

## Effects of deformation temperature on edge crack characteristics and mechanical properties of as-cast aluminum alloy

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In this study, the rolling technique of aluminum alloy was investigated, and the effects of deformation temperature on the edge cracks and mechanical properties of aluminum alloy were studied through a hot compression experiment on high magnesium aluminum alloy. Based on the test, DEFORM-3D software was introduced to optimize the selection of the influence conditions of the experiment. The research results suggested that the crack length of the as-cast aluminum alloy samples decreased with the increase of temperature when the deformation temperature was between 300 °C and 450 °C; the tensile strength and elongation after fracture increased with the increase of temperature when the deformation temperature was between 300 °C and 500 °C. Therefore it is concluded that the cracks of high magnesium aluminum alloy can be reduced through controlling deformation temperature, which provides an idea for the optimization of aluminium alloy.

**Keywords:** deformation temperature; as-cast aluminum alloy; heat compression; cracks; tensile strength; elongation after fracture.

Проведены исследования технологии прокатки алюминиевого сплава с высоким содержанием магния, исследовано влияние температуры деформации на краевые трещины и его механические свойства. На основе теста предложено программное обеспечение DEFORM-3D для оптимизации выбора условий эксперимента. Результаты исследований показали, что длина трещины образцов из алюминиевого сплава при температуре деформации в диапазоне от 300 до 450 ° C уменьшается с увеличением температуры; прочность на растяжение и удлинение увеличивалась с увеличением температуры в диапазоне от 300 до 500 ° C. Делается вывод, что трещины в высокомагниево алюминиевом сплаве могут быть уменьшены за счет контроля температуры деформации, что позволяет оптимизировать состав алюминиевого сплава.

**Вплив температури деформації на характеристики крайової тріщини і механічні властивості литого алюмінієвого сплаву.** *Yongyue Liu, Peng Jiang, Xueping Ren, Xian Luo, Zelin Gu, Dianyu Fu*

Проведено дослідження технології прокатки алюмінієвого сплаву з високим вмістом магнію, досліджено вплив температури деформації на крайові тріщини і його механічні

властивості. На основі тесту запропоновано програмне забезпечення DEFORM-3D для оптимізації вибору умов експерименту. Результати досліджень показали, що довжина тріщини зразків з алюмінієвого сплаву при температурі деформації у діапазоні від 300 до 450 °C зменшується зі збільшенням температури; міцність на розтягнення і подовження збільшувалася із збільшенням температури у діапазоні від 300 до 500 °C. Робиться висновок, що тріщини у високомангнієвому алюмінієвому сплаві можуть бути зменшені за рахунок контролю температури деформації, що дозволяє оптимізувати склад алюмінієвого сплаву.

### 1. Introduction:

Cracks generated in aluminium alloy during production may affect the overall quality of products; hence how to improve production techniques to improve the quality of aluminium alloy has become an important research direction. Zhou et al. [1] established the cross section of plastic deformation zone according to the distribution characteristics of equivalent plastic strain in radial rolling. The size effects of feed speed and lubrication condition on the distribution of strain and temperature and their homogeneity were investigated based on the newly developed finite element method of radial ring rolling technique and comprehensive numerical simulation and using 3D coupled thermo-mechanical finite element simulation. The results matched well with the experiment. Liu et al. [2] described the rolling process of semi-solid powder, analyzed the microstructure evolution after rolling, and investigated the combination mechanism of semi-solid powder in the process of rolling. The results demonstrated that the optimal percentage of liquid in the preparation of strips was between 45% and 65%; Flowing and filling of liquid (> 10%), densification by rolling and recrystallization (< 10%) were the three combination mechanisms of semi-solid powder in the process of rolling; semi-solid powder could be processed into strips with better micro-hardness and relative density through hot rolling.

