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Examining the microtexture evolution in a hole-edge punched into 780 MPa grade hot-rolled steel

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ABSTRACT

The deformation behavior in the hole-edge of 780 MPa grade hot-rolled steel during the punching process was investigated via microstructure characterization and computational simulation. Microstructure characterization was conducted to observe the edges of punched holes through the thickness direction, and electron back-scattered diffraction (EBSD) was used to analyze the heterogeneity of the deformation. Finite element analysis (FEA) that could account for a ductile fracture criterion was conducted to simulate the deformation and fracture behaviors of 780 MPa grade hot-rolled steel during the punching process. Calculation of rotation rate fields at the edges of the punched holes during the punching process revealed that metastable orientations in Euler space were confined to specific orientation groups. Rotation-rate fields effectively explained the stability of the initial texture components in the hole-edge region during the punching process. A visco-plastic self-consistent (VPSC) polycrystal model was used to calculate the microtexture evolution in the hole-edge region during the punching process. FEA revealed that the heterogeneous effective strain was closely related to the heterogeneity of the Kernel average misorientation (KAM) distribution in the hole-edge region. A simulation of the deformation microtexture evolution in the hole-edge region using a VPSC model was in good agreement with the experimental results.

1. Introduction

Recent demands for weight reduction in automobiles have increased globally because of environmental problems associated with global warming. To satisfy the demand, the automotive industry has ceaselessly pursued efforts to meet requirements such as passenger safety, fuel economy, and a reduction in CO_2 emissions via automotive weight reduction [1,2]. With respect to automotive parts, techniques for weight reduction have maximized the advantages of high-strength steel (HSS) [1,3–5]. The chassis of a car occupies >22% of its total weight and must support the engine, absorb road vibration, and protect the passengers [6–8]. Therefore, improving automotive performance via weight-reduction must be approached from various points of view, and weight-reduction in the chassis must not compromise the strength of this essential portion of a vehicle. Hot-rolled steels with a 370–440 MPa grade of tensile strength (TS) have been mainly used for steel chassis parts. In recent years, dual phase (DP) steels of TS-590 MPa grade and ferrite-bainite (FB) steels of TS-540 or 590 MPa grade have improved in elongation and stretch-flange formability, and their application has gradually increased in the subframe, frame arms and wheel disks. Applications of TS-780 MPa grade hot-rolled steels also have continually increased [2,6–8]. Flange and burring parts that are fabricated via hole-expansion processes have greatly enhanced the fatigue performance of automotive parts and automotive safety. In the hole-expansion process, the stretch-flange formability of a material can be evaluated via the hole-expansion ratio (HER) extracted from hole-expansion testing [9–11]. Before conducting the hole-expansion test, a 10 mm diameter hole must be punched in the steel. The hole-edge region will be severely deformed by the punching of the hole. Therefore, the heterogeneous deformation and micro-void formations near the punched edge of the hole will deteriorate the HER [12]. A hole-edge fabricated by punching is composed of rollover, a sheared zone, a fracture zone, and burrs [13–15]. Sheared- and fracture-zones exhibit different fracture behaviors during hole-expansion [8]. Many experimental and theoretical studies have been conducted to explain the effect of the initial microstructure, mechanical properties and punching conditions on the stretch-flange formability of HSS [8,10,13–24]. Experimental studies mainly have dealt with the effects that the punching-clearance [8], burr-direction [10,13], cracks, and micro-voids in the edge of a hole [14,16] exert on the stretch-flange formability. However, the effects of the microtexture evolution that develops at the edge of the punched hole on stretch-flange formability have not been properly examined. In theoretical studies, finite element analysis (FEA) that

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considers the ductile fracture criterion has been used to predict the HER of sheet metals [8,20,23]. FEA can use spatial distribution, crystallographic orientation and volume fraction of the real microstructure to simulate micromechanical deformation behaviors in the constituent phases during the expansion of a hole [16–19]. Most FEA has been limited to explaining the deformation and fracture behaviors in the edge of a punched hole, but the microtexture evolution that is induced by the punching of a hole has not been properly investigated [13,16,20,21,23]. An understanding of the microtexture evolution that is induced by the punching of a hole is required in order to perform a more accurate analysis of the HER.

In the present work, we investigated the microtexture evolution of the edges of holes as they were punched into 780 MPa grade hot-rolled steel. As an experimental study, microstructure characterization was conducted around the edges of holes in the thickness direction. As a theoretical study, FEA that can consider the ductile fracture criterion was used to analyze the deformation path and fracture behaviors in the hole-edge region during the punching process. Rotation rate fields at the punched hole-edge during the punching process were calculated to evaluate the orientation stability of the initial texture components in the hole-edge region during the punching process. A VPSC polycrystal model [25–27] was used to simulate the microtexture evolution in the hole-edge region during the punching process, and the simulation results were directly compared with the experimental results.

