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Original Research Article

Ultrasonic vibrations as an impulse for glass transition in microforming of bulk metallic glass

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ARTICLE INFO

Article history:
Received 28 January 2018
Accepted 3 September 2018
Available online

Keywords:
Microforming
Ultrasonic
Bulk metallic glasses
Glass transition

ABSTRACT

The paper presents the idea of the utilisation of ultrasonic vibrations in microforming at elevated temperature of a bulk metallic glasses as an impulse of additional energy for initiating a glass transition at lower than nominal temperature. The method of micro-upsetting at elevated temperature with non-uniform temperature distribution (MUNUT) was used. It is shown that applying ultrasonic vibrations on the tool could replace the part of the thermal energy needed for achieving the supercooled liquid state necessary for the microforming of bulk metallic glass. The results of research are limited to the analysis of two micro-specimens only and their final state of deformation. The commercial FEM code was used in the Thermal/Structural analysis class to determine the temperature distribution within the micro-specimen and to justify the linear approximation of this distribution. It was shown that the application of ultrasonic vibrations at 20 kHz frequency and the amplitude PP = 36.5 μm under the experiment conditions lowered the transformation temperature by approx. 32 °C. Results suggesting that applying ultrasonic vibrations could be also used as the tool which would provide additional energy for the transformation at the limited area of the micro-product.

1. Introduction

Stormy development of Micro-Electro-Mechanical Systems cause a growing demand on the micro-parts of a high strength and dimension accuracy. The metal forming technology is well suitable to fulfil these requirements [1,2]. Reducing dimensions of products to the size of one millimetre causes appearing of so called "scale effects". Applied laws on a macro scale must be verified with reference to micro world. The scale effects concern not only the structure of material in the reference to the sheet [3,4] and bulk metal microforming [5,6] and conditions of friction [7,8] but also of a structure of pre-stressed micro-tools [9,10] and of conditions of brittle cracking of plastically deformed material [11]. Also tendencies of replacing large presses and tooling by the newly constructed piezoelectric driven super-precise micro-presses [12] and complex [13] or active tools [14] are being observed. Reduction

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https://doi.org/10.1016/j.acme.2018.09.001

of size of microformed products causes the considerable worsening of terms of friction and tendencies to the presence of the galling [15] phenomenon and creation of build-ups [16]. The new, dedicated to conditions of microforming, models of contact phenomena are being created [17], designed new lubricants [18] and protective layers [19] on mikro-tools [20]. A grain size and its orientation in the micro-billet cannot be neglected. Billet might than be compared as ‘‘compound billet’’ with consequences on non-uniform contact pressure distribution [21]. A long time ago it was noticed that the introduction of vibrations favourably affects contact phenomena [22]. In microforming the galling tendency can be broke and friction coefficient reduced. It is regarding either to the low frequency vibrations, about 50–250 Hz, [23] or ultrasonic vibrations [24]. This phenomenon is called ‘‘the surface effect’’ of vibration introduction. The development of microforming processes increased the interest in using ultrasonic vibrations as an additional energy supplied to the deformation zone. It is, to a large extent, caused, by practically the disappearance of energy limitations occurring in attempts to support by ultrasonic vibrations ‘‘classical’’ metal forming processes.