Hallberg [3] investigated the microstructure evolution of AA1050 aluminum in the process of cold rolling through numerical simulation. It was found that per-pass thickness reduction and level of rolling friction had remarkable influence on dynamic recrystallization induced grain refinement, and the asymmetry of rolling process had a smaller influence; the increasing of asymmetry could reduce the changes of grain size and make the material recrystallized more homogeneously. Pouraliakbar et al. [4] studied the comprehensive influence of rolling and post-annealing on mechanical properties and microstructure evolution and took main effort on the malleability of specimens tolerating duplex straining paths. They found that proper annealing could effectively improve ductility; the strength of the test specimens had no obvious decline at 20002 °C and before recrystallization; during the evolution of microstructure structure, there was no rapid growth of grain/

microcrystal under low temperature; processing at 27502 °C significantly changed the mechanical characteristics by equiaxing the lamellar structure. This study aimed to explore the relationship between deformation temperature and edge crack characteristics and mechanical properties of as-cast aluminum alloy through hot compression experiment on high magnesium aluminum alloy to offer assistance to the optimization of processing techniques for aluminium alloy.

### 2. Experimental

**Weighing of raw materials:** The casting materials and equipments used in the experiment were provided by Ningbo Heli Mould Technology Co., Ltd., China. According to the design of composition proportion [7] (5% magnesium, 1% manganese, 0.4% silicon, 0.1% zinc and 93.5% aluminum) and the burn out rates of different alloy elements in the process of smelting, the dosages of the raw materials were weighed using TG328A electronic balance. Configuration of raw materials was performed two or three days before aluminum alloy melting to prevent the effects of oxidation on the raw materials.

**Preprocessing of raw materials before melting:** The surface of the raw materials such as aluminium block and magnesium block was polished [8] to remove the impurities such as oxide. One hour before smelting, the raw materials were preheated by a 101A-3 drying oven at 200 ~ 220 °C for two hours.

**Preparation before smelting:** Argon was checked to ensure security. Before smelting, the iron tools such as hawkbill, crucible tongs and slagging ladle were preheated before smelting, and the iron instruments were polished using 100# silicon carbide sand and preheated using a drying oven at 150 ~ 200 °C [9]. The instruments were brushed with coating which was composed of 3% ~ 5% water glass, 25% ~ 30% ZnO and water for two or three times after preheating to prevent pollution to melt. Then the instruments were dried using a drying oven. Before smelting, the casting moulds were preheated using a drying oven at 200 ~ 230 °C to avoid the damages of sudden cold or hot to the moulds, extend the service life of the moulds, relieve the packaging force between the casting and moulds, prevent welding, and benefit demoulding.

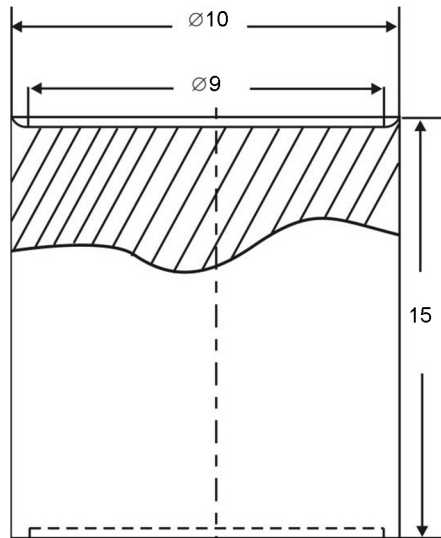


Fig. 1. The compression specimen of as-cast aluminum alloy (unit: mm).

Smelting and casting of aluminium alloy: Firstly a 12# graphite-clay crucible was put into an induction melting furnace, and the temperature was adjusted to 760 °C. Then the heat was preserved for one hour until the temperature in the furnace became homogeneous. The materials such as aluminium ingot and magnesium block were put into the crucible, heated, and stirred fully to make the components distribute evenly. After the complete melting of the raw materials, the temperature inside the oven was adjusted to 700 °C. The alloy melt was injected with high-purity argon via stainless steel tube for 5 min [10]. The enrichment of argon could protect the melt from furnace gas. Then the melt was refined. After oxidizing slag on the surface of the melt was removed using a slagging ladle, the melt was stirred using a stirring rod and then stood for 10 min. After standing, the melt in the crucible was casted to a preheated casting mould using crucible tongs. After the melt cooled and froze thoroughly, the mould was opened using a spanner. Finally as-cast aluminum alloy was obtained.

