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Investigation of indentation-, impact- and scratch-induced mechanically affected zones in a copper single crystal

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Many nanomechanical testings and surface mechanical treatments—burnishing, shot peening...—are based upon contact phenomena such as indentation, impact and scratch loadings. In this paper, the Mechanically Affected Zone (MAZ) induced by these standard contact loadings applied on a single crystal copper is investigated. We assume that the MAZ can be characterized by the lattice misorientation measured using backscattering electron diffraction. With the help of a Finite-Element analysis, it is shown that crystal plasticity theory can estimate with enough accuracy the lattice misorientation pattern. Experimental results highlight that the MAZ size is always related to the residual imprint dimension and its shape depends strongly on the kind of loading.

1. Introduction

Indentation, scratch and impact loadings are standard contact phenomena commonly used to characterize the mechanical properties of materials at the micro or nanoscale. Instrumented indentation testing is the most popular technique to determine local quasi-static mechanical properties [1–4]. Standard indentation testing is unfortunately unable to identify high strain-rate-dependent mechanical properties, and in this case, impact-based methods such as dynamic indentation or micro-impact testing [5–7] are more adequate. Identification of medium-to-large-strain mechanical properties is out of the scope of indentation and impact-based testing. For the medium strain range, microcompression testing is an available solution, but the fabrication of the micro-pillars and the running of the tests are expensive, time-consuming and require special care [8–10]. Scratch tests are a promising alternative because of the large strains induced in the near-surface without requiring specific cares to the test procedure [11–13]. Nevertheless, indentation, impact and scratch are non-homogeneous loadings and thus the relation with the sample stress–strain curves is not explicit. There is still today numerous works dealing with this topic [14–16], showing the need to better understand the responses of materials under such kinds of loading.

Indentation, scratch and impact loading types are also involved in many surface mechanical treatments. Surface treatments are usually connected with the modification of the surface properties by various actions of physical, chemical, thermal or metallurgical origin (quenching, nitriding...). However, mechanical loading may also result in modifications such as the

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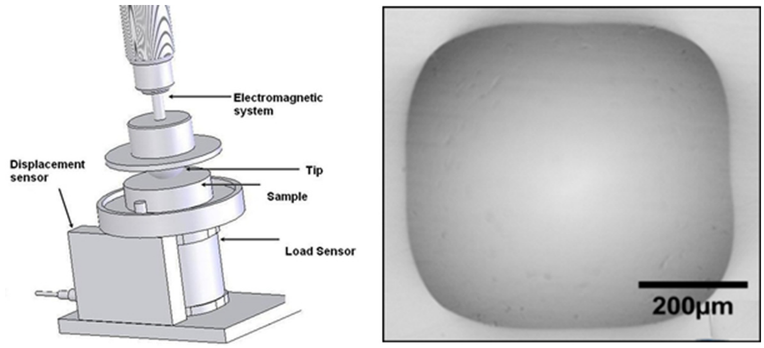

Fig. 1. Left: micro-impact set up [7], right: residual indent imprint resulting from a Brinell test (2.5 mm, 100 N) on a single-crystal copper surface ({100} face). The square-shaped imprint (not shown here) is also observed under impact loading and is a consequence of the single crystal anisotropic plastic flow.

creation of compressive residual stress fields [17–19] or refinement of the micro-structure [20,21] without any thermal or chemical phenomena. We distinguish treatments based on normal or quasi-normal contacts (like indentation, impact) such as shot peening [22–26] or hammering, and treatments based on tangential contacts (like scratching) such as burnishing [27–29] and polishing [30,31]. The understanding of the response to such contact loading types in terms of residual stress or in terms of induced microstructure changes is of primary importance in the context of the optimization of surface mechanical treatments.

This paper aims at characterizing and comparing the shape and the size of the Mechanically Affected Zone (MAZ) induced by indentation, impact and scratch loadings. The MAZ corresponds to the zone in which the microstructure was altered by the mechanical treatment. This concept defined in the present paper has been inspired from the well-known Heat Affected Zone (HAZ) induced by welding processes [32] or the Thermo-Mechanically Affected Zone (TMAZ) induced by friction stir welding processes [33]. One important issue is to find a reliable method to characterize the MAZ in such processes. For instance, the MAZ could correspond to the zone where severe plastic deformation occurs under repeated contact [34–38]. Nevertheless, this definition is not able to take into account the residual stress field zone [18], this last being also a consequence of small plastic deformation, not detectable by means of standard metallurgical characterization methods. In this paper, we propose to investigate the MAZ by means of the lattice misorientation measured using backscattering electron diffraction [39]. The drawback of this approach is that it is quantitative only if it is used on a single grain with no initial misorientation. This is the reason why we investigated the effect of these different loadings on a copper single crystal.

First, the sample preparation and experimental set-up are presented. A physically-motivated Crystal Plasticity Finite-Element Model (CPFEM) based on the works of Kubin et al. [40–42] is then detailed. Comparison of the CPFEM and the experimental lattice misorientation field is conducted for indentation loading over the cross-section of the residual print. It is then extended to the analyses of impact and scratch-induced lattice misorientation field, using the same contact geometry—i.e. equivalent ratio contact radius over ball radius. The difference between these three kinds of loading is then discussed in terms of size and shape of the resulting MAZ.

2. Materials and methods

A copper single crystal was produced by directional solidification using a standard zone melting method based on a horizontal Bridgman-type apparatus. The indented, impacted and scratched surfaces were {100}, oriented along the direction of the surface normal.

The indents were carried out using a standard Brinell Hardness set-up. The ball diameter is 2.5 mm and the maximum indentation load used was 100 N. Because of the anisotropic plastic flow of fcc single crystals, the resulting imprint is square-shaped as expected [43–46]. In the sequel of this paper, the term *imprint diameter* will refer to the side length of the square in order to be consistent with the literature about indentation testing.

The impacts were performed using the micro-impact set-up detailed in previous studies [16,7]. This device allows one to measure with high accuracy the impact speed and thus the impact energy (Fig. 1). The equivalent impact strain rate could be estimated as being proportional to the ratio between impact speed and contact radius. In the present investigation, the ball diameter is 2 mm, the impact speed was set to 100 $\text{mm}\,\text{s}^{-1}$. The resulting equivalent strain rate was estimated to be close to 100 s^{-1} using the relation proposed by Mok et al. [5]. Note that the imprint was also observed to be square-shaped similarly to static ball indentation.

Scratches were produced in a Hermle C800 machining center using an Ecoroll roller burnishing system 2, composed of a high-pressure hydraulic pump and a roller burnishing tool with a 6-mm-diameter ceramic ball. Similarly to impact testing, the equivalent strain rate could be approximated by the ratio between sliding speed and contact length. The scratching speed was set to 15 $\text{mm}\,\text{s}^{-1}$ and the resulting equivalent strain rate was estimated at 20 s^{-1} using the residual groove width (Fig. 2).