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A new methodology for evaluation of mechanical properties of materials at very high rates of loading

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Abstract

This paper focuses on the development of a straight forward and inexpensive testing machine, and methodology for the characterization of materials in working conditions similar to those found in metal cutting. Special emphasis is given to the material rate dependence and to the assessing of the proposed methodology against conventional testing at very high rates of loading. The experimental results have demonstrated that rate-dependent hardness can be used to estimate flow stress at high rates of loading and that contact phenomena become even more prominent for severe monotonic deformation.

Keywords: Mechanical characterization; Testing machine, Experimental methodology, Flow stress, Material hardness, High strain rate effect; AA1050.

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1. Main text

Flow stress is among the most determining input data for the numerical simulation of metal cutting. This instantaneous material response is governed by a complicated interaction of several factors such as microstructural evolution, deformation-history and temperature. There are many constitutive models that can be used to deal with material response modelling; some physically-based models have been proposed to correlate metallurgical or physical aspects with corresponding constitutive description [1]. However, this class of constitutive proposals demands a large number of experimental tests, requires complex optimization algorithms and large computational efforts to find associated model constants, and not always have an adequate outcome [2]. Therefore, material is assumed to be both continuous and isotropic, and less intricate semi-physical constitutive models, also known as phenomenological [3], as well empirical equations are used under the explanation of its simple form and good prediction characteristics. This is probably the reason why most of works in the literature have adopted the empirical Johnson–Cook constitutive model for the numerical simulation of metal cutting [4]. The literature seems also to show that model calibration for metal cutting simulation brings up some outstanding issues [5]. Severe plastic deformation through shear plane under high strain rates and temperatures tends to make the material characterization challenging. Because of this, inverse identification of the material parameters based on orthogonal machining tests carried out in advance is often used as an alternative approach for the calibration of constitutive models. But though inverse identification may allow a more efficient calibration from the viewpoint of the implementation effort, avoiding the costly and complexity of the experimental requirements, it is important to mention that obtained parameters include additional contributions not directly related to the plastic deformation (such as the tool geometry, friction,

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fracture toughness, etc). In fact, some researches claimed that even although material parameters may be made to achieve a satisfactory correlation with the measured process parameters (such as the cutting force, shear angle, chip curling, etc), it is impossible to match all at the same time [6]. Consequently, there is an increased need for new easy-to-perform and low-cost mechanical testing methodology, to allow direct and fast identification of the material parameters and promote the predictive capability of numerical simulation models.

Compression of solid cylinders is often used to assess the material parameters for the constitutive models. This simple mechanical test (usually performed quasi-statically) is obviously not representative of the levels of strain-rate and temperature that are currently attained by industrial metal cutting operations. As a result of this, some alternative testing procedures have been proposed, with emphasis for experimental high speed equipment such as Taylor's impact tests or Hopkinson's compression and shear devices, among others. These devices can provide working conditions close to machining, but some of them are based on inverse analysis techniques while others need expensive experimental apparatus only available on a limited number of research laboratories. Depending on the chosen technique, it will have advantages but also disadvantages depending on how it is employed, especially lack of knowledge in how other parameters such as friction coefficient can affect the results. Considering these constraints several researchers have been working to improve testing methods, yet there is still plenty of scope for further development in this area [5].

The abovementioned difficulties to obtain the flow curves at appropriate rates of loading justify the following two-fold goal of this paper: (i) to propose an experimental methodology to estimate flow stress at the appropriate rates found in real metal cutting and (ii) to validate the referred methodology against direct measurements of the flow stress. The proposed low-cost testing methodology is intended to be easy-to-perform at any research laboratory since there are no special requirements. This proposal is based on traditional indentation hardness test that is a well-known and highly accepted methodology for mechanical characterization at quasi-static conditions. Here it is used to assess the so-called strain rate history effect [7, 8] which means that strain rate plays an important role on key microstructural features, such as grain refinement, accumulation, arrangement of dislocations and dynamic failure mechanisms [9, 10].

The overall presentation is supported by specially designed compression experiments that were performed on aluminium alloy AA1050 test specimens in a full annealed condition under laboratory-controlled conditions. The testing machine was designed and fabricated by the authors; constructive details are given for those readers that may be interested in developing a low-cost equipment for mechanical characterization at high rates of loading. The flow stress of the aluminium alloy AA1050 is estimated by using the yield stress from static Vickers hardness and the obtained results are compared with those from high strain rate testing. Another important consideration, which is not explicitly addressed in the manuscript but is implicit in the proposal, is that frictional contribution plays a central role, above and beyond instantaneous flow stress rate-sensitivity. For that, a quick-stop device is also proposed which, will contribute towards further reducing frictional contribution on the plastic flow. Interrupted compression tests have allowed to clean and lubricate the contact interface for each incremental deformation. Real flow stress is expected to be much closer to yield stress at metastable conditions (after compression test) than to instantaneous flow stress under frictional influence (during compression test).

2. Experimental background

The material employed in the experimental tests was an aluminium alloy AA1050 (99.5% wt) with metallurgical properties resulting from annealing at 450ºC (2h followed by natural cooling in air). The initial grain size of the specimens after annealing were measured by metallographic examination and it was found to varies from 100 to 300μm. The stress–strain curves were obtained by means of compression tests carried out at room temperature on cylindrical specimens with 6mm diameter and 6mm height. The plan of experiments was designed in order to characterize the flow stress for a wide range of loading rates, and were carried out in a universal testing machine (quasi-static) and in a home-made equipment specifically intended for this research (high velocity).

The gas gun machine designed and implemented by the authors is schematically showed in Fig. 1. The main components can be divided into two main groups; (i) basic structural parts, and (ii) specific pneumatic and mechanical parts. No additional displacement monitorization or force sensors are required because of material strength and specimen deformation can be measured afterwards, and a more substantially compact design can be implemented. Basic structural parts comprise components such as the support table (bench), the guiding supports, and the pneumatic linear bearings, which are independent of the type of testing (e.g. monotonic or interrupted tests), operation conditions and materials to be characterized. These components are always to be used. Specific pneumatic and mechanical parts comprise those components such as the pressure vessel, the launcher tube, the striker bar, the quick-stop device (compression limiter) and the rubber dumper, whose design may be dependent on the type of testing, operation conditions and materials to be characterized. In general terms, currently installed compressed gas gun testing machine consist of two slender cylindrical bars of the same diameter, called the transmitter bar (motionless bar) and the striker bar (shorter cylindrical projectile). The compression plates used in the experimental tests have been machined and polished in order to limit surface roughness below $Ra < 0.1\mu m$. The control of asperity interlocking is important to promote uniform material expansion and homogeneous plastic deformation.

The striker bar is launched by a sudden release of the pressurized gas present in the pressure storage vessel and accelerates in a linear tubular guide until it impacts on the test specimen. The incident bar velocity is controlled by the gas pressure while the strain increment is limited by the quick-stop device (high strength metallic washer) defining the final height of the deformed specimen. Several configurations were used to evaluate the influence of the plastic strain on the material