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Dynamic Fracture of Ductile Materials

Design of an experimental program to assess the dynamic fracture properties of a dual phase automotive steel

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Abstract

The dynamic behavior of materials must be considered when determining the crashworthiness of a vehicle and the safe design of the vehicle components. Series of mechanical tests at wide ranges of stress and strain rates are essential to identify the material’s damage and fracture behavior identical to realistic conditions. In the present contribution, an extensive experimental program has been developed to assess the dynamic fracture properties of dual phase steel (DP-K 1000). Various tensile specimen geometries covering wide range of stress states are employed for testing at quasi static conditions. The limitations imposed on the sample geometries by clamping technique and requirements of high strain rate test based on split Hopkinson bar test principle restrict the use of static geometries for the dynamic range. An optimization approach based on finite element simulations has been adopted to determine the most suitable dimensions for various tensile specimen geometries quantified by stress triaxiality. The possibility of introducing a standard for dynamic sample geometries has also been investigated. Moreover, the influence of transition zone on the deformation of the specimen has been analyzed and incorporated into the optimization strategy. The optimized specimen geometries are finally adopted for dynamic material testing so as to derive enough inputs for constitutive material modeling and to facilitate fundamental material research.

Keywords: Dynamic, geometry, optimization, stress triaxiality, material modelling.

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1. Introduction

Steels are one of the most important structural materials, enabling technological breakthroughs in various fields, such as energy, transportation, safety and infrastructure. Profound progress in these fields have been achieved through the development of advanced high strength steels (AHSS) fueled by the conflicting demands on the automotive industry to simultaneously improve crash safety and fuel economy. AHSS offer excellent strength and formability properties. Indeed, a high strength is desirable, for weight reduction through down-gauging, while a large deformation capacity is important for good formability. One of the most important grade of advanced high strength steel is the dual phase steel which offers superior formability and energy absorption properties as compared to other steel grades. Dynamic behavior of the material must be considered in determining the crashworthiness of the vehicle and for the effective design of vehicle components. For automotive applications, crash worthiness and consequently, preservation of strength and ductility at high strain rates, is of major importance. Conformance of the product with the applicable standards (as in the case of a crash box) are ensured by performing a series of material and mechanical tests covering the entire range from small scale tensile tests to full scale crash tests under realistic conditions of use.

Mechanical tests at wide ranges of stress states and strain rates are essential to identify the material damage and fracture behavior congruent to real case scenarios. In the present contribution, an experimental program is developed to study the dynamic damage and fracture properties of a CR700Y-980T DP-K 1000 steel with average grain size below 2 μm. The initial yield strength is 765 MPa, the tensile strength 1000 MPa and the uniform tensile elongation 13%. The material was delivered as steel sheets of thickness 1.5 mm.

In order to obtain the strain rate dependent plasticity, damage and fracture properties of the material, an extensive experimental program has been designed. The program involves various tensile sample geometries to cover a wide range of stress states. Regular dog bone, central hole and notch dog bone specimen with different notch radii are adopted for the same purpose. The tests are performed under quasi-static and high strain rate conditions. For the high strain rate tests, a Split Hopkinson Bar (SHB) tensile setup is used. Predefined standards such as ASTM exists for sample geometries to be tested at quasi-static conditions and for basic dog bone geometry at high strain rates. However, the use of the SHB test technique imposes certain limitations on the sample geometry and sample clamping technique. As a consequence, similar geometries cannot be implemented for dynamic tests. Despite the applications of dynamic characterization of materials using SHB, plasticity and fracture tensile test specimens have not been standardized yet. The dimensions of the specimen was found to have direct influence on the force equilibrium as required for split Hopkinson bar testing and final stress-strain behavior [1]. The obtained stress strain curve at a particular strain rate is generally assumed to represent the material behavior. However, it is observed that the changes in specimen geometry -shape and dimensions- give rise to distinct differences in the established mechanical behavior. Size effects and the emergence of non-axial stresses and non-homogenous specimen deformation are to a large extent dependent on the specimen geometry. Hence, the observed behavior is a combination of structural and material response [2, 3]. Structural effects might also result in a delay between established and the actual onset of yielding.

