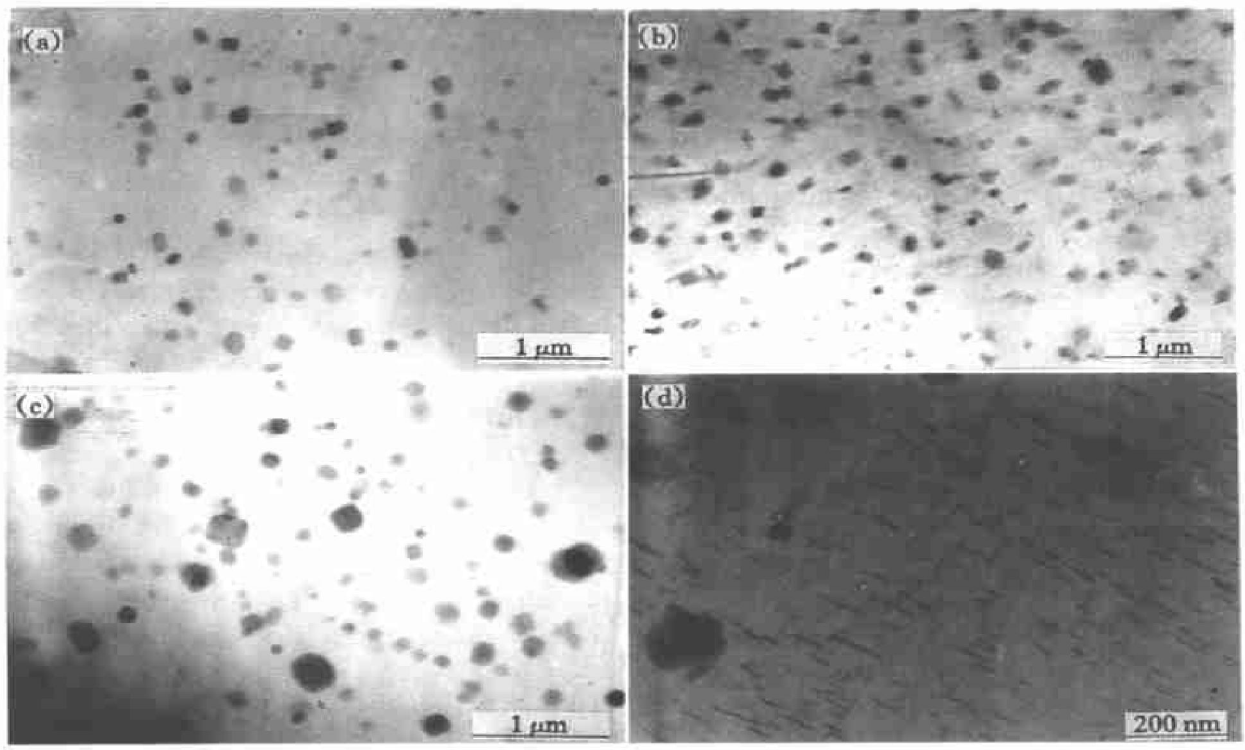

Fig.6 TEM images of forgings aged at 165 ℃ for different times
(a) —2 h; (b) —10 h; (c) —16 h; (d) —Needle-like phase

can improve the strength of the forgings.

From above, The new process with multidirectional severe deformation ($\lambda=12$), solution at 500 ℃ for 400 min and aging at 165 ℃ for 10 h has caused the forgings to be recrystallized and the very small and dispersed phases to precipitate completely.

3.4 Comparison of mechanical properties of forgings made by new process with traditional process

As above mentioned, the mechanical properties of the forgings made by the new process are much higher than those of the forgings made by the traditional process, and the anisotropies are very small as well. The forgings made by the new process took 10 h at 165 ℃ for peak-aging. The solution at 500 ℃ for 400 min was completed, and therefore the precipitation during aging was more. The precipitated phases have not become bigger, precipitates more complete after aging at 165 ℃ for 10 h (Fig.6(b)), at the same time, and the needle-like phases have been observed. However, the precipitated phases in some area of the forgings made by the traditional process become bigger after ageing at 150 ℃ for 4 h, but in some areas the precipitated phases have not precipitated completely (Fig. 7) because the density of the dislocations in the forgings was not homogeneous. The size of the precipitated phases will become bigger with increasing aging time, thus the strength of the forgings has decreased. The needle-like phases (S') precipitate only at high aging temperature for a long time. So they couldn't be found in the forgings made by the traditional process. The heterogeneous precipitation in the forgings made by the traditional process, the bigger precipitated phases and the incomplete precipitation have led to the low mechanical properties.

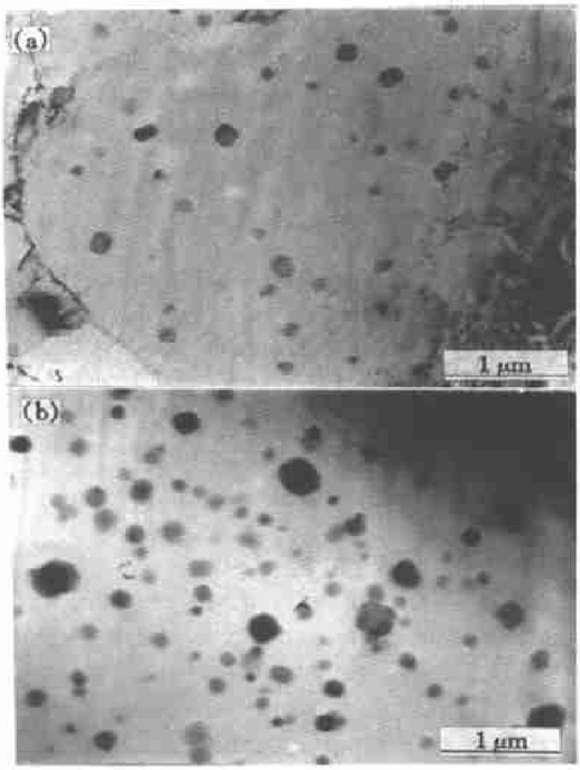

Fig. 7 TEM images of aged forgings by traditional process

(a) —Not completely precipitating area;
(b) —Coarsening particles

4 CONCLUSIONS

1) The severe deformation ($\lambda = 12$) results to the foundation for the homogeneous and fine structures which can contribute to improvement of the mechanical properties.

2) The new process with multidirectional severe deformation, solution at 500 ℃ for 400 min and aged at 165 ℃ for 10 h has changed structures and improved the mechanical properties of the forgings greatly.

3) The 2014 aluminium alloy forgings have 3 different aging stages as well: insufficient, peak and over-aging. But the completed recrystallization of the forgings during solution at high temperature have had the aging temperature enhanced and aging time increased.

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