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Analysis of fracture behavior and stress–strain distribution of martensite/austenite multilayered metallic sheet

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ABSTRACT

The properties of a multilayered metallic sheet tend to be different from those of a sheet made of monolithic material because of the layer interaction. Because of the change in the ductility and strength of each layer, the stress gradient changes; a brittle layer is deformed over the fracture limit of the monolithic material. Further, a new stress–strain distribution is observed in the form of a new fracture within materials. In the case that the observed strain is more than the fracture strain of a monolithic brittle material, micro-voids and cracks are generated and a tunnel crack is formed. As the layer interaction is changed by the suppression stress in the direction of necking, the stress components of two layers are changed. The suppression stress changes the features of the plastic zone, such as the defects range of dislocation, slip band, and void; consequently, the fracture strain is changed. The thinner the brittle layer, the greater is the increase in the fracture strain. This study suggests a method for predicting the fracture strain from the relation of the thickness change and the volume fraction in accordance with the lamination numbers.

1. Introduction

A multilayered metallic sheet (ML sheet) is fabricated for the improvement of light-weight transporters such as cars and aircrafts, for collision safety, and for the improvement of formability. Koseki et al. (2010) developed a ML sheet having high strength and an improved fracture strain achieved through the lamination of high strength steel and high ductility steel. This ML sheet was used in our study. Kawai (2001) reported the lightweight transport vehicle for environmentally conscious steel products and investigated the impact safety of sheet materials for this vehicle. Haug et al. (1994) emphasized the collision safety of a car through a research on transport vehicle crash, safety, and manufacturing simulation. Parsa and Yamaguchi (1998) investigated the increase in the formability of an aluminum-stainless laminated sheet. In the research conducted by Oya et al. (2010a), V-bending and hat-bending experiments were performed for the formability evaluation of an ML sheet. Park et al. (2004) investigated the flexural strength of a multilayer aluminum sheet. We want to obtain the desired properties of an ML sheet by combining all the good characteristics of a monolithic sheet. This ML sheet seems to be the promising material for the substitution of the high-strength steel sheets that are currently in use and for the realization of the high-strength, lightweight structural transporters with increased formability. Yanagimoto et al. (2010) recently demonstrated the enhancement of the bending formability of brittle sheet metal in multilayer metallic sheets in a study preceding the present study. However, as the study on formability and plastic forming is still insufficient, we investigate the stress–strain distribution or the fracture behavior. Through the study, we aim to devise a method for improving the formability of high-strength steel; further, we can find the defective part and use it for failure prediction and as data for a design.

By using an ML sheet that has alternately stacked ductile layers and brittle layers, we aim to develop a material that has excellent strength and ductility. The results of Nambu et al. (2009), who studied the effect of the interfacial bonding strength of a multilayered steel sheet, were referred to as a delamination data of this study. The method used in the research of Ohashi et al. (1992), which investigated the fracture behavior of a laminated composite in bend tests, was used for microstructure evaluation in the present study. Lee et al. (2007) studied the effect of annealing on clad-metal sheets. Oya et al. (2010b) have studied the characteristics and mechanical properties of an ML sheet through the experimental and analytical methods. As an ML sheet is fabricated using materials with different deformation behaviors, when tensile or bending deformation is applied to the sheet, mechanisms leading to a fracture can be considered to differ from those observed in the case of sheet

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with a normal monolithic layer. Therefore, in order to meet the design guidelines of the ML sheet or to clarify the forming limit, we need to investigate the mechanism of fracture. Inoue et al. (2008) investigated the fracture elongation of brittle/ductile multilayered steel composites, and Cao and Evans (1991) reported on the crack extension in ductile/brittle laminates. Coco et al. (2008) noted that a change in mechanical properties, strain localization, damage, and fracture mechanism occurred in compositionally graded materials because a change of flow stress brings about a change in strain hardening. We propose a new analysis method based on the stress change in the (*x*, *y*) direction with respect to the stress ratio of the two axes by using the research work of Kuwabara et al. (1998) and Geiger et al. (2005). Kuwabara et al. (1998) investigated work hardening in a steel sheet under biaxial tension, and Geiger et al. (2005) investigated the elliptical stress distribution graph. Chehab et al. (2010) investigated the characteristics of fracture strain as a function of the stress triaxiality of a lamellar structure and void nucleation by partial decohesion at the austenite–ferrite interface. Hannon and Tiernan (2008) also investigated the stress–strain distribution in the (*x*, *y*) direction. Elliptical plots were used to evaluate the change in stress and strain in order to investigate the changes in the stress gradient along the two axes of the ML sheet. The reason for the stretch increase with the improvement of ductility of the brittle layer is analyzed by the stress–strain distribution verification, and the necking and fracture that occur during the transformation process are evaluated by the micro-defects and the components of the consequently occurring stress–strain ratio. In this study, we conduct certain experiments on and an FEM analysis of an ML sheet, and evaluate the results.

