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Experimental investigation on yield behavior of PMMA under combined shear–compression loading

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The work experimentally studies the yielding behavior of polymethyl methacrylate (PMMA) at three different loading rates through a developed combined shear–compression test technique which contains a universal materials testing machine, mental blocks with double beveled ends (combined shear–compression loading setup) and a column sleeve made of Teflon. The results show that the failure loci agree well with theoretical predictions involving the strain rate dependence, which indicates the validity of this test method. Additionally, the experimental data enrich the previous experimental work about polymer yielding surface in the principle stress space.

Introduction

PMMA was a significant structural material of engineering components, therefore, information about the mechanical response of such material should be investigated. Some previous experimental studies dealing with the mechanical behavior of PMMA under simple loading conditions were reported [1–4]. Predicting the loaded response of PMMA under exterior loading is necessary to promote confidence in the service life of the material and allow informed design choices. In this case, a constitutive model is a useful tool for such predictions [5]. Establishment of this constitutive model is generally based on the confirmation of the failure criterion according to the traditional plastic theory [6–8]. For the cases under complex stress states, there were some experiments performed for the purpose of better understanding the yielding behavior [9–12]. Macroscopic failure loci of PMMA were determined experimentally and a relevant yield criterion was developed but limited to the shear–normal stress space [9]. Concerning the yield criterion of polymers, Drucker and Prager [13] proposed a yield function called MMP to describe the failure behavior of polymers, which was extended by Raghava et al. [14] and supported by Quinson et al. [15] with the experimental data of PS, PMMA and PC. Farrokh and Khan [12] developed the yield criterion proposed by Silano et al. [16], they experimentally investigated the yield behavior of semi-crystalline polymer–Nylon 101, then, an empirical hydrostatic pressure dependent yield equation was developed to simulate the behavior as a function of strain rate. Recently, in the aspect of the test technique about material yield behavior, Hou et al. [17] presented a combined shear–compression impact test for soft cellular materials designed in order to investigate their behavior under impact multi-axial loadings. The test setup consisted of two short cylindrical bars with one bevel end, resulting in the emergence of a transverse reaction force which could not be measured in the experimental design, so it was impossible to determine the multi-axial constitutive relation directly using the present biaxial loading device. To avoid this problem, a modified combined compression–shear test technique consisting of two short cylindrical bars with two bevel ends was developed by Zheng et al. [18]. Concerning the dependence of PMMA uniaxial compression strength on strain rate, some experimental [19,20] and theoretical studies [21,22] also point out that the yield and flow stresses of materials generally show a logarithmic dependence on deformation rate. Eyring theory provides the simplest explanation to this phenomenon by proposing that the thermal activation over an energy barrier decreases linearly with stress [23]. As the rate increases, less time is available for thermal activation, whereas the strength of PMMA increases in a non-linear fashion with the logarithm of strain rate [3,24]; this characteristic results in a more complex formation of the strain rate term. Therefore, a phenomenology-based strain rate dependent term following the power-law proposed by Farrokh and Khan [12] is applied in this paper to ensure convenience during engineering applications.

Given the lack of experimental data about PMMA yield surface in the fourth quadrant of principle stress space in previous investigations, it is necessary to capture the data within this range.

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Hence, this developed test technique was introduced to explore the yield behavior of PMMA under combined shear–compression loading. Simultaneously, the experimental outcomes were compared with the theoretical predictions.

Experimental procedure

The yielding behaviors of PMMA polymers (polymethyl methacrylate) under shear combined compression loading were taken into consideration. Plexiglas G PMMA specimens were produced through a traditional cell cast method, and thus no molecular chain orientation existed in the as-cast sheet [9,11]. In the tests, cylindrical specimens were identical and manufactured with the dimensions Φ10 mm × 5 mm, as given in Fig. 1. In order to fulfill this combined loading, an experimental approach [18] was employed as demonstrated in Fig. 1. Five kinds ($\theta = 0°$, 15°, 30°, 45°, 60°) of mental blocks with double beveled ends were applied for capturing the mechanical response of PMMA at different stress states. So as to grantee the accuracy of experiments, a column sleeve made of Teflon was used to fix the whole loading device. According to the ISO R257 standard, yield point was defined as the nominal maximum force reached by the polymer during uniaxial test. Systematically, three loading rates (5×10^{-3} mm s^{-1}, 5×10^{-2} mm s^{-1} and 5×10^{-1} mm s^{-1}) corresponding to three kinds of strain rates (10^{-3} s^{-1}, 10^{-2} s^{-1} and 10^{-1} s^{-1}) were also executed.