2. Experimental procedure

To observe the deformation and fracture behaviors in the hole-edge region during the punching process, we used 780 MPa grade hot-rolled steel with a thickness of 2.37 mm that was fabricated with laboratory-scale processing. The initial microstructure of the hot-rolled sheet had a nominal chemical composition of 0.05–0.1C-0.01–0.5Si-1.0–2.0Mn-Ti + Nb + V < 0.25 (wt%) in a ferrite phase. The punching process was carried out using a punching machine and a schematic diagram of the punching process before the hole-expansion test is shown in Fig. 1(a). A hot-rolled sheet was cut into a 110 mm square blank (110 × 110 mm^2), and a hole was punched at the center of the blank. The diameters of the punch and the die were 10 and 10.6 mm, respectively, with a clearance of 12.5% of the sheet thickness. Fractography analysis of the punched hole-edge was performed using a field emission scanning electron microscope (FE-SEM) (JEOL JSM-7100F). The microstructure and microtexture were measured via optical microscope (OM) (OLYMPUS GX-51) and electron back-scattered diffraction (EBSD) technique, respectively. In order to measure the microstructure and microtexture, a transverse direction (TD) section was cut in the center of the punched hole. Mechanical polishing was carried out for 9–1 μm using a diamond suspension. For the OM measurement, the specimen was etched using a 3% Nital (ethanol = 97 ml, HNO_3 = 3 ml) etchant, and the final polishing was performed using colloidal silica for the EBSD measurement. The initial texture of the 780 MPa grade hot-rolled steel was measured at different positions (S = 0.9, 0.5, 0.0) through the thickness direction of the TD section. The distances through the thickness direction had the parameters $S = \Delta x / (t_o / 2)$, where Δx and t_o were the distance of the examined plane from the center plane and the thickness of steel sheet, respectively. The scanned area and the measurement step size were 200 × 200 μm^2 and 0.4 μm, respectively. Deformation microtextures were measured within a scanned area of 50 × 30 μm^2 with a measurement step size of 0.06 μm. The spatial distribution of the Kernel average orientation (KAM) and the crystallographic orientation through the thickness direction were analyzed using TSL-OIM software. The KAM was used for quantitative analysis of the deformation heterogeneity in the hole-edge region during the punching process. The misorientation between a point at the center of the kernel and all points defined as the 3rd nearest neighbors was considered in order to calculate the spatial distribution of the KAM. The 3-D orientation distribution functions (ODF) were calculated from the measured crystallographic orientation maps, and were used to generate a set of 1000-grain orientations for the polycrystal modeling using orientation repartition functions.

3. Simulations

3.1. Finite element analysis

The finite element method (FEM) was used to simulate the deformation and fracture behaviors in the hole-edge region during the punching process. The tool geometry and boundary conditions for the punching simulation were the same as those of the experimental conditions described in Section 2. The finite element code (the commercial software, DEFORM-2D [28]) was based on the flow formulation approach using an updated Lagrange method. A Newton-Raphson method and a direct iteration method were employed to solve nonlinear equations [28,29]. The punch and die geometries required for the simulation are shown in Fig. 1(b). The punching was carried out under axisymmetry conditions to enhance the computational efficiency. The steel sheet was considered to be a plastic object, whereas the parts such as the punch, die

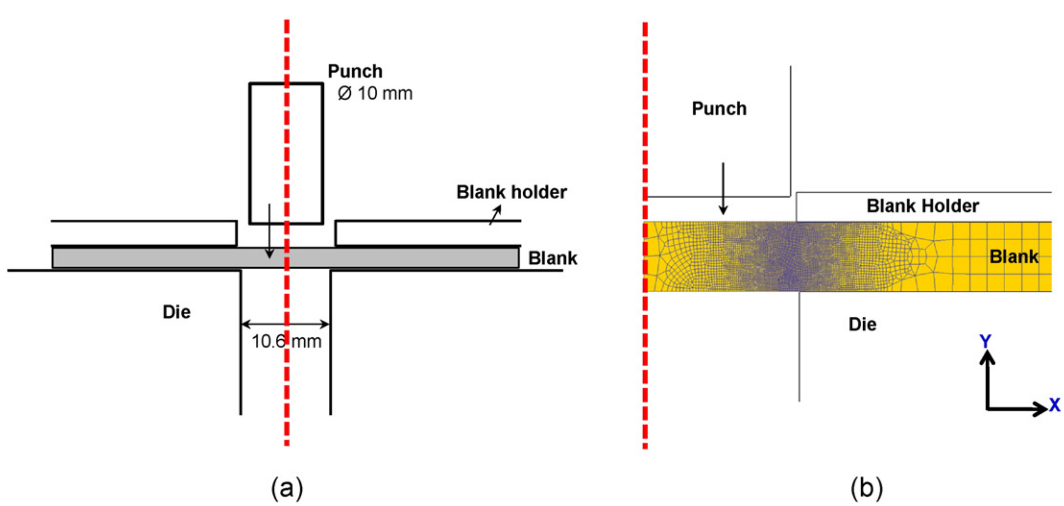

Fig. 1. (a) Schematic diagram for the punching process and (b) initial finite element mesh for FEA of the punching process.