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High strain rate torsional testing of a high manganese steel: Design and simulation

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ABSTRACT

In this study, some less-discussed aspects of designing a high strain rate torsional testing machine adapted from the Kolsky bar setup are surveyed with an emphasis on the clamping system design. Dynamic torsional experiments with true strain rates in the range of ~500–1700 /s are conducted on specimens of a high-Mn TRIP/TWIP steel. Deformation characteristics of torsional specimens with different geometries are studied through coupled field thermo-mechanical finite element analyses using ANSYS commercial software package. The effect of specimen geometry on the stress and strain distributions and accuracy of the experimental results is also studied. Using the FEM analysis, deformation temperature rise is attained over the specimen gauge zone and its influence on the stacking fault energy and mechanical behavior of the steel is investigated.

1. Introduction

There are numerous circumstances in which a material is exposed to impact stresses. Automobile body is a well-known example which should be developed from materials with sufficient crashworthiness [1]. Inevitably, candidate materials for such situations must be examined at the same high strain rate of their intended applications. Various methods for high strain rate testing of materials are introduced in the open literature starting with the original work of John Hopkinson [2]. Based on this work, Kolsky [3] invented the split-Hopkinson pressure bar to investigate the high rate deformation of ductile materials. Baker and Yew [4] were the first who extended these high rate techniques to torsional states of stress. Lewis and Campbell [5] proposed the employment of thin-walled tubular specimens in the so-called torsional Kolsky bar experiment. Gilat and Cheng [6] used tubular specimens of commercially pure aluminum with very short gauge lengths by which very high strain rates were reached in the torsional experiments. Wei and Ahmad [7] discussed the influence of radius to thickness ratio for the tubular specimens. It was found that both the strain and strain rate increase as this ratio increases, but at the same time a sharp decrease in the torsional stiffness was also observed. In addition to the geometry of the specimens which directly affects the imposed strain and strain rate, different components of the testing machine also affect the acquired data. In this regard, the clamping mechanism of the machine has a significant impact on different characteristics of the generated torsional pulses. Although of utmost importance for the accuracy of the attained stress–strain data, the mechanical aspects of designing this mechanism have not yet been discussed in the literature. This issue is thoroughly dealt with in the present paper.

The torsional Kolsky bar has been used to study the dynamic behavior of various groups of engineering materials including ferrous alloys. Lee et al. [8] performed high strain rate torsional experiments in order to study the dynamic behavior of 304L austenitic stainless steel. Extensive localized shearing was shown to be the primary failure mechanism. Hwang et al. [9] utilized the same technique to study the formation of adiabatic shear bands which led to the occurrence of dynamic recrystallization in a fine-grained low-carbon steel. Recently, a modern group of ferrous alloys, i.e. advanced high strength steels (AHSS), have attracted great attention because of their superior mechanical properties which are maintained even at high rates of strain [10]. Different categories of these steels have been studied by tensile or compressive versions of the split-Hopkinson experiments. Singh et al. [11] performed split-Hopkinson tensile tests on a multi-phase (MP) steel and employed the obtained data to determine the material parameters of Cowper–Symonds and Johnson–Cook models. In another work, a transformation induced plasticity steel (TRIP800) has been dynamically tested by tensile split-Hopkinson bars, showing a high ductility in dynamic conditions [12]. The compressive version of split-Hopkinson experiment has been used in studying a newer subcategory of AHSS with high manganese contents (15–30 wt%) known as twinning induced plasticity (TWIP) steel [13]. The investigated steel showed a slight strain rate softening behavior in the high strain rates of above 700/s. The same trend was observed in

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compression tests which were conducted by Li et al. [14] on a TWIP steel in the range of strain rates from ~400 to 1300/s. The TWIP steels which were tested in compression by Sahu et al. [15] showed slight increase in the strength as the strain rate increased beyond 1200/s. Xiong et al. [16] studied the mechanical behavior of a high-Mn TWIP steel using compression tests in a wide range of strain rates from quasi-static condition to high strain rates. It was found that within the various ranges of strain rate, the TWIP steel shows quite different behaviors of strain rate softening, strain rate insensitivity, and strain rate hardening.