The choice of the most appropriate specimen geometries for dynamic experiments is closely associated with the requirements arising from both fundamental and practical considerations. Herein, an approach using numerical analysis has been discussed which can help in identifying the most suitable specimen geometries which can ensure well controlled stress state and practically eliminate strain inhomogeneity in the specimen arising due to geometrical effects.

2. Methodology

The sample geometries displayed in Figs.1, are proposed for tensile tests on DP steel in static conditions: (a) regular dog bone, (b) specimen with a central hole, (c) Notched Dog Bone (NDB) with notch radius r of 6mm, (d) NDB R20 with r of 20mm and (e) NDB R50 with r of 50mm.
Following technique was used to obtain the optimized geometries for the DP-K1000 steel for dynamic testing. In a first step, finite element (FE) simulations were performed to gain more insight into the stress and strain distribution of the samples of Fig. 1 and variants. Dynamic counterparts of the samples were also designed based on FE simulations. For the dynamic counterparts, specimen geometries in Fig.1 were scaled down. In these samples, a state of quasi-static equilibrium and sufficiently high strain rate are aimed at. Additionally, since the stress state has a major influence on the damage and fracture of ductile materials, stress states similar to the ones in the static samples are targeted. It was observed that directly scaling down the geometries does not yield the targeted similar stress states for all samples. Especially, the central hole sample, which allows to assess the uniaxial fracture response provided that fracture initiates near the hole boundary, required advanced geometrical optimization [4,5]. The Plastic Equivalent Strain (PEEQ) vs stress triaxiality evolutions in the center of the gauge section or at the location where the fracture is assumed to initiate were used as basis for comparison between the static and dynamic geometries. Least square algorithm incorporating Levenburg-Marquardt gradient method is used as a parameter optimization routine to minimize the variation. The similarity between the evolutions in both geometries is used as optimization criterion.

3. Numerical Analysis

3.1 Finite element model

The FE models for the sample geometry optimization were generated using Abaqus Standard. For the DP-K1000 material, a J2-plasticity model with hardening parameters based on tensile test results was implemented. A fine mesh was chosen, with solid C3D8R elements incorporating 20 first order elements along the thickness direction for all the specimens. An extensive analysis was conducted to derive the evolution of stress states quantified by stress triaxiality and deviatoric Lode parameter for both the static and scaled down geometries.

3.2 Influence of transition zone

The contribution of the deformation of the shoulder of the specimen (transition zone) to the total deformation is not negligible. Deformation of the transition zone has a significant impact on the deformation of the central zone resulting in an overestimation of strain in that region when classical equations alone are used to evaluate the strains [3]. Radius of the transition zone is the geometrical parameter which contributes to this effect. Hence numerical observations were carried out for various radius of the shoulder (R=1, 2, 3, 4 and 5 mm) to understand the influence of this dimension on the equivalent plastic strain at the center for a smooth dog bone tensile specimen.

Fig. 1 Tensile sample geometries for low strain rate testing (all dimensions in mm): a) dog bone tensile, b) central hole, c) NDB R6 d) NDB R20, e) NDB R50
Fig. 2. Equivalent plastic strain at the centre of the gauge section vs displacement for various radius \((R=1, 2, 3, 4 \text{ and } 5)\) of the transition zone

Fig. 2 depicts the distribution of equivalent plastic strain at the centre of the gauge section for a uniaxial tensile sample when different transition radii are employed. It was observed from the numerical simulations that an increase in the radius of the transition zone leads to a decrease in the equivalent strain in the centre at a certain level of displacement. This substantiates the fact that a significant amount of deformation takes place in the transition region for larger radius thereby reducing the strain in the centre. Considering this influence and possibility of obtaining higher strain rates with smaller radius, transition radius of 1 mm was employed for regular dog bone specimen. Transition radius, R2, yielded satisfactory results for other fracture tensile specimen geometries based on numerical analysis.

