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# The deterministic nature of the fracture location in the dynamic tensile testing of steel sheets

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ABSTRACT

This paper investigates the key mechanisms which determine the fracture location in the dynamic tensile testing of steel sheets. For that purpose we have conducted experiments and finite element simulations. Experiments have been performed using samples with six different gauge lengths, ranging from 20 mm to 140 mm, that have been tested within a wide spectrum of loading velocities, ranging from 1 m/s to 7.5 m/s. Three are the key outcomes derived from the tests: (1) for a given gauge length and applied velocity, the repeatability in the failure location is extremely high, (2) there is a strong interplay between applied velocity, gauge length and fracture location and (3) multiple, and largely regular, localization patterns have been observed in a significant number of the experiments performed using the samples with the shorter gauge lengths. Our experimental findings are explained using the finite element simulations. On the one hand, we have shown that variations in the applied velocity and the gauge length alter the processes of reflection and interaction of waves taking place in the sample during the test, which leads to the systematic motion of the plastic localization along the gauge (as experimentally observed). On the other hand, we have detected that the emergence of multiple localization patterns requires short and equilibrated specimens with uniform stress and strain distributions along the gauge. We conclude that the experimental and numerical results presented in this paper show that, in the absence of significant material and/or geometrical defects, the location of plastic strain localization in the dynamic tensile test is deterministic.

## 1. Introduction

In the 1940s, the pioneering publications of Nadai and Manjoine [1], De Forest et al. [2], Clark [3], Parker and Ferguson [4] and Manjoine [5] represented a significant progress in the research of the dynamic tensile test. These works, motivated by the celebrated papers of Mann [6,7], definitely showed that high velocity tests are essential to reveal the true dynamic properties of materials. It was recognized that the performance of some materials under dynamic loading is different from that observed under static conditions. For the first time, the effect of velocity on the capacity of metallic materials to absorb energy was demonstrated. Within this context, special mention requires the thorough experimental investigation conducted in the Guggenheim Aeronautical Laboratory of the California Institute of Technology (directed at that time by Theodore Von Kármán) with the aim of evaluating the impact endurance limit of different metals used in aircraft construction [8–11]. Note that this extensive experimental research was directly driven by industrial concerns. In Beardsley and Coates [9] words *"with the current improvements in aircraft structural design methods, resulting in more efficient structures in which the material is worked at higher stresses, it is becoming increasingly more necessary to consider the effects of dynamic loading on the structure"*.

During the following years, with the continuous support of the aeronautical sector, the efforts were focused on developing a theoretical framework to explain the experimental findings. Thus, Clark and co-workers published a series of papers [12–15] in which the theory of the elastic and plastic strain propagation developed by Von Kármán and others [16–20] was used to interpret in a rational manner the experimental data. A key outcome of these theoretical investigations was to show that the strain rate in impact tests varies from point to point along the specimen, and for a given point it is also dependent upon time [14]. This behaviour, which is accentuated as the impact velocity increases, was identified as the main problem of the tension impact test to study the influence of the rate of strain on the properties of metals.

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The following decades, especially after the development of the tension version of the Hopkinson-bar technique in the early 1960s [21], were very much focused on overcoming this drawback. The belief that the use of very short specimens minimizes the importance of the inertia loads and allows to neglect the intervention of strain propagation phenomena within the specimen became widely accepted [22,23] and the dynamic stress–strain characteristics of different metallic materials were published, see for instance the works of Nicholas [24–26]. On the other hand, the works of Lubliner [27] and Botte et al. [28,29] strengthened the idea that the essential character of the tensile impact test is the non-uniformity in time and space of the state variables of the material. If long specimens are used the parameters which define the state of the material (stress, strain and particle velocity) assume different values in the different sections of the specimen, and they change with time. Botte et al. [28] explicitly stated that numerical analysis becomes indispensable to investigate the spatial–temporal variation of the field variables in detail.

Thus, the advent of computational mechanics gave new impetus to the analysis and understanding of the impact tensile test [30–32]. The finite element method has been widely used over the last years in the design of tensile specimens suitable to extract the true dynamic properties of metallic materials [33–35]. Within this context, it has to be highlighted the work of Rusinek et al. [36] who reviewed the performance of six different specimen geometries loaded in impact tension. Driven by the earlier work of Nemes and Eftis [31], Rusinek et al. [36] paid special attention to the interplay between necking inception, impact velocity and specimen geometry. They showed that, as soon as the impact velocity is such that the strain propagation effects become relevant, the necking moves away from the central point of the sample (where it locates under quasi-static conditions). This observation, which agrees with previous experimental results published by Wood [37], suggests that the necking inception in the dynamic tensile test is a deterministic process. Nevertheless, whether the nature of the necking location is deterministic or random is still a controversial issue, as can be seen from the number of recent publications dealing with this precise topic [38–40].