Results and discussions

Normal compression

In the case of normal compression, the normal stress and strain can be obtained from the following equations,

$$\sigma_n = \frac{F_{UTM}}{A_0}, \quad \varepsilon_n = \frac{S}{L} \qquad (1)$$

where F_{UTM} and S are the load and displacement signals output directly from the universal testing machine, respectively. A_0 and L are the initial cross-section area and length of cylindrical specimens. The results are shown in Fig. 2. The characteristic shape of the stress–strain curve is in agreement with the findings reported by other researchers [1,3,9]. The yield stress of PMMA is positively correlated with strain rates, meanwhile, Yong's modulus seems to possess the similar trend. Noticeably, there is a soften phenomenon after the yielding point especially for the case at the low strain rate, this may be owing to the fact that heat will be released during the compression, while the compression under a low strain rate offers more time for heat transfer, in other words, the specimen seems to be heated, which results in the soften phenomenon. In short, PMMA was observed to exhibit rate sensitivity of the failure behavior under compression.

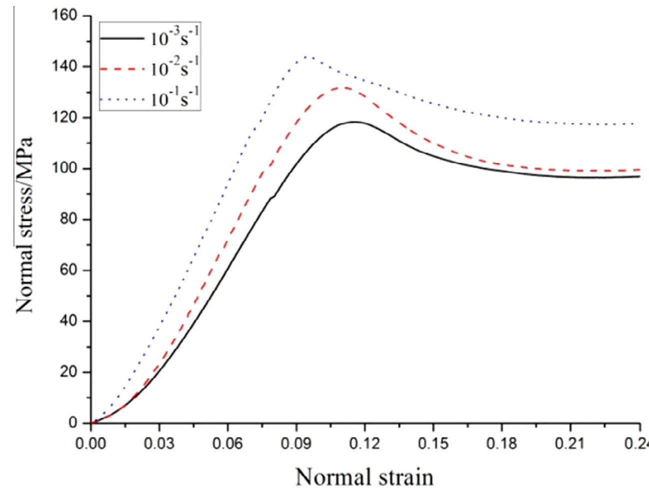

Fig. 2. Normal stress–strain curves at different strain rates.

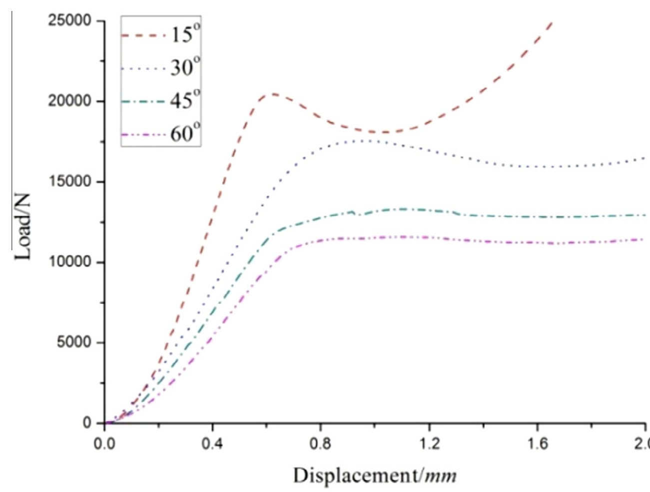

Fig. 3. Load–displacement curves at $\dot{\varepsilon} = 10^{-1}$ s^{-1}.

Shear–compressive test

Fig. 3 shows the load–displacement relationships at $\dot{\varepsilon} = 10^{-1}$ s^{-1}. From the figure, under the shear combined

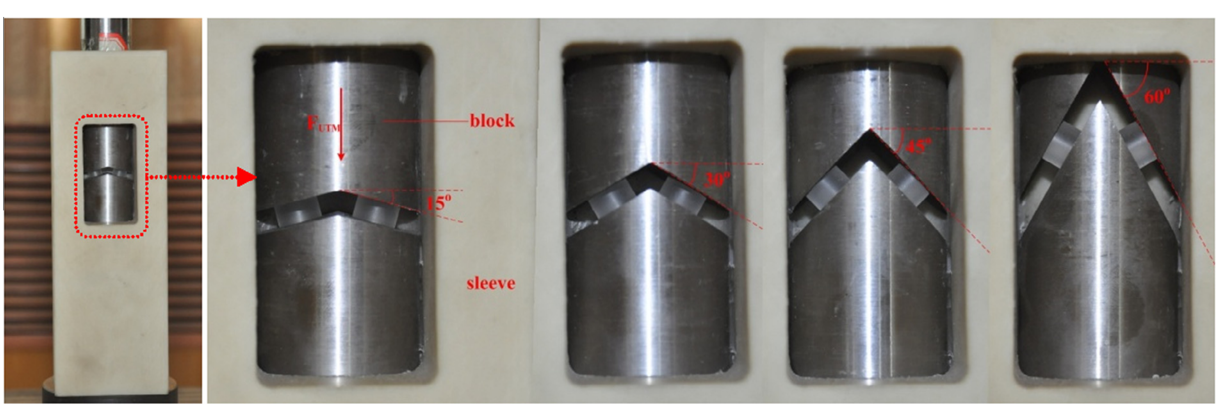

Fig. 1. Specimens and experimental device.