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Finite element analysis of AISI 304 steel sheets subjected to dynamic tension: The effects of martensitic transformation and plastic strain development on flow localization

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A B S T R A C T

The paper presents a finite element study of the dynamic necking formation and energy absorption in AISI 304 steel sheets. The analysis emphasizes the effects of strain induced martensitic transformation (SIMT) and plastic strain development on flow localization and sample ductility. The material behavior is described by a constitutive model proposed by the authors which includes the SIMT at high strain rates. The process of martensitic transformation is alternatively switched on and off in the simulations in order to highlight its effect on the necking inception. Two different initial conditions have been applied: specimen at rest which is representative of a regular dynamic tensile test, and specimen with a prescribed initial velocity field in the gauge which minimizes longitudinal plastic wave propagation in the tensile specimen. Plastic waves are found to be responsible for a shift in the neck location, may also mask the actual constitutive performance of the material, hiding the expected increase in ductility and energy absorption linked to the improved strain hardening effect of martensitic transformation. On the contrary, initializing the velocity field leads to a symmetric necking pattern of the kind described in theoretical works, which reveals the actual material behavior. Finally the analysis shows that in absence of plastic waves, and under high loading rates, the SIMT may not further increase the material ductility.

1. Introduction

The characterization of the mechanical properties of materials at high strain rates has become increasingly relevant for the industry. Accurate knowledge of those properties is usually required in different engineering applications such as aeronautical [1,2], automotive [3,4], naval [5,6] and manufacturing [7,8], where service conditions involve large strains at high strain rates.

Among the experimental characterization tests, the uniaxial tensile arrangement is definitely the most commonly used due to its simplicity. The uniform state of stress and strain along the gauge for this test greatly simplifies the interpretation of results. However the homogeneous deformation eventually ceases due to the onset of necking in the specimen. Necking in uniaxial stress conditions has been largely studied since it indicates the onset of a process which leads to material failure, and therefore determines the suitability of materials to absorb energy. For quasi-static loading, Considère [9] showed that in a long and thin bar, the neck develops at maximum load. Within the framework developed by Hill [10] on the theory of bifurcation in elastic–plastic solids, different authors [11,12] demonstrated that the strain at maximum load provides a lower bound to the strain at which bifurcation occurs; in specimens showing large length/width ratio localization starts slightly after the maximum load whereas in specimens showing small length/width ratio localization is further delayed.

Under dynamic conditions, the onset of necking is additionally influenced by other factors. Different authors concluded that the condition for instability in tensile tests also depends on the strain rate sensitivity of the material; Woodford [13] and Ghosh [14] collected data from tensile tests of a number of metals, showing a strong delay in necking with increasing logarithmic strain rate sensitivity. In the meanwhile, a number of theoretical works were developed to explain this influence. Hart [15] formulated a stability criterion for materials exhibiting strain rate sensitivity that was later re-examined by Ghosh [16]. Klepaczko [17] developed a theoretical framework to include the effect of temperature in the analysis of instabilities in rate-dependent materials. Hutchinson and Neale [18] concluded that strain rate sensitivity has a strong

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influence on the post-uniform elongation, retarding necking localization. In the recent years, a number of papers has been published which provided further understanding of the interplay between strain rate sensitivity and necking formation [19–23]. Inertia was the following effect considered as influential in the development of dynamic instabilities. Fressengeas and Molinari [24] used a perturbation analysis to discuss dynamic effects on ductility, showing that geometrical perturbations are stabilized by inertia effects. Using a bifurcation analysis, in this case under plain strain conditions, Shenoy and Freund [25] demonstrated also the stabilizing effect of inertia. More recently, one should mention a number of theoretical and numerical works that have provided additional verification of the benefits provided by material inertia to delay necking formation [19,20,26–29]. Material strain hardening is certainly an additional factor which enhances ductility. The Considère condition [9] clearly outlines the favorable effect of a high strain-hardening coefficient in quasi-static conditions, but this effect has also been addressed by different authors under high rate loading conditions [16,17,21,29,30]. These studies considered the influence of parameters, such as material inertia, strain hardening and strain rate sensitivity in absence of wave propagation phenomena.

Among the previous effects modifying the onset of dynamic necking, strain hardening is known to be influenced by microstructural effects such as dynamic phase transformations. Specifically, Strain Induced Martensitic Transformation (SIMT) acts as a highly potent mechanism of martensite germination associated with plastic deformation in the austenitic phase. The transformation of austenite into martensite is comparable to a dynamic composite effect due to the progressive appearance of the martensite during straining, enhancing strain hardening of the steel. Different authors have recently addressed the role played by the SIMT in the dynamic behavior of different steel grades [31–34]. It was observed that this phase transformation mechanism can reasonably be expected to affect the propensity of a material for dynamic necking, a point that deserves further investigation.