To facilitate the hot compression experiment, DEFORM-3D [11] was used for simulation. The experiment was simplified according to actual conditions. Parameters such as the safety range of temperature, compression deformation amount and strain rate were simulated to figure out which parameters were more suitable to the experiment.

The aluminium alloy casting ingot was processed by homogenization treatment at 560 °C in a muffle furnace [12], quenched with water, and immediately given aging treatment at 175 °C in a drying oven for 6 h.

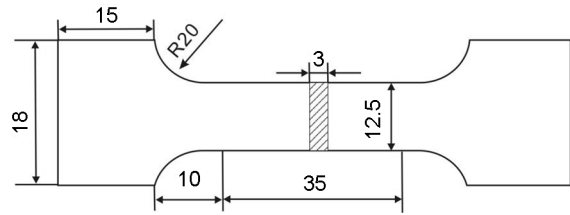


Fig. 2 The tensile test specimen (unit: mm).

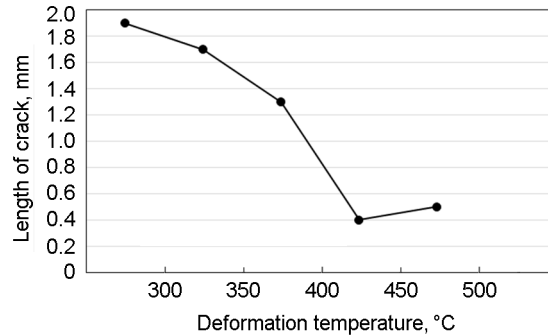


Fig. 3. The relationship between deformation temperature and length of cracks.

The as-cast aluminum alloy was processed into a compression sample in a size of  $\varnothing 10\text{mm} \times 15\text{mm}$  using lathe process, as shown in Fig. 1. A hole in a size of  $\varnothing 0.5\text{mm} \times 1\text{mm}$  was punched in the middle of the lateral side of the test specimen. The compression deformation test was performed on a Gleeble-1500 dynamic thermal simulated test machine. The temperature was set as 250 °C, 300 °C, 350 °C, 400 °C, 450 °C and 500 °C, the strain rate was set as 0.002 s<sup>-1</sup>, 0.01 s<sup>-1</sup>, 0.1 s<sup>-1</sup> and 10 s<sup>-1</sup>, and the deformation amount was set as 50%. The both ends of the test specimen were smeared with lubricant to reduce frictional force.

Before tensile test, wire-electrode cutting was performed to cut the aluminum alloy specimen into three groups. Standard processing for the size of the specimens was designed according to GB/T228-2002 [13]. The standard tensile specimens were drawn using CAD software, as shown in Fig.2. The tensile as-cast aluminum alloy specimens were processed and polished using 600 metallographic abrasive papers to remove machining marks and washed using acetone reagent in an ultrasonic cleaner to remove dirt. AGS-X10 KN electronic universal tester (Shimadzu Group, Japan) [14] was used, and its beam movement speed and tensile speed were set as 1 mm/min and 1 mm/min, respectively. The whole experimental process followed GB/T228-2010 Metallic Materials - Tensile Testing at Ambient Temperature. Each test specimen was tested for three times, and the average value of the three tests was taken as the test data.

