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Effect of residual stresses on fatigue strength of high strength steel sheets with punched holes

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ABSTRACT

The effect of residual stresses on the reverse bending fatigue strength of steel sheets with punched holes was studied for steels with tensile strength grades of 540 MPa and 780 MPa. Tensile and compressive residual stresses were induced around the punched holes. Heat treatment of the specimens with punched holes at 873 K for 1 h decreased the residual stresses around the holes and improved the fatigue strength of the sheets. This result means that the tensile residual stresses induced in the sidewalls of the holes and near the hole edges by punching reduced fatigue strength. The effect of the residual stresses on the fatigue limits of the edges was estimated by the modified Goodman relation using the residual stresses after cyclic loading and the ultimate tensile strength at the fatigue crack initiation sites.

1. Introduction

Automotive chassis parts manufactured using steel sheets have cut edges formed by mechanical cutting operations, e.g. blanking, punching and trimming, in which a punch and die are used. There is the risk that fatigue cracks may initiate from these cut edges when the chassis parts are subjected to cyclic loading. Therefore, the fatigue strength of the cut edges as well as welds should be considered carefully. Some chassis components are now being constructed with high strength steel sheets with tensile strength up to 600–800 MPa for weight reduction [1,2]. It is more and more important to understand the fatigue strength of cut edges because notch sensitivity increases with increasing tensile strength of materials [3].

The cut edges formed with a punch and die have four characteristic areas that are called rollover, burnish zone, fracture zone and burr [4]. The surfaces of the fracture zone and the burr are rough because the material is torn in the cutting process. Furthermore, work hardening and residual stresses are induced by local plastic deformation near the cut edges [5,6]. The fatigue strength of the cut edges depends on the microstructure and the yield ratio of steel sheets [7–9]. The cut edges of Al–Si coated 22MnB5 press hardened steel sheets with tensile strength of 1500 MPa, which have recently been applied to structural body parts of vehicles, were subjected to cyclic loading because the need for further weight reductions in vehicles was expected to lead to potential applications in chassis components. The fatigue properties of the cut edges of the press hardened steel sheets were markedly sensitive to burrs and cracks at the edges [10]. The effect of cutting conditions was investigated focusing on the clearance between the punch and the die. The introduction of a cut edge decreased the fatigue property with a constant ratio up to a critical clearance. When the clearance exceeded that threshold, fatigue properties dropped drastically [11]. Variation of the clearance led to variation of the roughness of the fracture zone at the cut edge. The fatigue strength of specimens with a punched hole under bending and tensile cyclic loading was related to the roughness of the fracture zones at the cut edges in steels with tensile strength grades of 440–780 MPa [12]. It was suggested that tensile residual stresses induced in the loading direction at cut edges reduced fatigue strength by increasing the local stress ratio and the effective stress intensity factor range where microcracks were present [5]. Various post-treatments have been applied to cut edges to improve fatigue properties. Coining the burr fringe area around a punched hole by a conical punch increased the fatigue strength of the steel with the tensile strength grade of 780 MPa. The fatigue strength of the coined specimen was similar to that of a drilled-reamed specimen [13]. Punched holes of 6061-T6 aluminum were treated by seven techniques: abrasive flow machining, flow drill, hole expansion without reaming, hole expansion with reaming, shot peening (traditional), strain shot peening and laser shot (shock) peening. Hole expansion with and without reaming resulted in the best performance [14]. Fatigue crack growth was investigated in specimens

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with a modified SAE keyhole geometry with compact tension grips for the industry standard heat-treated steel (MET1123) and an ultra high strength steel (120XF). The crack growth resistance of the keyhole prepared with a punch press was compared with that prepared by drill, CO_2 laser and plasma processes. The threshold stress intensity, K_{th} and crack growth rates were most favorable with the punch press [15].

Although roughness, work hardening and residual stress simultaneously affect the fatigue performance of the cut edge formed by a punch and die, few reports have described those effects individually.

The purpose of this study is to clarify the effect of residual stresses on the fatigue strength of the punched edges of high strength steels. Therefore, the relationship between residual stresses and fatigue strength was investigated for as-punched specimens and specimens subjected to stress relief heat treatment after punching a hole.