The finite element method (FEM) has been utilized in a number of research works to study the high strain rate experiments. Ramirez and Rubio-Gonzalez [17] employed the FEM to show that increasing the pulse rise time minimizes the wave dispersion in split-Hopkinson pressure bars. In contrast to the compressive split-Hopkinson experiment, in the torsional version of the experiment, no geometric dispersion occurs for waves travelling along the bars [18]. Gilat and Cheng [19] performed the FEM modeling of dynamic torsional tests on a commercially pure aluminum. The results which were obtained from a time dependent analysis were quite similar to those obtained from time-independent analysis with a rate-dependent constitutive relation for the specimen. An important feature of high rate deformation processes, i.e. the phenomenon of adiabatic temperature rise, is rarely considered in the finite element modeling of split-Hopkinson experiments. Kapoor and Nemat-Nasser [20] experimentally measured a temperature rise of about 90 °C during high strain rate compression tests on mild steel. Utilizing the finite element method, Zhou and Clode [21] showed that the specimen geometry and the initial test temperature influence the deformation temperature rise during the hot torsion tests on an aluminum alloy. Higher values of temperature rise were obtained in case of lower initial test temperatures. Quang et al. [22] performed coupled field thermo-mechanical finite element analysis for modeling of severe plastic deformation in aluminum and steel specimens. A considerable increase in the temperature (~180 °C) was attained during deformation of the steel specimens. It should be noted that the impact of the deformation temperature rise is even more important in a high-manganese steel which is the case of the present study. This is due to the dependence of the stacking fault energy (SFE) of the steel on its temperature [23].

All of the above-mentioned studies on high strain rate deformation of high-Mn steels have been accomplished using tensile or compressive split-Hokinson techniques. However, to the best of authors' knowledge, high-Mn steels have not yet been examined under dynamic torsional loading condition. The torsional version of Kolsky bar has been thoroughly reviewed by Gilat [18]. Nevertheless, designing the clamping mechanism as an essential component of the machine has not been discussed in detail. Additionally, the evolution of strain distribution and the resultant adiabatic temperature rise of the material which greatly affects its mechanical behavior during high rate testing of torsion specimens are not yet covered in the literature.

In the present work, authors designed and constructed a high strain rate torsional testing machine adapted from the torsional Kolsky bar setup. Some mechanical aspects of designing the machine and particularly its clamping mechanism are investigated. Several high strain rate torsional tests are conducted on samples of a high-Mn TRIP/TWIP steel. The dynamic torsional straining of specimens with different gage lengths (1–3 mm) is studied by means of transient coupled field thermo-mechanical FEM analyses using the well-known ANSYS commercial software package.

2. Designing the machine

High strain rate torsional testing of materials provides more accurate results compared to similar compressive experiments [19]. The torsional testing setup which was constructed and used in the present study is shown in Fig. 1. Initially, clamp 2 is tightened and the end of the incident bar is twisted up to a certain angle by operation of the motor and gearbox. As the result, a specific amount of torque is stored in the part of the incident bar between clamp 2 and the gearbox. At this moment, clamp 1 is tightened and clamp 2 is suddenly released. Therefore, a torsional pulse travels in

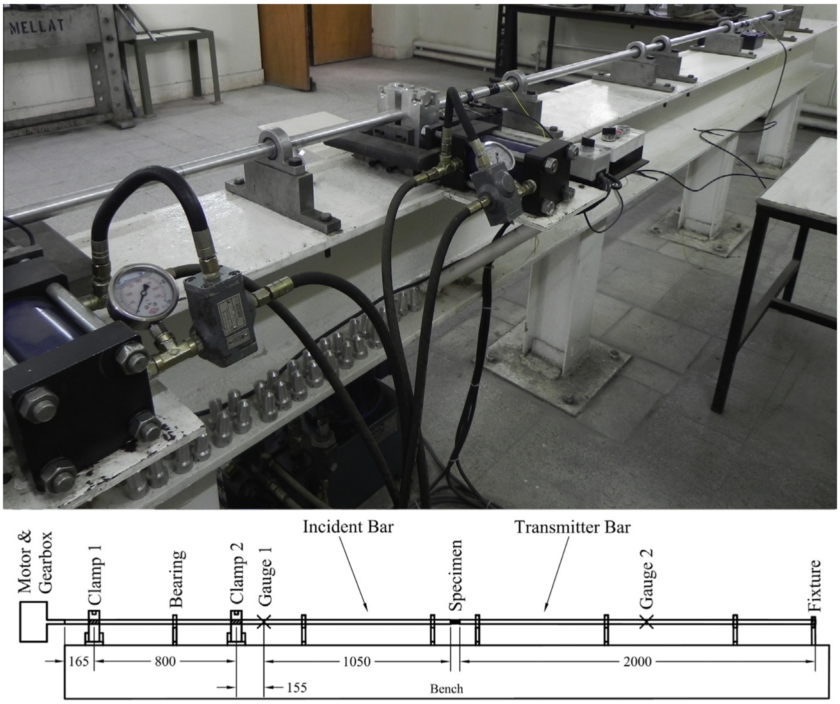

Fig. 1. The high strain rate torsional testing setup used in the present study (dimensions in mm).