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# Effect of aging treatment on the microstructure and flow behavior of 6063 aluminum alloy compressed over a wide range of strain rate

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ABSTRACT

The compression deformation behavior of an as-casting 6063 aluminum alloy has been studied under quasi-static and impact loading conditions at strain rate ranges from $1 \times 10^{-3}$ to $3.5 \times 10^{3}$ s$^{-1}$ and a constant strain of 0.2. The results showed that the flow stress response of the as-casting 6063 alloy was sensitive to the aging treatment as well as strain rate. For the solution treated (ST) alloy, slight strain rate sensitivity was detected both under quasi-static and dynamic loading. However, the artificial aging (AA) alloy exhibits an obvious positive strain rate sensitivity under dynamic compression, while the sensitivity under quasi-static compression is low. The constants of the modified Johnson–Cook constitutive model were determined by using the measured flow stress data, which was consistent with the experimental results. Dislocations in the form of vein or cell structures with thick walls containing many parallel dislocation lines were observed in the ST alloy under high strain rate loading. By contrast, a relative high density of dislocations and a large number of homogeneous distributed needle-like $\beta''$ precipitates were detected in the matrix of deformed AA samples. As compared with the AA alloy, the strain hardening and strain rate hardening of ST alloy are balanced by the thermal softening, which results from the adiabatic temperature rise during dynamic deformation. The interactions among them are related to the initial and corresponding evolved microstructure, which leads to its insensitivity to the applied strain rate.


## 1. Introduction

Al–Mg–Si alloys have been used extensively in the fabrication of aerospace, automotive and marine components due to their superior mechanical properties such as low density, high strength/weight ratio, excellent weldability [1,2]. Solution treatment and artificial aging are common heat treatment processes for Al alloys to improve the mechanical performance [3–5]. Many experiments have been conducted to investigate the effects of heat treatment on the mechanical behavior of 6063 aluminum alloys under quasi-static loading [6,7]. However, the materials are inescapably used in circumstances that involve high strain rate deformation [8,9], such as automobile crash, bird strike on aircraft and defense industries. Therefore, it is necessary to characterize the dynamic mechanical behavior of Al–Mg–Si aluminum alloy under different heat treatments and to clarify the microstructure evolution during the dynamic deformation.

In recent years, numerous investigations have focused on characterization of the comprehensive behavior of aluminum alloys under dynamic loading [10,11]. For most metallic materials, the strain rate sensitivity (SRS) increases significantly when the strain rate exceeds a critical value [12,13], which is the significant factor for mechanical behavior. Gupta et al. [14] found that the A356, A357, F357 aluminum alloys are sensitive to strain rate and the dynamic flow stress under compression is approximately 4–8% higher than the quasi-static flow stress value. The mechanical behavior of the casting alloys is similar to that reported for 6061-T6 in Lee's research [12]. Moreover, some researchers studied the dynamic compressive behavior on 2000 and 7000 series by using split Hopkinson pressure bar (SHPB) or with a computer servo-controlled Gleeble 1500 system at normal and elevated temperature [15,16]. They found that the mechanical properties of aluminum alloys seriously depend on the applied strain rate and temperature. Moreover, it has been reported that the fracture behavior of aluminum alloys, especially the damage evolution, also depends of the strain rate [17,18].

In fact, the mechanical behavior of materials depends not only on the strain rate, but also on its microstructure evolution [19]. As reported, the SRS of Al alloys is strongly associated with the transformation of precipitations and dislocations, which apparently affects the mechanical properties of materials [20]. The evolution of the

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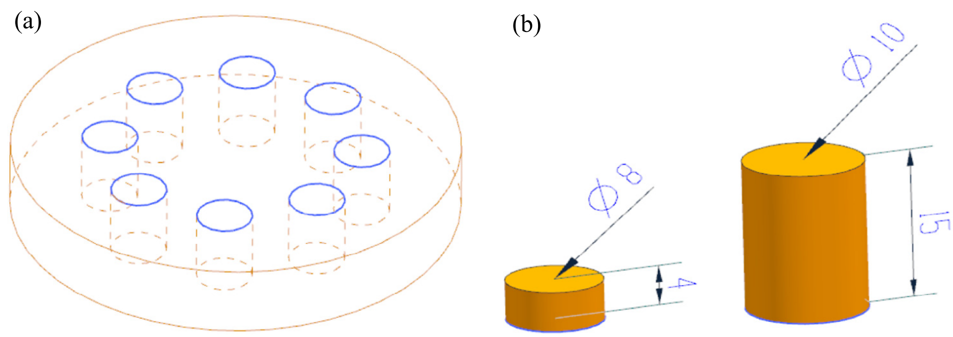