The history of trials to apply ultrasonic vibrations dates back to the 50s of the last century. Gale and Nevill (1957) [25] applied ultrasounds in a test of drawing low-carbon steel wire. Standing longitudinal waves were generated. Based on the research, they suggested that the observed decrease in yield stress is independent of the vibration frequency in the range of 15–80 kHz. Blaha and Langenecker (1959) [26] after similar experiments also stated that the "softening" of the material is independent of the frequency of vibrations when the frequency is from 15 kHz to 106 kHz. Their explanation was based on the fact that the frequency of vibrations in this range is much smaller than the own resonant frequency of the dislocation loop, which according to literature reports is usually about 109 kHz. The view that vibrations with lower frequencies than the natural frequency of dislocations can't directly affect their movement, and the softening effects are mainly related to the increase of temperature and/or the superposition of stresses was dominant for many next years. On the other hand, more and more studies showed the impact of ultrasonic assistance on parameters of microforming processes and properties of micro-formed products. Ultrasonic-vibration can reduce the ECAP [27] and micro-extrusions [28] forces when friction is eliminated a can increase the temperatures of a material at the same time. Increasing temperature by ultrasonic-vibration may reduce the flow stress, but may increase the interfacial friction in hot and cold micro-upsetting [29]. However, in some cases, the maximum oscillatory forming force can exceed the static forming force [30]. The use of ultrasonic vibrations in relation to microformed objects can also cause specific macroscopic consequences in terms of cracking. Investigating samples made of hardened aluminium, Presz and Cacko (2017) [31] observed the formation of many parallel fracture surfaces being ‘‘on line’’ welded during micro-upsetting process. With the increase in the number of investigations and their accuracy, the view of the direct impact of ultrasonic vibrations on the structure of the deformed material in isolation from the simple increase in temperature began to prevail. Daud et al. (2007) [32] investigated the process of upsetting and stretching of aluminium samples. They found that the decrease in yield stress at the time of adding ultrasonic vibrations to the static load cannot be explained only by the superposition of stresses and deformations and the decrease of friction on the contact surface with the vibrating tool. Siddiq and El Sayed (2011) [33] introduced factor of ultrasonic softening in previous known constitutive equations. Then, conducting FEM simulations showed the effect of the amplitude of vibrations on the, generated by these vibrations, rotation of grains around all 3 axes. Siu and Ngan (2011) [34] conducted 2d and 3d simulations of the dynamics of dislocations. Based on the analysis and experimental research, they suggested that an important mechanism having a large share in the observed reduction of yield stress supported by the use of vibrations is the annihilation of dislocations. Lum et al. (2009) [35] investigating the deformation of gold balls using an ultrasonic welding machine for wire, found the presence of both curing and softening effect in the presence of ultrasonic vibrations. Curing was interpreted by the multiplication of dislocations, but also by the formation of point defects much earlier observed in KCl crystals by Tyapunin et al. (1980) [36]. The latest and groundbreaking information is the result of investigating the process of stretching aluminium specimen with the application of transversely introduced ultrasonic vibrations. Abhishek et al. (2017) [37] proposed modification of (previously proposed) constitutive models [38], including thermal activation of dislocation motion. They suggested that ultrasonic vibrations affect the activation energy by generating additional lattice vibrations that facilitate dislocation movement. An important but rather isolated report is the suggestion of the impact of ultrasonic vibrations on phase transitions and in consequence on the dislocation movement. Myshlyaev et al. (2015) [39] suggested the impact of ultrasonic vibrations on dislocation motion inside the grains during stretching of aluminium-lithium alloys under superplastic conditions. They associate it with the induced phase change leading to blocking the dislocation motion by ultrafine precipitates of a new phase at the grain boundaries. Zhou et al. (2017) [40] conducted an EBSD test to investigate the effects caused by ultrasonic vibrations during upsetting of aluminium and titanium. They found that for aluminium, the vibrations reduced grain size and changed their orientation. Both effects were found to result in hardening of the samples.

Use of high-intensity ultrasonic vibration can induce severe plastic deformation and improve the grain refinement efficiency. Liu et al (2013) [41] found that the grains of the specimens processed by the ultrasonic upsetting process were refined to even 100 nm. Reducing the grain size of the material is considered a beneficial phenomenon and increases the dimensional accuracy and surface quality of micro-products [42]. Can happen that grain size has no influence on mentioned features [43] or even that the increase of a grain size improves a product quality [44]. There is then however an exceptional situation and in most processes aspires to application of materials with possible smallest grain – ultra-fined grained. Following this path of thinking it is begun to apply in microforming processes amorphous materials, namely bulk metallic glasses [45]. These materials exhibit some unique physical properties as compared to their corresponding crystalline alloys [46,47]. They behave like a Newtonian fluid in their supercooled liquid region. This feature has been successful used for example by Wanga et al (2010) [48] and Quiang et al (2012) [49] in net-shape microforming