

Research Article

Numerical and Experimental Research on Cold Compression Deformation Method for Reducing Quenching Residual Stress of 7A85 Aluminum Alloy Thick Block Forging

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In aeronautical machining industry, the most difficult problem to deal with is the distortion of aviation integral component, one main cause of which is the existence of quenching residual stress of forgings, especially for large-sized ones. Therefore, it is important to study the methods that can reduce the quenching residual stress. In this work, the distribution of quenching residual stress of 7A85 aluminum alloy thick block forging, as well as the effect of cold compression deformation method on reducing quenching residual stress, has been investigated by simulation. The results show that, in length direction of 7A85 aluminum alloy thick block with a large size of 260 (*H*) × 1150 (*W*) × 5300 (*L*) mm, quenching residual stress can be significantly reduced by about 2.5% cold compression deformation along the direction of highness, with residual stress in length direction ranging from -65 MPa to 60 MPa, compared with its counterpart after quenching from -170 MPa to 140 MPa. Then a cold compression experiment was carried out, in which the forging residual stress on the surface was measured by X-ray diffraction device. The experimental results indicate that the optimal compression deformation value is 1%-2%, reducing 70% residual stress for 7A85 aluminum alloy specimens in size of 100 (*L*) × 60 (*W*) × 40 (*H*) mm.

1. Introduction

Aluminum alloys are the primary material for structural components of military aircrafts, helicopters, amphibious warships, and so forth for several decades. This is because of the low specific gravity of aluminum which favors the selection of aluminum alloys in weight-critical applications [1]. 7A85 aluminum alloy developed in China in recent years is a new type of high-strength aluminum alloys, whose performance is similar to 7085 aluminum alloy that has been developed by Alcoa company since 2002. In order to gain high-strength performance, a series of heat treatment processes must be carried out including a severe quenching operation which introduces a very high level of residual stress in these aluminum alloys forgings. Quenching residual stress not only results in unexpected machining distortion, but also increases the possibility of unpredicted fatigue failures and stress corrosion cracks (SCC) [2, 3]. Therefore, it is of

great significance to investigate quenching residual stress prediction and reduction methods in aircraft aluminum parts.

A lot of research on quenching residual stress has been carried out by researchers. Particularly with development of computer technology in recent years, numerical simulation technology has become an effective way to simulate the generation and distribution of residual stress during quenching process. Koç et al. used the finite element method to simulate the quenching and prestretching process to predict residual stress value of quenched and prestretched aluminum blocks [4–6]. Wu et al. studied the residual stress in aluminum blocks with different quenching processes [7–9]. Prime and Hill used the crack compliance method to measure the residual stress value in products of Alcoa and obtained residual stress distribution of quenched aluminum block and the corresponding prestretched block [10, 11]. Muammer et al. studied the residual stresses in quenched aluminum blocks

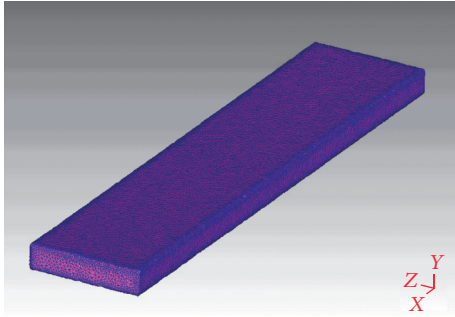


FIGURE 1: Finite element model.

TABLE 1: Heat transfer coefficient of 7A85 aluminum alloy.

Temperature (°C)	20	100	200	300	400	500
Transfer coefficient (W/m ² ·C)	2500	5000	13857	10000	3000	700

and their reduction through cold working processes [12, 13]. In this work, the effect of cold compression deformation on reducing quenching residual stress was studied through numerical simulation and experiment.

2. Simulation

2.1. Finite Element Model and Simulation Parameters. A thick block forging of 7A85 aluminum alloy with a large size of 260 (H) × 1150 (W) × 5300 (L) mm was chosen as the test component for the numerical analysis. The quenching and cold compression processes were subjected to numerical simulation in this study. The block was quenched in water of 20°C from initial 470°C and then 1%–5% cold compression deformation was conducted on the block along the highness direction. Finite Element Code Deform-3D was used to simulate the two processes. The shape and finite element model are shown in Figure 1.