3.3 Effect of mesh size

The size of the mesh utilized directly controls the accuracy of the finite element simulations. For the analysis, different mesh sizes were applied to study its influence on the effective distribution of stresses and strains. Rather coarse to very fine mesh arrangements were adopted. Table 1 displays the size of the mesh and the corresponding number of elements over the thickness for the proposed mesh. From 5 to about 30 elements were applied over the thickness of the specimen to obtain different ranges of mesh sizes.

<table>
<thead>
<tr>
<th>Mesh size</th>
<th>Total number of elements</th>
<th>Elements over the thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>16420</td>
<td>5</td>
</tr>
<tr>
<td>Moderate</td>
<td>47299</td>
<td>10</td>
</tr>
<tr>
<td>Fine</td>
<td>90438</td>
<td>20</td>
</tr>
<tr>
<td>Very fine</td>
<td>168405</td>
<td>30</td>
</tr>
</tbody>
</table>

Fig 3 shows the distribution of equivalent plastic strain for the highest strained element of NDBR20. Coarse mesh exhibited large variations in the distribution throughout the loading cycle. On the other hand, mesh with 20 and 30 elements over the thickness provided very good and consistent results for the entire loading range. Similarly, mesh sizes as depicted in Table 1 was applied for all the tensile specimen geometries and evaluation based on the variation of equivalent plastic strain with stress triaxiality was performed for all the specimen geometries to arrive at a conclusive result for the most appropriate mesh configuration. Similar observation as in Fig.3 was made for other specimen geometries, wherein larger deviation from the intended stress state was observed for coarse and moderate mesh sizes and higher conformance with the targeted stress state was achieved with fine and very fine meshes.
Fig. 3. Equivalent plastic strain of the highest strained element (NDBR20) vs stress triaxiality for different mesh sizes

The fine mesh was ultimately selected for the finite element approach in view of the extensive computational effort needed for very fine meshes.

3.4 Analysis of the geometrical parameters

As previously stated in section 2, for numerical analysis of the specimen geometry parameters, static and dynamic geometries are designed based on FE simulations and evolution of equivalent plastic strain as a function of stress triaxiality and lode parameter are compared for selected integration points across the surface and over the thickness of the specimen. The entire specimen is modeled so as to have an indication of the in-plane and through thickness stress and strain gradients. 6 elements namely center, edgeface1, edgeface2, midface1, midface2 and thickness center are defined across the surface and over the thickness for the dog bone and notched samples.

Fig. 4 Elements or integration points over the surface and thickness of the specimen of a) dog bone and notched dog bone specimen b) central-hole specimen

Similar integration points are also defined for central-hole specimen excluding the centre. Additionally, 4 elements are further defined; holeedge1, holeedge2, thickness centre at holeedge1 and thickness centre at holeedge2. Selected elements for all the specimens are described in Figs. 4. The selection of the length of the dynamic specimen geometry is heavily constrained by the objective to achieve very high strain rates. As such, specimen gauge length of 6 mm was arbitrarily selected for all the samples.
Fig 5 illustrates the impact of Lode parameter on the equivalent plastic strain distribution at selected integration points over the surface and over the thickness of dog bone specimen geometry. The effect of the deviatoric component was found to be minimal and nearly constant. Similar observations were also obtained for other tensile sample geometries. Hence, the optimization was primarily focusing on the evolution of stress triaxiality and the analysis of stress gradients.

Considerable disparities were observed in the stress and strain evolutions at the defined integration points between static geometries and their scaled down (25%) dynamic counterparts. Figs. 6 (left and middle) depict the stress distribution and thickness reduction for a notched dog bone specimen with a radius of 20 mm. Through thickness necking results in out of plane stresses and leads to an increase in the stress triaxiality after the maximum force has been obtained. The existence of stress gradients in plane and over the thickness in the center of the gauge section was evident from the simulations, as can be seen in Fig. 6 (right), which shows the PEEQ vs stress triaxiality for several points over the thickness in the center of the gauge section.