With the aim of clarifying this controversial issue, in this investigation we have performed an extensive experimental and numerical campaign that reveals the deterministic character of the necking (and fracture) location in the dynamic tensile test. We have carried out dynamic tensile experiments using steel sheet specimens with six different gauge lengths (20 mm, 40 mm, 60 mm, 80 mm, 100 mm and 140 mm) for seven impact velocities (1 m/s, 1.75 m/s, 2.5 m/s, 3.75 m/s, 5 m/s, 6.25 m/s and 7.5 m/s). Similarly to the experiments reported by Wood [37], we have observed that the fracture location moves systematically from side to side of the sample with the variations in impact velocity and gauge length. Further, for each combination of gauge length and applied velocity several repeats are performed which show an extremely high repeatability in the necking (and failure) location. A key, and very unusual, experimental finding of this work is the multiple, and largely regular, localization patterns that have been observed in a significant number of the shortest samples tested. We have explained all these experimental findings with finite element simulations performed in ABAQUS/Explicit [41]. Thus, in agreement with the experiments, the computations have shown that variations in the applied velocity and gauge length lead to the systematic motion of the plastic localization along the gauge. Further, our numerical calculations serve to prove that the emergence of multiple localization patterns is associated to equilibrated specimens with low slenderness ratios and *hardly* subjected to the influence of stress waves.

## 2. Experimental setup and mechanical characterization

### 2.1. Material and specimens

The material of this study is annealed AISI 430 stainless steel. Its chemical composition is given in Table 1.

The AISI 430 is one of the most widely used ferritic stainless steels. It shows excellent stress corrosion cracking resistance and good resistance to pitting and crevice corrosion in chlorine environments. Typical consumer product applications include automotive trim and molding and furnace combustion chambers. Industrial and commercial applications range from interior architectural applications to nitric acid plant equipment and oil refinery equipment [42].

The material is supplied in plates of thickness $h = 1$ mm from which tensile specimens are machined. The specimens' geometry and dimensions are shown in Fig. 1. The impacted side is the left side of the specimen in the figure (and therefore the clamped side is the right side). $L_0$, $L_1$, $L_2$, $L_3$, $W$ and $R$ denote respectively the overall length of the sample, the length of the grip section of the clamped side, the length of the gauge, the length of the grip section of the impacted side, the width of the gauge and the radius of the fillets. The specimens are machined by laser cutting with accuracy of ±0.1 mm. We distinguish between samples used in the quasi-static tests and samples used in the dynamic tests. The quasi-static specimens, identical to those used in Ref. [43], have a gauge length of 20 mm. Note that the quasi-static tests are a requisite to characterize the mechanical response of the material rather than a specific goal of this investigation. The dynamic samples are machined with six different gauge lengths: type 1 with 20 mm, type 2 with 40 mm, type 3 with 60 mm, type 4 with 80 mm, type 5 with 100 mm and type 6 with 140 mm. The dynamic tests are performed in order to uncover the interplay between specimen gauge length, the impact velocity and the fracture location, as further discussed in Section 3. Whether it is a quasi-static or dynamic experiment, at least three repeats are conducted.

### 2.2. Quasi-static testing

The quasi-static experiments at room temperature were conducted using a servo-hydraulic testing machine INSTRON 8516 100 kN under displacement control. We tested specimens whose loading direction formed angles of 0° (parallel), 45° and 90° (perpendicular) with the rolling direction of the plate. The goal was to investigate whether the material displays anisotropy caused by the rolling of the plate. Experiments were conducted for three (initial) strain rates: $\dot{\varepsilon}_0 = 10^{-3}\,\mathrm{s}^{-1}$, $\dot{\varepsilon}_0 = 10^{-2}\,\mathrm{s}^{-1}$ and $\dot{\varepsilon}_0 = 10^{-1}\,\mathrm{s}^{-1}$. In all the experiments the axial strain in the specimen is calculated relying on the cross-head displacement of the machine which has been corrected with knowledge of the elastic modulus of the material as described, for instance, in Ref. [44].

Fig. 2 shows stress–strain curves obtained from specimens tested at $10^{-3}\,\mathrm{s}^{-1}$, that have been cut following the three different orientations (0°, 45°, 90°) investigated. It is shown that the orientation plays a minor role in the material behaviour since the three

**Table 1**
Chemical composition of the AISI 430 stainless steel (wt %) as taken from Ref. [42].

| Fe | C | Mn | P | S | Si | C | Ni |
|---|---|---|---|---|---|---|---|
| Balance | 0.12 max. | 1.00 max. | 0.04 max. | 0.03 max. | 1.00 max. | 16.00–18.00 | 0.5 max. |