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Technical Paper

The anvil effect in the spherical indentation testing of sheet metals

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ABSTRACT

Spherical indentation hardness tests are widely used in manufacturing industry to obtain material property of the workpiece. For the indentation test on sheet metals, significant error can occur in measuring the penetration depth due to the anvil effect. This anvil effect is manifested with decreasing specimen thickness and increasing indentation depth. As micro/nano indentations are not suitable alternatives for measuring bulk material property, the present work critically reviews the experimental observations and studies the mechanism of anvil effect with numerical simulations. The results suggest that, when the thickness of the specimen is reduced, a change in deformation mode is experienced during the indentation process. A correction method for the anvil effect is proposed and an empirical equation is derived to determine the effective indentation depth. The experimental and numerical investigations have important implications for the interpretation of the anvil effect in indentation tests; and the developed method can be used to obtain accurate material property from a common hardness test without resorting to the use of instrumented indentation method.

Introduction

The hardness of a material is one of the most important material properties. It is a measure of how resistant the material is to permanent shape change when external load is applied [1]. Indentation hardness tests are performed in almost all the manufacturing industries. It is non-destructive, adaptable to any specimen shape, and is easy to perform. However, to carry out hardness tests on sheet metals, it is important to keep the indentation depth below a certain critical value, since the anvil is normally harder than the sheet metal and large penetration depth will introduce the anvil effect into hardness measurements [2].

To avoid such flawed measurements, a common rule indicated by both ASTM Standard E10-27 and E18 [3] is followed. The "rule of thumb" suggests that if the thickness of the specimen is more than ten times the depth of the indentation, the influence of the anvil in resisting the indentation deformation could be ignored, and the hardness reading obtained from the test is very close to the true hardness reading of material [4]. However, it was reported that this "one-tenth of rule of thumb" does not always ensure the absence of the anvil effect. It was also demonstrated that the critical ratio of the specimen thickness to the indentation depth varies significantly for different material types of sheet metals [5] and for different specimen to anvil yield strength ratios [6,7].

Significant efforts have been made to obtain the critical thickness of the thin sheet metals for indentation test, better understand the anvil effect, and evaluate the effect of the thickness on the accuracy of the hardness measurement [8,9]. Comprehensive studies were conducted on establishing an expression for material properties, thickness of the specimen, applied load, and dimension of the spherical indenter [10–12]. However, no study has been carried out to rectify the error introduced by the anvil effect in terms of correcting the hardness measurement of sheet metal in the spherical indentation test.

Some research has been conducted on hard substrate coated with thin films [13–16]. Finite element method was used to investigate the effect of the radius of a spherical indenter on the critical indentation depth of a hard thin film in order to avoid the influence of the substrate [17–19]. While the studies have resulted in many advances in the field of thin film deposition on a substrate, the indentation response is significantly different from that found in the hardness test of sheet metals; as the thin sheet is not adhere to the anvil, whereas the coating is adhere to the substrate [20]. Furthermore, the nano and micro indentation techniques used in these studies evaluate material in an extremely localized area [21,22]. Therefore, their ability to evaluate the bulk material property is limited. In contrast, the conventional macro scale hardness tests use

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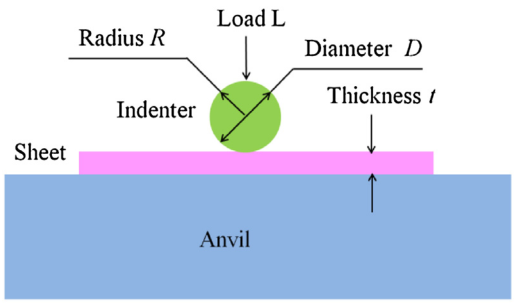

Fig. 1. Schematic of indentation system.

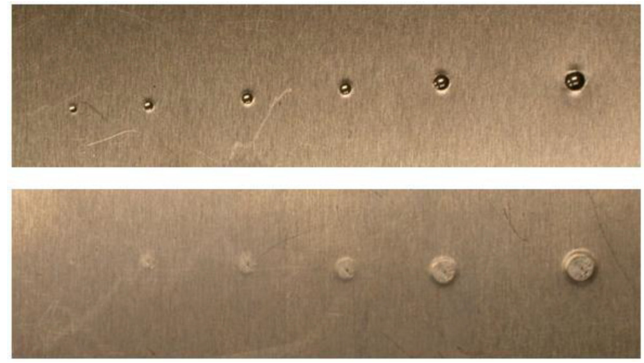

Fig. 2. Surface image of top and bottom faces of 0.813 mm thick Al 3003-H14 sheet metal indented with loads of 15, 30, 45, 60, 100, and 150 kgf (from left to right).