In fig 6 (c) solid lines represent the evolution as defined by the static geometries, whereas the dotted lines belong to dynamic specimens. It is clearly seen that plastic strain evolution of both the specimen geometries does not match. Such difference was also displayed by the other tensile specimen geometries. Hence, a parameter optimization was performed to identify the dimensions for each specimen geometry. Width of the specimen and radius of the notch were the parameters to be optimized for dog bone and notched dog bone specimens whereas appropriate width and hole diameter were to be identified for the central-hole specimen.

Design of the dog bone was relatively straightforward as it was subjected to conform to the standards as stated under DIN-ISO 26203-1:2010 for elastic bar type systems [6]. The ratio of the length of the specimen to its width is suggested to be greater than or equal to 2 as per the standard. Hence, it was taken into consideration while selecting the geometry. Comparable results were achieved for a dog bone specimen geometry with a length of 6 mm, width of 3 mm and transition radius of 1 mm.

Parameter analysis was then performed on notched dog bone specimens to determine the optimum dimensions from a wide range of width and notch radii. Numerical analysis on these specimens resulted in some
interesting observation. The width of the specimen was found to be influential on the variations in the through thickness gradients whereas the radius of the notch has substantial effect on the in-plane gradients exhibited by the specimen.

![Stress triaxiality vs notch radius](image1)

![Stress triaxiality at highest strained element vs Width/Notch radius](image2)

**Fig. 7** a) Effect of notch radius on the in-plane gradients b) Effect of width/ notch radius on stress triaxiality of the highest strained element

Figure 7 (a) displays the effect of the radius of the notch on the in-plane gradients and stress triaxiality at the highest strained element of NDBR6 having a specified width of 3mm. It can be seen that stress triaxiality gradually approaches the uniaxial condition (triaxiality=0.33) from a triaxiality of 0.43 for smaller notch radii in the range 0.4-0.5. Beyond this range, triaxiality keeps on increasing up until notch radius R1. Thereafter, a decreasing trend is observed for triaxiality with notch radius. Effect of the ratio of width of the specimen at the centre to the radius of the notch (W/R) on the stress state of the highest strained element was extensively analysed while undergoing the parameter optimization, see Fig 7 (b). Higher stress triaxiality was obtained for smaller W/R. Here, smaller width of the specimen give rise to noticeable through thickness gradients which eventually result in non-axial stresses in the specimen as a consequence of through thickness necking. Uniaxial condition was attained for a ratio of 4 and sufficiently close stress states were obtained in the range 3.5-4.2. Larger ratios also tend to increase the triaxiality however much lower than triaxialities at smaller ratios.

Optimised dimensions of 6, 1.6 and 0.4 mm were obtained for respectively the gauge length, width at the centre of gauge section and notch radius for dynamic variants of the NDBR6 specimen. Similarly, parameter analysis on the counterparts of NDBR20 and NDBR50 specimens delivered the following optimised geometrical values; Gauge length, width at centre and notch radius of 6, 2 and 1.8 mm respectively for NDBR20 and 6, 1.6 and 4.5 mm for NDBR50. Width to notch radius ratio greater than 3.5 is preferable for triaxiality close to the uniaxial stress condition.

Central hole specimen is highly significant for fracture response as this geometry provides a better insight into the material’s fracture behaviour and aid in characterizing the material’s ductility under uniaxial tension better than a dog bone specimen provided that the fracture initiates near the hole boundary. Gauge length of 6mm was also adopted for this specimen geometry to account for high strain rates. Hence, the geometry has to be optimised for determining the most suitable specimen width and more importantly the diameter of the hole. Variations in hole diameter has a direct consequence on the plastic strain distribution within the specimen.