Heat transfer coefficient between 7A85 aluminum alloy block and water which is the most important parameter in quenching process is given in Table 1 [14]. The heat capacity of 7A85 aluminum alloy obtained through DSC method by using the instrument NETZSCH STA 449 C is shown in Table 2. Flash method was used to get the thermal conductivity coefficient of 7A85 aluminum alloy by JR-3 machine. The measurement of thermal expansion coefficient was completed through NETZSCH DIL402C device. Both of them are given in Table 2.

2.2. Quenching Simulation Results and Discussion. Figure 2 shows the simulated results of temperature profile for the cooling time 10 s. Obviously, the temperature of edge at the block is the lowest and the temperature difference between the edge and the highest temperature of the block is about 400°C. This is due severely to heat convection at the edge along any two axis directions. The temperature gradient and temperature difference gradually decrease with prolonging cooling time. Two characteristic points 1 (surface) and 2

TABLE 2: Thermal conductivity and thermal expansion coefficient of 7A85 aluminum alloy.

Temperature (°C)	15	100	200	300	400	550
Heat capacity (J/g·°C)	1.02	0.95	1.1	1.07	1.24	1.07
Conductivity (W/m·°C)	185.3	182.0	217.3	218.2	228.1	187.2
Expansion (10 ⁻⁶ /°C)	*	24.3	25.9	26.7	28.2	*

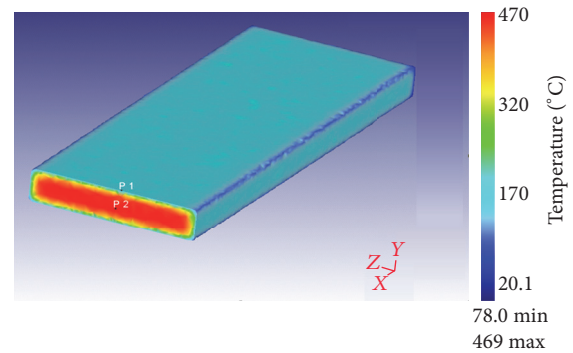


FIGURE 2: Results of temperature after cooling time 10 s.

(core) of the block shown in Figure 2 were employed for observing the temperature (T) change with cooling time (t) from 470°C to 20. Figure 3 gives the relative calculated results. The largest temperature difference between points 1 and 2 occurs in range of cooling time 10 to 15 s. The temperature difference produces the thermal stress in the internal, which leads to the deformation of the block. At the same time, the release of phase transition latent heat results in a decrease in the slope of T - t curves. Because the quenching process is very severe, the effect of the phase transition latent heat release on the temperature could be ignored. After quenching for about 350 seconds, the temperature distribution in the block evolves to be uniform and the magnitude is close to the water temperature. With increasing time, the temperature of the two points gradually reduces; it takes about 650 s for them to be cooled to the target temperature 20°C.

The final residual stress distribution of quenched block in length direction is shown in Figure 4. Figure 5 gives stress (X)-time curves for points 1 (surface) and 2 (core) of the block. In the initial stage of quenching, the normal stress was tensile at the surfaces and compressive in the core. Because of the sudden contraction of the surfaces and the great temperature gradient in the vicinity of the surface, the normal stress at surface point 1 increases sharply to about 70 MPa and then decreases slowly with the decreasing temperature gradient. At the same time, the compressive normal stress at the center point 2 gradually increases. During this process, the block undergoes plastic deformation. The plastic deformation finally results in the fact that the surface tensile residual stress shifts to compressive and the core

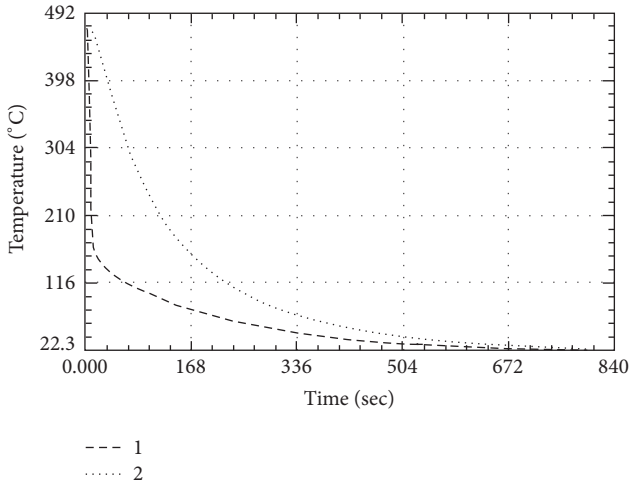


FIGURE 3: Temperature-time curves for points 1 and 2 in Figure 2.

