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Investigation on the influence of loading-rate on fracture toughness of AHSS grades

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ABSTRACT

The automotive industry is striving for light body-in-white structures while maintaining or improving passenger safety. The aim of this paper is to investigate the influence of the loading rate on the fracture toughness of thin steel sheet metal of three advanced high strength steels. Although steel is a heavy material it plays a significant role for lightweight solutions in car bodies. Three different advanced high strength steel (AHSS) grades, namely dual-phase (DP), quench-partitioning (Q&P) and TRIP-assisted bainitic-ferritic (TBF), are investigated in the present paper. For crash relevant components it is of importance to know the material response under high loading velocities i.e. high strain rates. A standard tensile test system is used for low loading rates, a high-speed tensile testing setup is used to obtain high loading rates. The fracture toughness of the three AHSS grades is evaluated using the methodology of the Essential Work of Fracture (EWF). The tensile specimen used in the present work is the double edge notched tensile (DENT) geometry with a pre-developed crack. High-speed imaging is applied to verify the validity of the evaluation method Essential Work of Fracture at high rates of loading. Results from this work show that knowledge of fracture toughness would improve the understanding of fracture and crack propagation mechanisms for third generation high strength steels used for automotive components.

1. Introduction

In engineering applications the use of AHSS grades is favored due to there excellent strength to weight ratio. In many light weighting applications it is not possible to use materials with lower weight, like for example aluminum or magnesium, because of load bearing considerations or energy absorption capacity. The use of AHSS grades is advantageous in applications where energy absorption is of importance. Such an application is for example the low speed crash-box in automobiles. A low speed crash box is located between the bumper and the chassis of car. The main purpose of this particular crash box is the absorption of impact energy at low vehicle speeds, deformation occurs in this specially designed part and prohibits damage of the remaining chassis. At higher impact speeds the crash box absorbs the initial impact energy and transfers the not dissipated energy into the chassis. The integrity of this systems is of importance for passenger safety and advantageous for manufacturers for their insurance ratings.

The influence of the rate of loading on the mechanical properties of materials has a long history in investigations. One of the earliest studies on the effect of the strain rate on the plastic flow of steel was conducted by Zener and Hollomon [1] in 1944. In early works the split Hopkinson pressure-bar method is usually applied to achieve high loading rates. Kolsky [2] investigated different materials like rubbers, polythene and different metals at high loading rates. Twenty years later Lindholm and Yeakley [3] investigated aluminum in tension and compression at loading rates of 1000/s. Another twenty years later Kalthoff [4] studied the fracture behavior of a polymer and high-strength-steel at high rates of loading and captured the onset of crack propagation using high-speed photography and determined the fracture toughness. Investigations on the influence of the strain rate on the mechanical properties of material continued also in the next century. Bleck and Schael [5] investigated the strain rate sensitivity of eight different steel grades and could show the influence on yield and ultimate tensile strength as well as uniform and total elongation. Radwaski et al. [6] pointed out the role of the microstructure morphology and chemical composition of phase constituents on the mechanical properties of AHSS steels, with particular focus on a DP grade. Alturk et al. [7] studied the influence of the microstructure in DP and Q&P steel grades and results suggest a relationship between the phase-content of the steels grades and their response to the loading rate. Gronostajski et al. [8] investigated the

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stress-strain relationship and effects on the microstructure of DP and TRIP steel caused by strain rate effects. Flow behavior and strain rate sensitivity are two factors of interest, the influence of the strain rate on the fracture behavior is another key point, especially if emphasizes is put on components or structures that are loaded and fracture is a possible scenario. The influence of the strain rate on fracture toughness has been investigated by Kim et al. [9] and Vendra et al. [10], both studies focus on aluminum alloys and apply different test setups for fracture toughness determination, pointing out the importance of considering loading rate on determination of fracture toughness.

Knowledge on the fracture behavior, in terms of fracture toughness, is an important material property for the design of automotive components. Rahmatabadi et al. [11] evaluated experimentally the fracture toughness of ultra-fine grained aluminum in plane stress, relevant for sheet metal applications. During manufacturing of sheet metal components different operations are necessary, Efthymiadis et al. [13] contributed to the understanding of fracture toughness in forming and flanging operations while Pouranvari [12] contributed with a study on spot welds. Recently Casellas et al. [14] showed that tougher steels present higher higher resistance to edge cracking. Frómeta et al. [15] evaluated the crash resistance by means of fracture toughness and crash index. The crash index is a value describing the appearance and size of cracks in a hat profile after axial impact. A linear correlation between the crash index (CI) and the fracture toughness evaluated by means of the essential work of fracture was shown. Accordingly, fracture toughness is a relevant material property for the design of, for example, crash relevant components.