2. Experimental procedure

2.1. Materials and specimen

The materials used in this study were two hot-rolled high strength steels with tensile strength grades of 540 MPa (HT540) and 780 MPa (HT780) and thickness of 2.6 mm. The chemical composition and mechanical properties of the steel sheets are shown in Tables 1 and 2, respectively. HT540 and HT780 are high strength low alloy steels strengthened by precipitation hardening.

The geometry of the specimens is shown in Fig. 1. A hole 10 mm in diameter was punched at the center of a specimen. The stress concentration factor for the punched hole was 1.45 under bending load according to Peterson [16]. Fig. 2 shows the cross sections of the punching tools and the definition of punching clearance. The clearance by percent was defined as the ratio of the distance between a punch and a die to the thickness of the specimen. In this study, the holes in the specimens were punched with the clearances of 10% and 25%. The edge of the punched hole was characterized into four regions, namely, rollover, burnish zone, fracture zone and burr, as shown in Fig. 3

The punching process induces residual stresses near the cut edges. In order to reduce the residual stresses in the specimens, stress relief heat treatment was carried out with a vacuum furnace. The specimens were heated at 823 K for 1 h and then cooled in the furnace.

The hardness near the punched hole edges was measured with a Vickers hardness testing machine on the cutting planes at the centers of the specimens. The test load for the hardness measurements was 0.245 N. The measurement position was 50 μm from the surface on the burr side of the specimen, as shown in Fig. 4.

2.2. Residual stress measurement

The residual stresses near the punched hole edges in the specimens were measured by the X-ray diffraction (XRD) technique. The measurement was based on the $\sin^2\psi$ method. It was necessary to cut the specimens in order to measure the residual stresses on the sidewalls of the punched holes. Therefore, measurements were carried out before and after cutting the specimens in order to

Table 1
Chemical composition of hot-rolled high strength steels (wt.%).

Grade	C	Si	Mn	P	S	Others
HT540	0.12	0.01	0.77	0.024	0.006	Nb
HT780	0.04	0.03	1.35	0.012	<0.001	Mo, Ti

Table 2
Mechanical properties of hot-rolled high strength steels.

Grade	YS (MPa)	TS (MPa)	El (%)
HT540	457	570	26.9
HT780	728	796	19.5

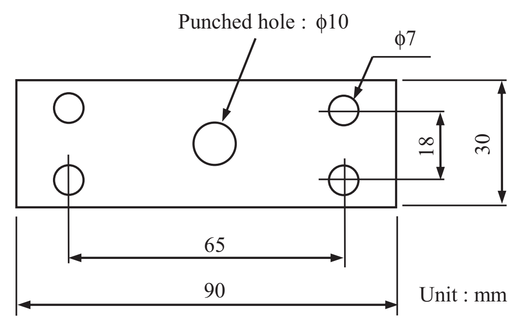

Fig. 1. Geometry of specimen used for fatigue test.

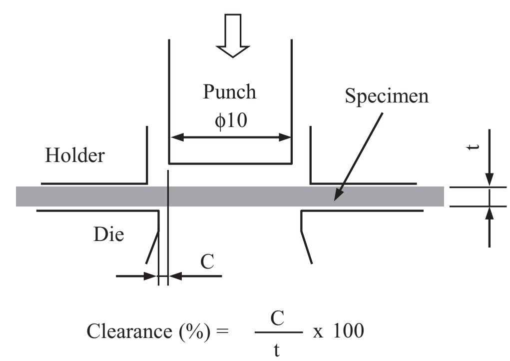

Fig. 2. Cross section of tools and definition of clearance.

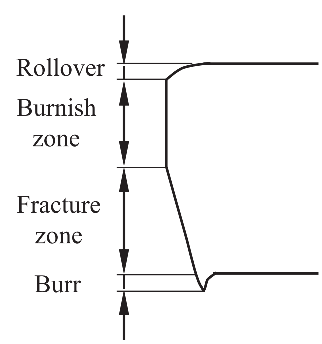

Fig. 3. Nomenclature of a punched hole edge.

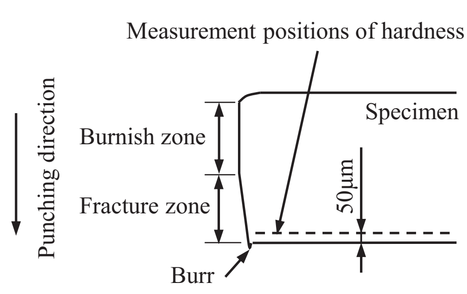

Fig. 4. Measurement positions of hardness.