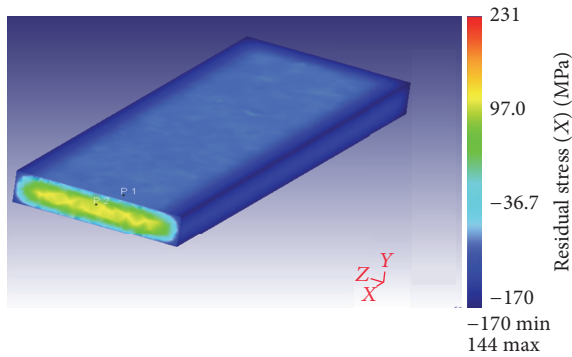


FIGURE 4: Results of residual stress (X) after quenching.

compressive stress switches into tensile stress at the later stage of quenching.

2.3. Compression Simulation Results and Discussion. Figure 6 shows the simulated results of residual stress distribution of the block for different cold compression values 0%, 1%, 2.5%, 4%, and 5%. The x - and y -axes stand for residual stress value and percentage of the block forging, respectively. It can be seen that the residual stress in length direction ranged from -170 MPa to 140 MPa when the quenching process was completed (Figure 6(a)). After conducting 1% cold compression deformation on the block along the direction of highness, the distribution range of residual stress in length direction significantly reduced that ranged from -110 MPa to 120 MPa (Figure 6(b)). This is due to the plastic deformation that redistributed the residual stress of the block. The range of residual stress in length direction of the block sharply reduces to the range from -65 MPa to 60 MPa as the compression deformation value runs up to 2.5%, and the uniformity was better than before (Figure 6(c)). However, when the deformation continued to come up to 4% and 5%, the ranges of residual stress in length direction of the block sharply widened which are from -90 MPa to 100 MPa and from -110 MPa to 120 MPa, respectively (Figures 6(d) and 6(e)).

TABLE 3: Cold compression deformation scheme.

Percentage	1%	2%	3%	4%	5%
Plastic deformation (mm)	0.4	0.8	1.2	1.6	2.0
Experimental deformation (mm)	0.9	1.2	1.6	2.0	2.4

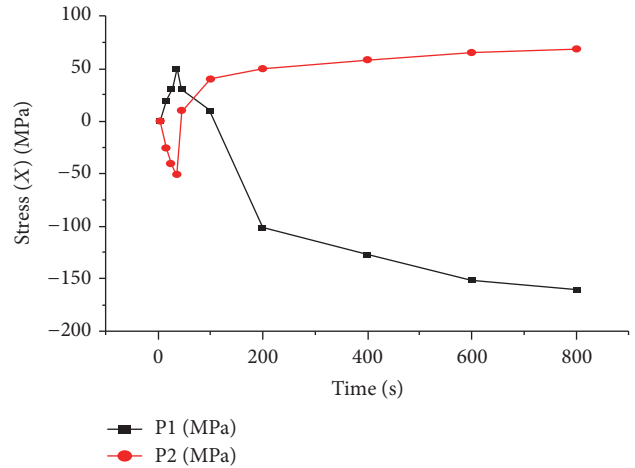


FIGURE 5: Stress (X)-time curves for points 1 and 2 in Figure 4.

This phenomenon can be explained by the fact that if the cold compression deformation continues to increase, it will produce much more elastic deformation in the block which is the main cause of the increase of residual stress. Therefore, for this simulation, it can be concluded that the optimal compression deformation value is about 2.5% for this large-sized block forging.

3. Cold Compression Experiment

Figure 7 shows the cold compression experimental specimens of 7A85 aluminum alloy forging with the size of 100 (L) \times 60 (W) \times 40 (H) mm provided by Southwest Aluminum Company and equipment of Central South University including X-ray diffraction device, and 4000t CNC hydraulic press machine. The entire experimental course was subdivided into four operations, which are quenching, measuring residual stress for the first time, cold compression deformation along the highness direction of specimens, and measuring residual stress for the second time. 1%–5% cold compression deformation was conducted on the quenched specimens along highness direction, respectively. The data of plastic deformation is shown in Table 3. Compression speed was 0.1 mm/s, which can be accurately controlled by the hydraulic control system. The residual stress of the same points on the surface of compressed specimens was measured by X-ray diffraction device in X, Y, and Z directions.

