ABSTRACT OF THE DISSERTATION

Title: The experimental and computational studies on the impact energy absorption characteristic of TRIP steel at various deformation rate

(様々な変形速度における TRIP 鋼の衝撃エネルギー吸収特性に関する実験的ならびに数値解析的研究)

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Recently, transformation-induced plasticity (TRIP) steel has attracted the interest of the scientific community because it has promising mechanical properties such as high strength, excellent formability, and toughness because of strain-induced martensitic transformation (SIMT). In addition, TRIP steel might have a high energy-absorption characteristic because it could possibly consume impact energy by not only plastic deformation but also SIMT during deformation. Generally, bending deformation due to buckling is one of the major collapse modes of automotive structures. At the same time, a dominant mechanism to keep the safety in automobiles by structures upon the collision is buckling because much kinetic energy with higher speed of the vehicles can be consumed by inelastic deformation of components during crashing vehicles for protection of the passengers. Therefore, an investigation on the bending deformation behavior and energy-absorption characteristic in TRIP steel at high deformation rate is indispensable to clarify the mechanism of better performance.

Some past studies have focused on the improvement of mechanical properties by means of SIMT in TRIP steel; however, the mechanism through which the energy-absorption characteristic in the steel can be improved is still unclear and has become a critical issue in the design process of vehicles. Generally, the energy absorption of materials can be evaluated from the stress-strain curve obtained by a tensile test. However, at a high deformation rate, an interaction between a plastic wave and unstable deformation during tension induces difficulties that prevent the onset of necking in a specimen. As a result, the specimen always fractures earlier than the expected period at a high velocity of tensile loading. Thus, the mechanism governing the energy-absorption capacity for tensile deformation is quite complicated, especially at high strain rate. Otherwise, the bending deformation mode is considered to be relatively simple. In fact, large deformation of a smooth plate specimen without such unstable deformation can be obtained under bending deformation. Thus, a large amount of energy may be dissipated by plastic bending deformation and phase transformation during the bending deformation of TRIP steel. In addition, an experiment for the bending mode provides more stable results than one for the axial mode at a structural level.

This dissertation investigated energy-absorption characteristic of TRIP steel in bending deformation at various deformation rate in experiment as well as computational simulation. Firstly, energy absorption is experimentally evaluated by quasi-static and impact three-point bending test for both smooth and pre-cracked specimens made of type-304 austenitic stainless steel, a kind of TRIP steel. Then, finite-element simulations are performed in order to discuss the mechanism of energy-absorption characteristic in three-point bending deformation of the smooth specimen as well as the small punch test at different deflection rates. The dissertation includes the following chapters:

Chapter 1 introduces the research background, literature review, problem description, objective and structure of dissertation.

Next, the transformation kinetic model proposed by Iwamoto et al. (1998), multiaxial constitutive equation to include the asymmetry of stress-strain curves for tension and compression (Iwamoto and Tsuta, 2002), the heat conduction equation considering the transformation latent heat (Tomita and Iwamoto, 1995); and an FE formula (Iwamoto et al., 2008) are overviewed in detail in Chapter 2. In addition, an incorporation of damage model into constitutive equation of the material in FE simulation is proposed.

In the Chapter 3 of this dissertation, the performance of both smooth and pre-cracked specimens made of TRIP steel is investigated experimentally at various deflection rates. The three-point bending tests are conducted by an Instron-type conventional material testing machines for quasi-static loading, a drop-weight testing machine, and a testing apparatus based on the split Hopkinson pressure bar method for the smooth specimen. Then, the three-point bending tests are conducted under quasi-static and impact conditions for the pre-cracked specimen based on the ASTM standard. Energy absorption for TRIP steel during plastic deformation and fracture process was discussed by examination of characteristic of force-deflection curves and value of J-integral. Additionally, stretch zone width was also investigated at different deflection rate to show the validity for the result of J-integral. The results showed a positive rate sensitivity of the external force in TRIP steel from quasi-static to impact deformation. Moreover, TRIP steel indicated higher value of J-integral at higher normalized deflection rate. The positive rate sensitivity of *J*-integral was also confirmed by an investigation of stretch zone width of fracture surface after bending deformation. As a result, it could be concluded that TRIP steel might have excellent energy-absorption characteristic under impact loading deformation.

Although energy absorption of TRIP steel can be determined experimentally as reported in Chapter 3, the mechanism for the high performance in impact condition is still unclear and might not be clarified through merely experimental works. Therefore, in Chapter 4, computational simulations are performed by the three-dimensional finite-element method described in Chapter 2 for three-point bending test on the smooth specimen. The effect of deflection rate including temperature and martensitic transformation on bending deformation behavior is examined. The mechanism for a higher capability of energy absorption in TRIP steel is challenged to be clarified. The computational results showed a fairly good agreement with experimental results in both the quasi-static and impact conditions. A positive rate sensitivity of the energy-absorption characteristic in TRIP steel could be observed from quasi-static to impact deformation as similar as that in experiment. At room temperature, the effect of SIMT on energy absorption in TRIP steel could not be seen at high deformation rate because of a stability of the parent phase as well as a relatively high temperature rise near the loading point. The mechanism of higher energy absorption at higher normalized deflection rate in TRIP steel could be explained from the viewpoint of rate sensitivity on strain hardening in austenite. Moreover, at high deflection rate, the concentration of relatively-high temperature rise induced a localization of deformation near the loading point; however, this localization was retarded because of SIMT at low test temperature. At low test temperature, the impact energy-absorption characteristic in TRIP steel was clearly improved by an increase in the strain hardening as well as the ductility because of SIMT.

In Chapter 5, finite-element simulations are performed for the small punch test at different deflection rates by an inclusion of isotropic damage variable and its evolution equation by Dey et al. (2007) in the parent phase. The validity of computation was confirmed by a good correspondence with experimental result as well as other publication. From the obtained results, TRIP steel indicated a negative rate-sensitivity of maximum force and deflection at the maximum force in the small punch test. At higher deflection rate, the damage occurred when deflection is lower level. The mode of failure in the specimen of the small punch test presented a rate-sensitivity. Moreover, although the total consumption energy was considerably higher in case of larger puncher and bigger specimen, a similar tendency of deflection at the maximum force could be obtained for different sizes of the puncher and specimen. At room temperature, fracture-mechanical characteristics in the case of lower deflection rate were enhanced by means of SIMT. The impact fracture-mechanical characteristics of TRIP steel were clearly improved at 80 K due to an increase in the deflection at the maximum force because of a saturated value of volume fraction of martensite at high deformation rate. A correlation between equivalent fracture strain and fracture toughness of material could not be obtained based on the conventional method because of an opposite rate-sensitivity and a different method for normalization of deflection rate in the small punch test and three-point bending test.

In Chapter 6, the main findings and conclusions derived from the results of the dissertation are described. In addition, the required further works were sketched.