2. Characteristics of ML sheet and outline of research

It is certain that the increase in the fracture strain of the brittle layer improves the formability of the ML sheet. It is necessary to verify the changes in the stress gradient and the plastic zone between the lamination layers for the quantification of the mechanical characteristics of the sheet. Changes in the loading-direction stress or effective stress between the two layers can be explained by studying the correlations of the changes in the vertically loaded stress. The increase in the lateral stress of the broken specimen implies an increase in the effective stress, and this phenomenon reveals an increase in the strength. In contrast, when ductility is increased, the fracture strain increases. If brittle layers and ductile layers are laminated, a stress gradient is formed between the two layers, and hence, the characteristics of each layer are transferred to the characteristics of another layer; this transfer leads to the difference in the mechanical characteristics of the ML sheet and those of the monolithic material. The improvement in ductility via suppression of the stress of necking in the brittle layer is explained by a method relying on the constant volume fraction in our previous work. However, this new work presents an improvement realized by using a stress gradient and a change in the *x*- and *y*-direction stress. In the distribution elliptic graph of the *x*, *y*-direction stress analyzed by using the method of Geiger et al. (2005) and Hannon and Tiernan (2008), the stress distribution moves toward the inside when the ductility increases and moves toward the outside when the strength increases. Moreover, the lateral stress of a ductile layer suppressing the necking of the constrained brittle layer is caused by the layer interaction. This suppression stress is the cause of the ductility increase of the brittle layer and leads to an increase in stress for the same strain in the soft layer. Because the material is fractured with a sudden decrease in stress caused by the necking after the elastic–plastic deformation and reaching the maximum stress, the confirmation and prediction of the stress–strain distribution on the necking point are very important. As the necking occurs in the vertical direction of the tensile stress, the ductility improvement at the stress point of necking can be explained by the confirmation of the stress variation in the transverse direction.

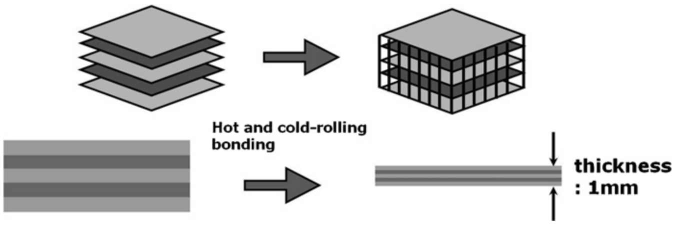

Fig. 1. Lamination process to produce a ML sheet.

The fracture strain of the ML sheet is the result of the correlations between the high-strength layer and the high-ductility layer; on the basis of each layer's strain, we can predict the fracture strain of the ML sheet. If the brittle layer exceeds the critical deformation point of the monolithic material when the deformation is in progress, because of the suppression of necking by the ductile layers, the deformation increases without a fracture and micro-voids and cracks occur. These defects eventually cause the tunnel cracks in the brittle layers, and by stress concentration, a plastic zone is formed at the tip of a tunnel crack in the ductile layer. Then, because of the increase in the stress, necking occurs all around the specimen and the specimen finally breaks. As the fracture strain is decided through this process, we verify the micro-defects that occur as a result of the interlayer stress gradient and the strain increase in accordance with the ductility improvement.

3. Experimental procedure

The ML sheet is laminated alternately with austenitic stainless steel in the soft layer and martensitic stainless steel in the hard layer. SS304 is used as the ductile layer, and WT780C and SS420J2 are used in the brittle layer as a high strength layer. The specimens are 1-mm-thick ML sheets with sufficient interface strength to prevent de-lamination. First, the soft layer is located at the outermost layer, and the hard layer is laminated inside of the soft layer; hot and cold rolling processes are repeated to produce the desired specimens. Specimens were cold rolled to a total thickness of 1 mm after hot rolling at 1200 °C for 60 min down to a thickness of 3 mm. Finally, the specimens were heat treated at 1000 °C for 2 min and quenched in water. The peel strength of the roll-bonded specimen (>10 N/mm) was over 10 times higher than that of the adhesive-bonded specimen (<1 N/mm). The fracture elongation (≈0.25) of the roll-bonded specimen was also higher than that of the adhesive-bonded specimen (≈0.19). Fig. 1 presents a schematic of the lamination process to produce ML sheets. The chemical composition of the materials is shown in Table 1.

Table 2 shows the mechanical properties of monolithic materials. YP, TS, and f-EL denote the yield strength, tensile strength, and fracture elongation, respectively. Tensile tests were performed at room temperature with a constant cross-head speed corresponding to an engineering strain rate of $1.0 \times 10^{-3}\ \mathrm{s}^{-1}$. The tensile specimen had a gauge length of 50 mm, width of 12.5 mm, and an initial thickness of 1 mm. The difference in strength between the soft material and the hard material is considerable, and the fracture elongation of brittle material is very low. In particular, SS420J2 is fractured with very little plastic deformation. Mechanical properties such as stress–strain characteristics, yield strength, tensile strength, and uniform elongation area of the ML sheet from the experiment are compared with the properties of a monolithic material. Further, the microstructural analysis of the ML sheet is carried out for the analysis of the generation of micro-defects and fractures. An optical microscope and a scanning electron microscope are used