The results of cold compression deformation experiment are shown in Table 4 and Figure 8. The average values of residual stress for quenched specimens are -174.9 MPa,

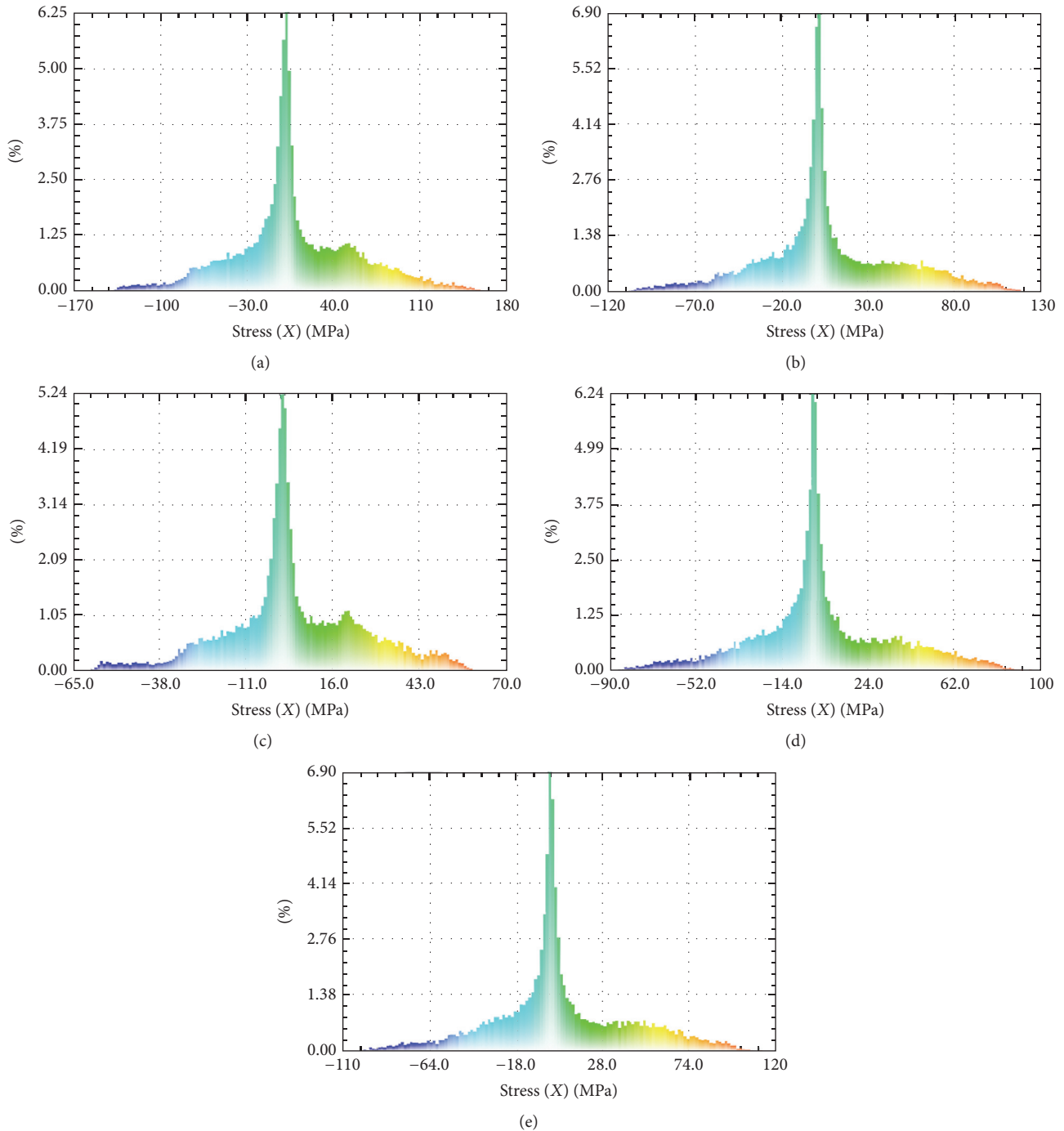


FIGURE 6: Results of residual stress (X) distribution for different compression value: (a) quenched; (b) 1%; (c) 2.5%; (d) 4%; (e) 5%.

-156.7 MPa, and -150.6 MPa, in X, Y, and Z directions, respectively. After conducting 1% compression deformation, the values of them reduced to 7 MPa, 53.4 MPa, and -5.9 MPa, respectively. When compression deformation exceeded 2%, the level of residual stress in three directions both obviously increased. It can be concluded that 1%-2% is the optimal compression deformation value which can reduce

70% residual stress for these 7A85 aluminum alloy specimens sized 100 (L) × 60 (W) × 40 (H) mm.