High-speed hydraulic machines and Split Hopkinson (Kolsky) Bar devices have been successfully applied to investigate the mechanical behavior of materials at intermediate to high strain rates [35,36], the goal being the determination of the intrinsic properties of the tested material under uniform uniaxial stress conditions. Therefore different authors introduced original tensile specimens to optimize the geometry, favor a homogeneous strain field and delay instabilities [37–40]. However, imposing a velocity boundary condition on one side of a solid at rest – which is needed for dynamic testing – necessarily produces a plastic wave front. In such a case the strain gradients due to the effect of plastic wave propagation in the specimen may hinder the actual constitutive behavior of the material. Under large impact velocities, the strain field becomes rapidly non-uniform, affecting the ductility of the specimen and shifting the position of the neck in the sample. Hopkinson [41,42] and Hopkinson [43] analyzed the dynamic loading of steel wires and observed that they broke at different points along their length depending on the loading velocity; the elastic wave propagation phenomena were considered as responsible for this behavior. Furthermore, Von Kàrman and Duwez [44] and Clark and Wood [45] reported a Critical Impact Velocity (CIV) such that, when exceeded, the force equilibrium is not fulfilled and necking occurs close to the impacted end with negligible subsequent plastic strain in the rest of the specimen. The first theoretical work on CIV was proposed by Von Kàrman and Duwez [44], while Klepaczko [17,46] extended this theory to consider strain rate and temperature effects.

In order to avoid the drawback of the wave disturbances on determining material ductility at high strain rates, the ring expansion test was developed [47] and investigated by different authors [19,30,48,49]. Here, complications resulting from wave propagation are eliminated until the onset of necking due to the symmetry of the problem, which implies that the influence of loading velocity on material ductility can be studied, virtually, without limits on the applied velocity. However, the complicated experimental arrangement required for the ring expansion test impedes the determination of the material stress-strain characteristics. Thus, the uniaxial tensile test, in its dynamic version, cannot simply be ruled out because of suspected wave-related effects, at the benefit of the ring expansion test. This remark calls for an in-depth additional evaluation of the dynamic tensile test, in order to better assess its benefits and also its limitations, while taking into account the occurrence of dynamic phase transformation of the above-mentioned kind.

This paper investigates necking formation in AISI 304 steel sheets subjected to dynamic tension. This steel grade is considered a reference metastable austenitic stainless steel for studying the SIMT process at high strain rates since it shows a large amount of transformed martensite even under adiabatic conditions [50]. The analysis emphasizes the effects of martensitic transformation and plastic wave propagation on flow localization and sample ductility. For that purpose, finite element simulations of a dynamic tensile test have been performed, in which the SIMT has been switched on and off to disclose the effect of the enhanced strain hardening produced by the SIMT. In addition, two different initial conditions have been considered: specimen at rest and specimen with an initial velocity field in the gauge. The analysis shows that in absence of an initial velocity field and within certain ranges of impact velocity the neck may be shifted from the middle toward the ends of the specimen. The shifting of the neck is found to be a limiting factor for the sample ductility. On the contrary, the initial velocity field minimizes the propagation of plastic waves along the longitudinal direction of the sample, thus leading to a rather symmetric necking pattern of the kind described in aforementioned theoretical works [19,27]. Plastic wave propagation phenomena not only affects the ductility of the specimen but may also invert the expected increase in energy absorption due to the SIMT. Furthermore, the role played by the plastic wave propagation hiding the actual material behavior has been highlighted; and a range of strain rates for which the measured dynamic tensile characteristics of a material can be considered as actual material properties has been determined. Finally the analysis shows that in absence of plastic waves, and under high loading rates, the SIMT may not provide further benefits to the material ductility.

The paper is organized as follows. Section 2 provides a brief summary of the thermo-viscoplastic constitutive equations used to model the mechanical behavior of the AISI 304 steel and emphasizes the enhanced strain hardening of the material due to martensitic transformation. Section 3 describes the different finite element models developed to perform the study. In Section 4 the results of the numerical simulations are shown and discussed, focusing the attention on the effects of martensitic transformation and plastic wave propagation on flow localization and sample ductility. The concluding section outlines the main outcomes of this study.

2. Constitutive modeling of strain induced martensitic transformation and calculation of effective properties

A complete description of the model, the values of the parameters identified for AISI 304 stainless steel and its validation with dynamic tensile tests results can be found in Zaera et al. [34,51], but here the key points of the constitutive formulation are further discussed for completeness. The constitutive description is based