**Fig. 1.** (a) Schematic of samples cut from the as-received alloys, (b) dimensions for quasi-static and dynamic compression.

precipitates during a high loading impact is one of the important reliable indexes to determine the dynamic mechanical behavior of aluminum alloys. Previous works showed that the distribution and the denser of precipitates change during high strain rate deformation, which strongly affect the flow stress of the material [21–23]. It is acknowledged that high strains and strain rates can lead to the extension and transformation of metastable phase [24,25]. During impact tests, the coarsening of precipitates would adversely affect the mechanical properties. Moreover, various studies showed that the rate of dislocation multiplication increases with increasing strain rate and leads to a higher material strength. For example, under high strain rate loading conditions, the enhanced flow stress is the result of the generation and accumulation of dislocations in the deformed microstructure [26]. It has also been reported that the cell size and the number of dislocation undergo a great change for the alloy under dynamic compression [12].

However, up to now, there have been few works concerning the effects of heat treatment on the flow stress response of 6063 alloy, as well as the evolution of the microstructure during dynamic impact deformation. To warrant a good understanding of the microscopic mechanism of flow stress response under dynamic loading for the 6063 aluminum alloy at room temperature, a systematic study on the dynamic evolution of microstructure is extraordinarily necessary. The aim of current study is to investigate the flow stress response and the corresponding microstructure evolution of an as-casting 6063 alloy with different aging conditions over a wide range of strain rates based on the quasi-static and dynamic compression tests.

## 2. Experimental procedure

The material investigated was commercially semi-continuous casting 6063 aluminum alloy with the following chemical composition: Mg 0.65, Si 0.55, Fe 0.35, Mn 0.1, Cr 0.1, Ti 0.1, Cu 0.05, Zn 0.05, and a balance of Al (wt. %). The ingots were solution treated at 813 K for 50 min and water quenched to room temperature. After solution heat treatment, the 6063 aluminum alloy samples were kept in a freezer. This is effective to avoid the natural aging of the alloy at room temperature. In order to investigate the effect of aging treatment on the dynamic deformation behavior, the solution treated alloy was artificial aged (AA) at 453 K for 6 h and cooled naturally at room temperature. Cylindrical specimens for quasi-static and dynamic compression tests with size of ∅10 mm × 15 mm and ∅8 mm × 4 mm were cut from a 6063 plate and their relative positions are schematically shown in Fig. 1.

Quasi-static compressions in present work were conducted using a 100 kN MTS servo-hydraulic machine at strain rates of $1 \times 10^{-3}$, $1 \times 10^{-2}$ and $8 \times 10^{-1}$ $s^{-1}$, the corresponding data of force and length-reduction were automatically acquired by data acquisition system of MTS Test Suite 4.0. Dynamic compressive tests were performed by a SHPB system (Fig. 2) with strain rate ranging from 1500 to 3500 $s^{-1}$. During the tests, the samples were put between the incident and transmitter bars. The incident, reflection and transmission strain-time waves were recorded by a data collection system of the equipment. Based on one dimensional wave theory with an assumption that the sample deforms uniformly, the true stress, true

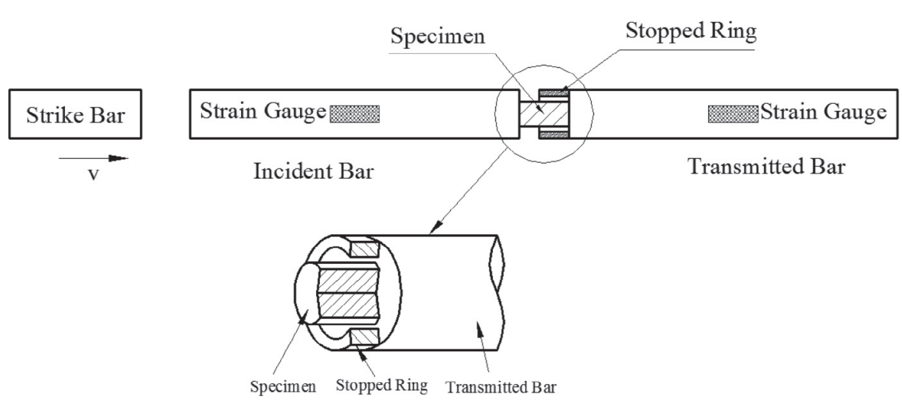


**Fig. 2.** Schematic illustration of the SHPB apparatus.