![Plastic strain distribution](image3)

**Fig. 8** Plastic strain distribution for specimen with a) smaller dia b) larger dia

Figure 8 (a) and (b) describes the effect of hole size on the plastic strain distribution of a central-hole sample. Highest strained element in the specimen with larger holes was found to propagate from hole edge to the hole ligament.
centre. In such a scenario, two hole ligaments behaves similarly to two parallel uniaxial tensile specimens. Hence, stress triaxiality remains constant (0.33–0.34) up until the occurrence of through thickness necking. Conversely, for very small holes, gradients in the mechanical fields were found to rise considerably.

Fig. 9.a) Influence of hole-dia/width on the stress triaxiality at the highest strained element b) Variation of stress triaxiality with nominal thickness

A higher ratio of hole diameter to the width exhibited stress response closer to a uniaxial stress condition. A uniaxial stress state was purely achieved for the highest strained element at a hole diameter to width ratio of 0.625. Figure 9 (a) displays the impact of this ratio on the stress state for central hole specimens. Triaxiality continuously describes a declining trend with increase in the ratio. Hole diameter to the width ratio greater than 0.575 can be adopted for such specimens as these conditions results in a stress state closer to uniaxial state. Nominal thickness or in other words width of each ligament in a central-hole specimen can also be utilized to standardize the central hole geometry. Figure 9(b) shows the variation in the stress triaxiality for a wide range of nominal thicknesses considered for parameter optimization. Lower nominal diameter values can be adopted as stress triaxiality values near to uniaxial condition can be obtained for such ratios. A nominal thickness of 0.75 yielded uniaxial homogenous stress condition for the highest strained element in a central-hole specimen. Range of nominal thickness less than 0.8 can also be adopted for similar geometries.

Hole diameter of 2.5 mm was obtained as the most suitable hole size in conjunction with width of 4 mm for the central hole specimen based on the results from the parameter analysis.
Figure 10 Equivalent plastic strain as a function of stress triaxiality for a) Simple dog bone specimen- top left b) NDBR6- top right c) NDBR20- mid left d) NDBR50 – mid right e) Central hole – bottom

Figs. 10 (a) to (e) illustrates the evolution of equivalent plastic strain as a function of stress triaxiality for different tensile static geometries and their comparison with optimized dynamic counterparts. Solid lines represents plastic strain evolution of the static geometries at discrete integration points as defined earlier. Dotted lines represents their dynamic variants. The geometries obtained as a result of parametric optimization were found to deliver stress states similar or closer to that of the quasi static geometries at all the integration points considered for this analysis. The uniaxial stress state is maintained up to the point of through thickness necking, triaxiality increases beyond that point. Hence, the final geometries can be used for mechanical testing at high strain rates to obtain stress-strain behavior with minimal structural response.

4. Conclusions

A numerical approach was carried out to determine a standard in deciding the geometries for dynamic tensile experiments. Although, the proposed method is adopted and optimized for DP-K 1000 steel, the technique can be tailored to any material to find out the most appropriate specimen dimensions. Following conclusions were derived from the study:

- Length to width ratio greater than or equal to 2 yields satisfactory results for mechanical behavior for pure tensile dog bone sample geometry.
- Transition zone has a significant impact on the total deformation of the specimen and deformation locally at the center of the gauge section. As such, transition region should also be included in the optimization process.
- Smaller notch radius is preferred to achieve constant uniaxial stress state and width to the notch radius ratio greater than 3.5 was found to deliver acceptable ranges of stress states for the dual phase material.
- Larger ratio of hole diameter to width (>0.575) and smaller nominal thickness (<0.8) was found to be optimal for ensuring the continual uniaxial stress state by the central hole specimen geometry.

Figs 11 (a) to (e) shows the final tensile specimen geometries obtained after applying the optimization approach mentioned in this paper:
The newly developed specimen geometries help obtain experimental data for fundamental material research and constitutive material modelling, including damage and fracture.

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References