It is well known that the evaluation of fracture toughness in thin sheets, in the range of 1–3 mm, is experimentally difficult and out of the conventional ASTM procedures for metals. An alternative approach is the methodology based on the evaluation of the essential work of fracture (EWF). The foundation of the EWF is that the non elastic deforming region at the crack tip can be divided into two sections, one section is the fracture process zone i.e. the region where the fracture process takes place. The second section is surrounding the first section and accommodates the plastic strains. In ductile material, the region where plastic deformation occurs is large compared to the fracture process zone. The work performed in the fracture process zone can be seen as a material constant. This material constant was first described by Broberg [16] and termed essential work. In later publications Broberg [17,18] discussed further topics and details of the essential work. For the case of plane stress, which is a common assumption for thin sheets, the fracture process zone can be identified with necking. For this case the essential work is not a true material constant as it has a dependency on the sheet thickness. The plastic deformation in a test specimen is dependent on the specimen geometry. Therefore, the plastic work in the surrounding of the fracture process zone is not a material constant.

The EWF methodology is a common technique in the characterization of the fracture toughness in thin films and polymers. Some works have been addressed to metal sheets. Cotterell and Reddel [19] investigated the essential work of fracture for plane stress conditions and ductile fracture in a low alloyed, cold rolled, steel. Cotterell and Reddel [20] studied the influence of the test parameters on the measurement of the EWF in zinc sheets. Recent works by Munoz [21] and Casellas [22] show the possibility of determining fracture toughness using the essential work of fracture methodology for several AHSS grades like dual and complex phase, press hardened steels, TRIP and high manganese steels.

Using a high-speed camera it is possible to capture the deformation of the specimen surface. Furthermore, it is possible to capture the crack initiation and propagation during loading. The use of digital image correlation (DIC) as post-processing tool allows the determination of the strain field on the specimen surface. For the EWF to be valid a fully yielded specimen ligament is required, visualizing the strain field allows to examine the validity of the test procedure. During dynamic testing wave propagation phenomena can be seen in test specimens, for samples similar to those in the present study literature did not reveal images. Tarigopula et al. [23] investigated a DP steel using DIC and high-speed imaging during tensile tests in a split Hopkinson tension setup. Wave propagation in meta-materials is studied by Ruzzene et al. [24] and schaeffer et al. [25], both studies are conducted on materials similar to honeycomb cores. Their results show that DIC can be used to capture wave propagation in materials.

The intention of the authors' is to extend the knowledge on fracture toughness of advanced high strength steel sheet metal at different loading rates. Therefore, the essential work of fracture is determined for three AHSS grades at two loading rates, ranging from quasi-static to dynamic loading. To our knowledge such a study is not available in literature. The aim of the present study is to fill this gap of knowledge and provide experimental test data and fracture toughness values for the use in industrial applications.

2. Experiment

2.1. Materials used in the investigation

The present study focuses on three AHSS grades, DP, Q&P and TBF. To introduce the unacquainted reader to these steel grades a brief summary is given. Dual-phase (DP) steels are commonly found in automotive applications, as structural reinforcements for crash resistant structures. DP steels consist of a ferritic matrix containing a hard martensitic second phase in the form of islands. Usually the soft ferrite forms a continuous pattern in the microstructure, causing high ductility. During deformation of DP steels the strain concentrates into the lower-strength ferrite which is surrounding the martensite islands, this effect causes high work-hardening. Quench & Partitioning (Q&P) steels are produced by quenching and partitioning steps. In recent years Q&P steels attract high attention because of their mechanical properties. The fully austenitized steel is quenched to a temperature, termed "quench" temperature, between the martensite start and finish temperature in order to form a controlled volume fraction of martensite. The quenched steel is then held at the quench temperature or higher during the subsequent partitioning step. The remaining austenite after quenching is considered to be stabilized. The austenite stabilization is achieved by carbon partitioning from martensite into austenite during the partitioning step. The final microstructure consists mainly of tempered martensite and retained austenite, Zhu et al. [26]. Q&P steels show a deformation induced martensitic transformation, Zou et al. [27], providing high strength and good ductility. Q&P processes can also be applied on local level, for example in sections of an automotive component, where modified mechanical properties are desired, Forouzan et al. [28]. Modifications of the heat treatment process of Q&P steel grades bridge the gap to the third steel part in the present investigation. Huang et al. [29] reports on an isothermal process introducing bainite into a Q&P process. The microstructure of the TBF (TRIP assited bainitic-ferritic) steels consist of a bainitic and/or tempered martensitic matrix containing retained austenite, which gives the TRIP assisted effect, see Bachmaier et al. [30] and Hausmann et al. [31]. TBF steel grades possess in addition to a high tensile strength a very good property combination of high deep drawability and stretch flangeability. Therefore these steel grades are suitable for the manufacturing of complicated safety related parts for the body-in-white (BIW) lightweight construction in the automotive industry, Winkelhofer et al. [32].

2.2. Specimen preparation

Two different sheet thicknesses are used in the present study for DP and Q&P steels the thickness is $t = 1.38\ mm$, for TBF a thickness of $t = 1.48\ mm$ is available. Double edge notched tensile (DENT) specimens were extracted from the coil perpendicularly to the rolling direction. Notches in the DENT specimens are machined with a notch root