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Development of an improved method for identifying material stress–strain curve using repeated micro-impact testing

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ABSTRACT

Impact-based Mechanical Surface Treatments such as shot peening are widely used in aerospace, nuclear and other industries to improve the mechanical resistance of components. Measuring the stress–strain curve of materials under high-strain rate using repeated impacts is a key issue to improve such processes. This study presents an extension of a method developed by Kermouche (2013) for identifying the material stress–strain curve. It combines numerical and experimental approach using micro-impact testing. The main originality of the present work is the use of the impact load values instead of the depth of the residual imprint as an input parameter of the inverse identification. The reliability of the proposed method is then checked from a set of numerical blind tests. A direct method derived from Tabor's pioneering work (Tabor, 2000) is also proposed to convert the impact measurements into an approximate stress–strain curve. These two methods have been applied on a commercially pure copper and show very good agreement. The main advantage of this analysis is to determine the mechanical behaviour of metallic surface at high strain rate using limited numbers of samples and tests.

1. Introduction

Shot peening is a surface treatment process used in many industrial branches to improve the mechanical properties of materials by producing a compressive residual stress from the projection of spherical balls at high speed (between 100–500 mm.s^{-1}). The ball impacts result in large plastic deformations on the treated area that induce surface hardening and beneficial compressive residual stress (Abramov et al., 1998). To further develop this process or apply it to new alloys, a better knowledge of the behaviour of materials under similar process conditions is required. In particular, the determination of the stress–strain curve at high strain rate is of main interest for prediction of strain and residual stress fields.

Several techniques are available to determine the mechanical behaviour of materials subject to high speed loadings. Among them Hopkinson bar testing is the most widely used (Jaspers and Dautzenberg, 2002). However, it requires specific samples that are material and cost consuming. Moreover the resulting stress–strain curve corresponds to bulk behaviour and does not take into account the effect of surface preparations or surface treatments. It therefore cannot be used to accurately describe the shot-peening process for example. For these reasons, other kinds of mechanical testing have been developed. Some works (Beghini et al., 2006; Collin et al., 2009, 2008) deal with the use of instrumented indentation tests under single or repeated load cycles for determining the stress–strain curve of material. However shot peening consists of a dynamic high speed impact which cannot be repeated in the case of quasi-static methods such as static indentation methods. Other works (Subhash et al., 1999;

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Sundararajan and Tirupataiah, 2006; Tirupataiah and Sundararajan, 1991) are based on the use of specific dynamic indentations performed on instrumented nano-impact tests. More specifically Lu and al. (Lu et al., 2003) studied the load-depth response of dynamic indentation to determine the strain-rate sensitivity of metals. However it's proved to be costly and challenging especially when the penetration depth is required, which limits their practical use.

In our previous works (Kermouche et al., 2013; Lamri et al., 2010; Sekkal et al., 2005), an experimental setup was designed, based on a commercial micro-marking device (CN312C Technifor®), that projects a spherical indenter with controlled displacement. Combining measurements of radius and depth of the residual scar as a function of the impact number and a database containing the results of numerical simulations, it was possible to extract the stress–strain curve of the impacted material for a strain rate in the range of [100–1000] s^{-1}.

However, the determination of the depth of the residual imprint requires 3D measurements which could be time-consuming and/or inaccurate. This paper presents a new inverse identification which uses the impact load values instead of the depth values. The reliability of the proposed method is then checked from a set of numerical blind tests.

Then, the method is applied on commercially pure copper. The obtained results are then compared to a direct identification based on Tabor pioneering work (Tabor, 2000) and on the model proposed by Kermouche et al for sharp indentation (Kermouche et al., 2008), the latter being based on a direct analysis of the impact tests.

2. The repeated impact set-up

The repeated impact device Fig. 1 has been extensively described in previous papers (Kermouche et al., 2013; Lamri et al., 2013). Thus only the main features are described in this paper. An electromagnetic system pushes a rigid indenter (spherical end) into the sample surface at high speed and normal incidence. The power control of the electromagnet as well as the initial distance between the indentor and the samples allow to settle the impact energy. During this work, 2 mm diameter Zirconia balls (grade 10) ($E = 200$ GPa, hardness: 800 Hv) have been used as an impacting tip, leading to a total indenter mass of 169.9 g.

As the impact frequency (controlled by electromagnets) is kept constant at 10 Hz and impact durations are in the 10 sec range, ultra-fast displacement sensor (EOTECH SA) tracks the movement of the ball before, during and after the impact, then the indenter velocity can be deduced from the displacement of the indenter. Considering the indenter weight, the kinetic energy can be determined by $E_{impact} = mv^2/2$, where m the indenter mass and v the indenter speed when it hits the sample surface. During each impact, the normal component of the induced load is recorded using a piezoelectric load sensor (KISTLER). The impact load ranges from 50 to 2500 N. The technical characteristics of the two sensors were specifically chosen to be relevant with the impact conditions (impact duration, repetition frequency, measuring range...).

The usual impact energy ranges from [1 to 21] mJ, which corresponds to an impact speed of 100–500 mm/s and thus to a representative material strain rate equivalent to [100–1000] s^{-1}. The letter can be computed as the ratio between the normal impact speed and the contact radius. This representative material strain and its definition that can appear quite simplistic is frequently used in indentation studies as the strain rate field is not homogenous and does not depend on time (Kermouche et al., 2013).

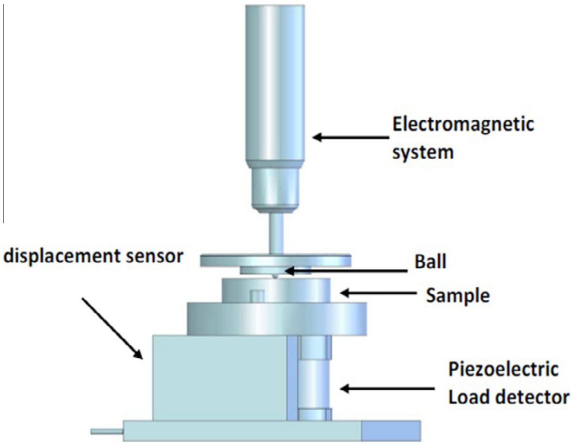

Fig. 1. Instrumented impact testing device.

3. Finite element model

3.1. Presentation

Repeated impacts have been modelled using non-linear dynamic axisymmetric simulations in Abaqus Explicit (Systems, 2011). The mesh has been created using linear elements with different grades. It has been specially refined near the contact zone (Fig. 2) in order to get more accurate radius and load values.

The tested substrate is an elastic-plastic solid considered as semi-infinite with isotropic hardening work. It

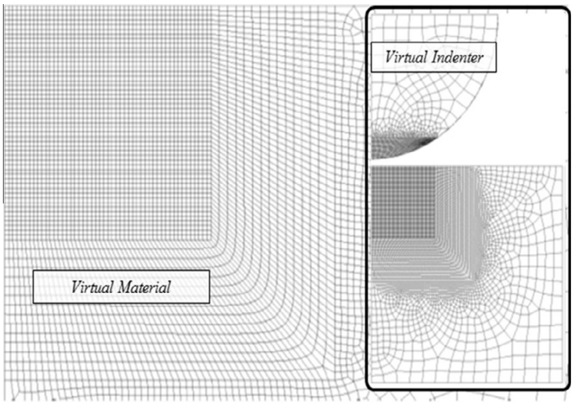

Fig. 2. Finite element model.