4. Conclusions

- (1) Physical property parameters of 7A85 aluminum alloy such as heat capacity, thermal conductivity,

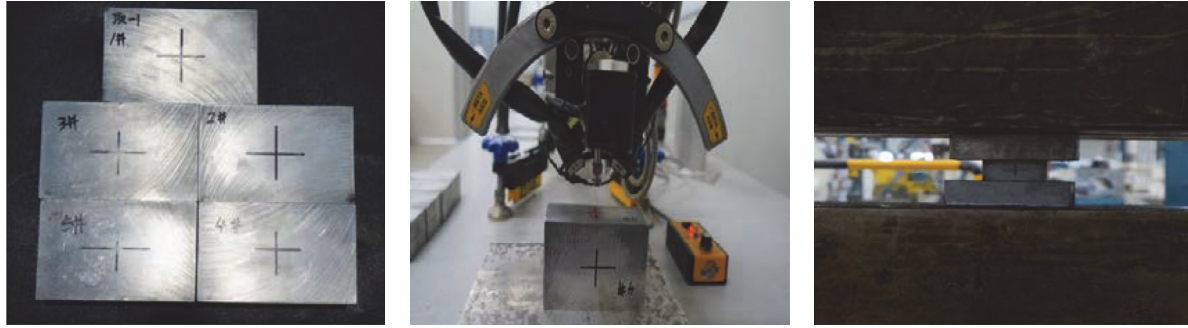


FIGURE 7: Experimental specimens and equipment.

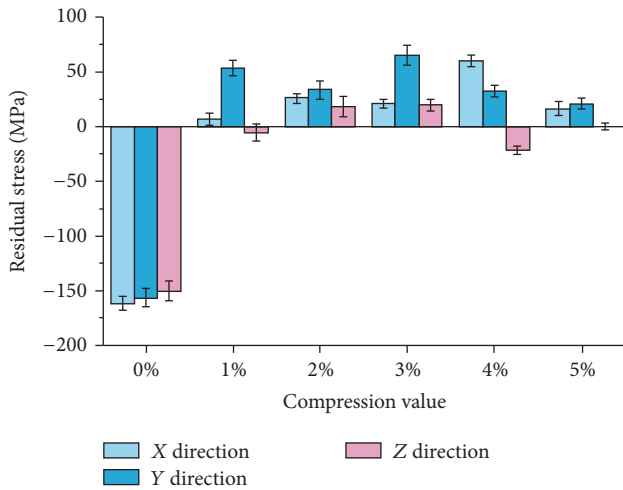


FIGURE 8: The error for measurement data.

TABLE 4: Residual stress of quenched and compressed specimens.

Compression value	X direction (MPa)	Y direction (MPa)	Z direction (MPa)
0%	-174.9	-156.7	-150.6
1%	7.0	53.4	-5.9
2%	28.2	33.7	18.3
3%	22.4	65.3	19.1
4%	64.9	32.4	-22
5%	17.8	20.8	-0.1

and expansion coefficient were obtained through experiments, which are the foundation of subsequent simulative and experimental research.

- (2) Cold compression deformation method has a significant effect on reducing quenching residual stress if an appropriate amount of compression deformation is chosen. The simulation results show that, in length direction of 7A85 aluminum alloy thick block with a large size of $260 \times 1150 \times 5300$ mm, quenching residual stress can be significantly reduced by about 2.5% cold compression deformation along the direction of highness, with residual stress in

length direction ranging from -65 MPa to 60 MPa, compared with that from -170 MPa to 140 MPa after quenching. The experimental results indicate that the optimal compression deformation value is about 1%-2%, reducing 70% residual stress for 7A85 aluminum alloy specimens sized $100 \times 60 \times 40$ mm.

Competing Interests

The authors declare that they have no competing interests.

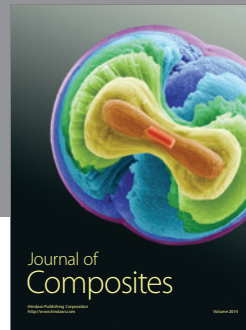
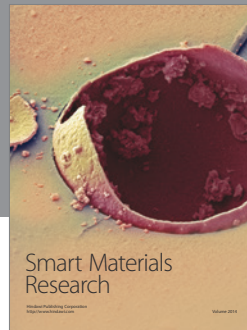
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