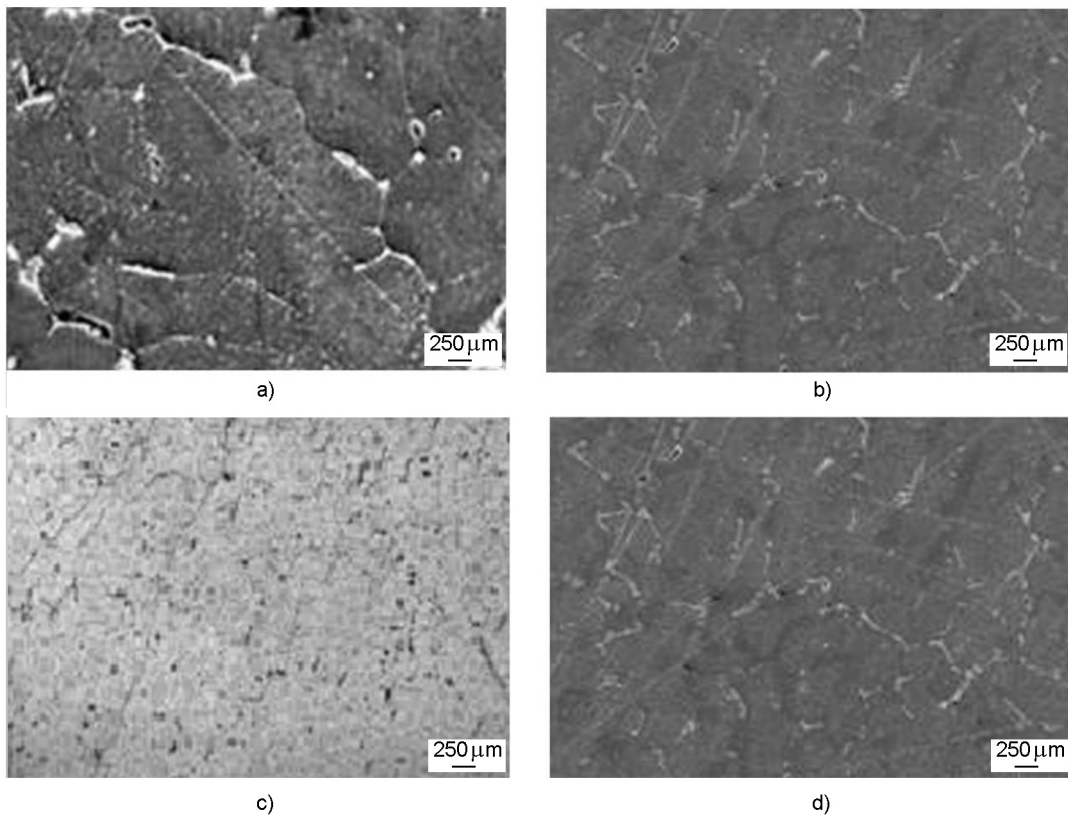


Fig.4. The micro-structure of the as-cast aluminium alloy after thermal compression deformation (A: 300 °C, B: 400 °C, C: 450 °C; D: 500 °C)

Elongation after fracture, the major plasticity index, refers to the ratio of the gauge length extension amount of the test specimens to the original gauge length after fracture, denoted as  $A$ . Its formula is:

$$A = \frac{L_u - L_0}{L_0} \times 100\%,$$

where  $L_u$  stands for the gauge length after fracture and  $L_0$  stands for the original gauge length.

#### Observation of cracks

The test specimens which had been processed by thermocompression were observed under an optical microscope (100X). Edge cracks were searched and photographed, and the length of the cracks was measured using an electronic ruler.

#### Observation under metallurgical microscope

Firstly a square specimen in a size of 10 mm × 10 mm × 10 mm was cut from the as-cast aluminum alloy using a DK7740 wire cutting machine. Then the analysis surface of the test specimens were manually grinded using silicon carbide metallographic abrasive papers (100#, 200#, 400#, 600#, 800#, 1000#) until there was no scratch on the surface of the analysis surface. Moreover the analysis

surface was polished using a PG-1A metallographic polishing machine. Next, the analysis surface was etched using Keller reagent (HF : HCl : HNO<sub>3</sub> : H<sub>2</sub>O = 2:3:5:190) for 25 s. Finally the test specimens were photographed using a Leica DM-4000M metallographic microscope and an Olympus H2-UMA metallographic collection system [15].