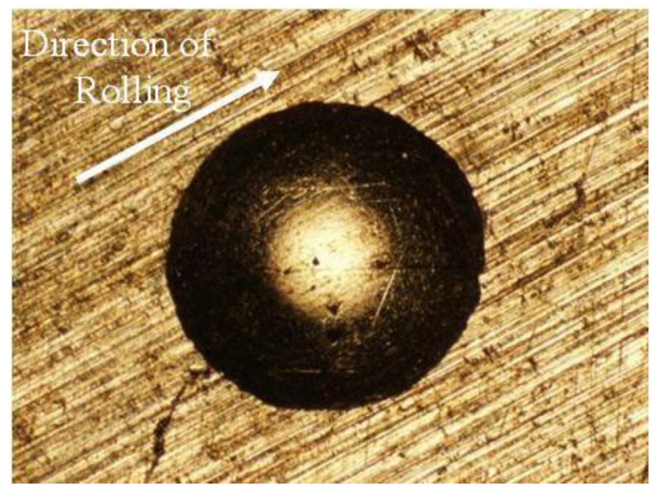

Fig. 3. Microscopic image of an indentation from a 3.175 mm diameter indenter on the 0.813 mm thick Al 3003-H14 sheet metal. (a) Al 3003-H14 (b) Al 6061-T6.

large indenters to ensure that each impression covers many grains. Thus, the macro scale tests provide a much better indication of the sheet metal properties for manufacturing applications.

For the spherical indentation test, it is often desirable to obtain the true hardness measurement of the sheet metal without the involvement of anvil effect. It was demonstrated that the instrumented indentation methods are able to address this need [23–25]. In these indentation tests, the mechanical responses of the specimens are continuously monitored, and the material property data are extracted from the load-displacement curve. Such approach was demonstrated by Kim et al. [26] to evaluate the material properties of high-strength materials. It is also shown that, with instrumented indentation, the use of a spherical anvil and adequate theoretical correction can be a solution for measuring the property of thin specimen with curvature [27].

The current work was motivated by the need for a better understanding of the deformation of sheet metals during an indentation test, as well as developing a correction method for hardness measurement when anvil effect is present, without resorting to the use of expensive instrumented indentation methods. The spherical indentation tests were carried out to evaluate anvil effects for different specimens under various applied loads and indenter dimensions. Numerical simulation of the indentation process was performed to understand the deformation of specimens and to quantify the anvil effect. A method to correct the indentation depth is proposed and the developed procedure is verified with further confirmation tests.

Experiments

Macro-spherical indentation testing is a well-established method to measure the hardness of sheet metals. The schematic of the indentation testing system is shown in Fig. 1. In this work, the Brinell and Rockwell type hardness tests were used to study the anvil effect aiming at correlating various testing parameters to the hardness property of sheet metal.

Experimental set-up and specimen preparation

The indentation tests were carried out on two general purpose aluminum alloys Al 3003-H14 and Al 6061-T6. Three different metal sheets were tested for each material, and the thicknesses of sheets were 0.813 mm (0.032″), 2.030 mm (0.080″), and 1.270 mm (0.050″). Two hardened steel ball indenters with diameter of 3.175 mm and 10.000 mm were used to make indentations. The indentation loads were applied for 30 s at different locations on the specimen. The loads were increased stepwise as per the following list: 15, 30, 45, 60, 100, 150, 500, 1000, and 1500 kgf. The diameter and depth of the indentation were measured using an OLYMPUS STM6 3D measuring microscope. This optical microscope has a very fine resolution of 0.0001 mm in x, y, and z directions. The depth of the indentation was measured as the vertical distance between the center of the impression and the edge of crater. This is achieved through focusing on the two locations and taking the difference of the focus distances. The anvil used in all the experiments was a flat and circular plate made of steel.

Experimental results

As the indentation load increased, an indentation mark started to appear on the bottom face of the sheet metal. Surface images of top and bottom faces of the sheet metal were taken in order to study the effect of increased load on marks. Fig. 2 shows the surface image of 0.813 mm thick sheet metal made of Al 3003-H14 tested under an indenter with diameter of 3.175 mm. It is clearly seen that the mark started to appear under the load of 30 kgf, and became more apparent with the increasing load. The shape of the indentation was not perfectly circular but was rather elliptical as shown in Fig. 3. The elliptical shape of indentations was observed for both materials and for all loads with its diameter being larger in the longitudinal direction (rolling direction) than in the transverse direction (direction perpendicular to rolling direction). This is due to different material properties in two directions causing different amount of springback after the removal of the indentation load. In this work, only properties in the longitudinal direction were considered.

The variations of indentation depths with applied loads on Al 3003-H14 and Al 6061-T6 sheet metals with different thicknesses are depicted in Fig. 4(a) and (b). In both cases, the first six loads were applied using an indenter with diameter of 3.175 mm, while