### 3. Results and discussion

Parameters which were suitable for processing of aluminium alloy were selected according to the finite element simulation based on DEFORM-3D: deformation temperature between 300 °C and 500 °C, strain rate between 0.01 s<sup>-1</sup> and 0.1 s<sup>-1</sup> and 50% deformation amount. The experiment was performed based on the above setting. The experimental results and analysis were as follows.

As shown in Fig. 3, deformation temperature could obviously affect the generation of edge cracks on the as-cast aluminium alloy when other conditions were fixed; under the condition of 50% deformation amount, the length of the edge crack was 1.93 cm, 1.72 cm and 1.35 mm, respectively, when the deformation temperature was 300 °C, 350 °C, 400 °C and 450 °C; the crack was 0.39 mm long when the



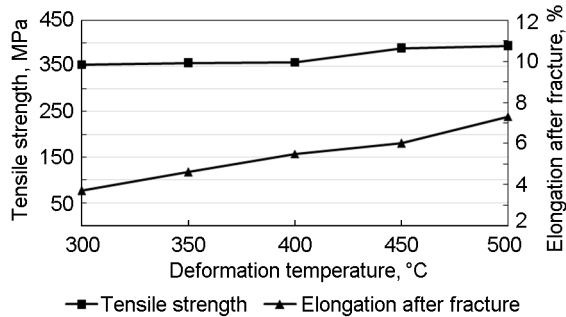


Fig. 5. Effects of deformation temperature on the tensile strength and elongation after fracture of the test specimens

deformation temperature was 450 °C, and the decrease amplitude of the crack length was large; the crack became longer when the deformation temperature was 500 °C. It could be concluded that the length of edge cracks on the as-cast aluminium alloy decreased gradually with the increase of the deformation temperature when the temperature was between 300 °C and 450 °C, and the edge cracks grew again when the temperature was higher than 450 °C.

Fig. 4 exhibits the micro-structure of the as-cast aluminium alloy. When the temperature was between 300 °C and 450 °C, the grain of the aluminium alloy became smaller, and the stress on the edge of the test specimens decreased; therefore the length of the edge crack decreased. When the temperature was higher than 500 °C, recrystallization occurred, which resulted in strengthened stress, and the cracks grew. The metallographic microscopic results explained the changes of cracks.

Fig. 5 shows the changes of the mechanical performance of the prepared high magnesium aluminum alloy which was processed by compression and T6 thermal treatment under different deformation temperatures. When the deformation temperature increased from 300 °C to 500 °C, the tensile strength and elongation after fracture of the aluminum alloy gradually increased. The tensile strength and elongation after fracture were 3.8% and 352 MPa, respectively, the smallest, when the deformation temperature was 300 °C. The tensile strength and elongation after fracture were 392 KPa respectively, the largest, when the deformation temperature was 500 °C; there was an increase of 105.3% and 11.4% compared to those at 300 °C, and there was an increase of 3.7% and 44.4% compared to those at 450 °C.

#### 4. Conclusions

This study firstly introduced the superiority of aluminium alloy and the possible problems in the processing of aluminium alloy and

then explored the relationship of deformation temperature with the generation of edge cracks and changes of mechanical performance in the aspect of hot compression processing. In this study, aluminium alloy was casted in strict accordance with laboratory standards. Before experiment, finite element simulation was made using DEFORM-3D to determine the parameters which were beneficial to processing of aluminium alloy. Then the prepared as-cast high magnesium aluminum alloy test specimen was tested using thermocompression and tensile experiments. The crack length, elongation after fracture and tensile strength of the test specimens were observed using high-power microscope and metallographic microscopic observation and calculated. The experimental results demonstrated that the length of edge crack of the as-cast aluminium alloy test specimen decreased with the increase of deformation temperature when the temperature was between 300 °C and 450 °C; the elongation after fracture and tensile strength of the as-cast aluminium alloy test specimen increased with the increase of deformation temperature when the temperature was between 300 °C and 500 °C. The results obtained in this study can offer a reference and assistance to the processing of high magnesium aluminium alloy and reduce the defects of aluminium alloy.

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