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Analysis and modeling of the failure behavior of carbonitrided parts

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Abstract

This work aims at a better understanding and modeling of the failure of carbonitrided pinions made out of 20MnB5 steel. Carbonitriding is a thermochemical treatment inducing high surface hardness while preserving significant core ductility. This results in graded microstructure and properties which makes the prediction of failure particularly complex: brittle external layer, ductile core material. A test bench was specifically designed to load one tooth of the studied pinions with a lateral force until complete failure. In situ observations were performed and the load-displacement curve recorded, showing a variety of behaviors as a function of the teeth engagement depth. The presence of the carbonitrided layer induces only a slight force and toughness increase. The main failure mechanism comes from shear failure of the ductile core material which will therefore be studied in this paper. Experimental tests with various stress states were conducted to measure plastic properties as well as to calibrate fracture criteria for the core steel. Von Mises plasticity and a simple strain hardening curve fit very well all these experiments. As fracture criteria from the literature were unable to predict failure correctly for all the mechanical tests, an adapted criterion has therefore been proposed as an outcome of this extensive mechanical testing campaign. Fracture simulations in LS Dyna were performed using the element erosion technique, the limitations of which are discussed. Comparison with the experimental tooth fracture allows evaluation of the proposed failure criteria, and enables to highlight and discuss the present limits of the simulation.

Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.

Keywords: carbonitriding; ductile - brittle failure; graded material; failure criteria; stress triaxiality ratio; Lode parameter

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1. Introduction

In the automotive industry, carbonitriding is a common thermochemical treatment for improving steel components' surface hardness. The study focuses on carbonitrided pinions made out of 20MnB5 steel, inserted in a "recliner", a safety mechanism controlling the inclination of the back of automotive seats (see Fig. 1.a). Carbonitriding consists in enriching in Carbon and Nitrogen a superficial layer of steel components by heating them in the austenitic range in an atmosphere enriched in the aforementioned elements. Then the parts are quenched to trigger martensitic transformation. The treated steel is thus a gradient property material, with a continuous transition (Fig. 1.b) between a 200 µm deep very hard external layer (high %C martensite, 850 Hv) and a more ductile core material (bainite and/or low %C martensite, 450 Hv). This is an interesting feature for power transmission parts such as gears. These recliners may be severely loaded during crash analyses and it is essential to predict failure correctly. However, these gradient properties make the prediction of failure particularly complex.

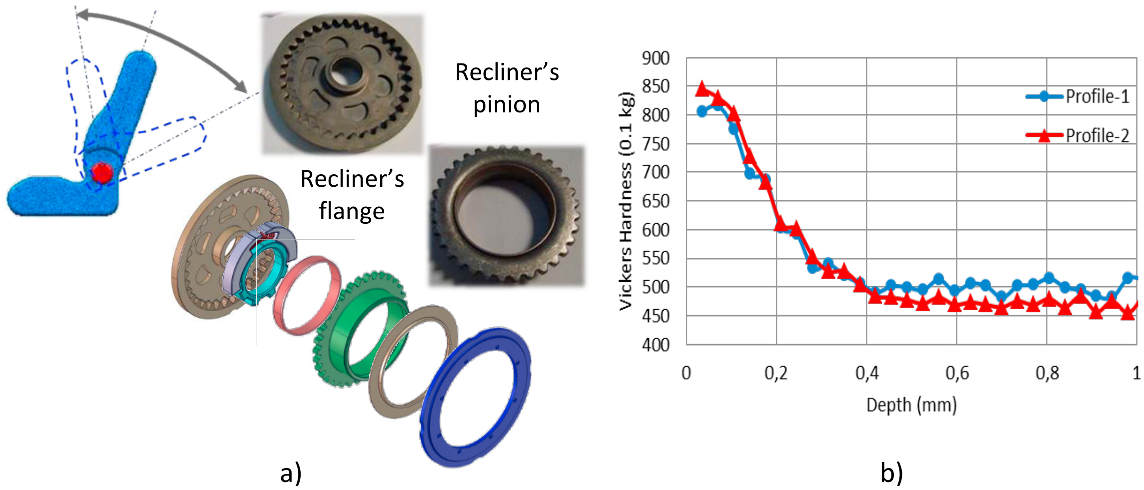

Fig. 1. (a) Seat recliner; (b) hardness profile after carbonitriding.

To understand these failure mechanisms, an analysis of the failure behavior of the teeth of the pinions of seat recliners in an industrial test has been conducted. This analysis confirms the dual failure behavior in a shear mode: brittle in the external carbonitrided layer and ductile in the core material, with a transition area around 250 µm depth [1].

In order to get a better control of the most important parameters, a dedicated test bench where one single tooth of the pinion is submitted to a lateral force until complete failure was developed and is presented in *Section 2*. In situ observations can be performed and the load-displacement curve recorded, both showing a variety of behaviors as a function of the teeth engagement depth and of the presence or not of the carbonitrided layer. Based on these observations, it appears that the driving mechanism leading to final teeth failure is ductile fracture of the core material. Only the core material will thus be presented in the following. *Section 3* describes the failure criteria adopted as well as the calibration procedure. Simulations of teeth shearing tests were conducted with the LS Dyna finite element software. Failure modeling was therefore restricted to the element erosion technique, the limitations of which are discussed with the results in *Section 4*. Comparison with the experimental tooth fracture measurements achieved on the test bench allows evaluation of the proposed failure criteria, and enables to emphasize and discuss the present limits of the simulation for future improvements in S*ection 5*.

2. Design of a semi-industrial test bench and observed failure mechanisms

The test-bench was designed so as to analyze precisely failure mechanisms occurring during the shear loading of a carbonitrided pinion tooth. Fig. 2.a shows a schematic view of the test bench, where the pinion (in red) moves up and the pinion tooth is sheared by the tool (dark green) which is fixed. In order to get the exact local displacements, digital image correlation (DIC) is used on both the tool and the pinion (See Fig. 2.b). Finally, the test-bench is also designed to enable the analysis of various engagement depths *e* (defined in Fig. 2.c) on failure modes.

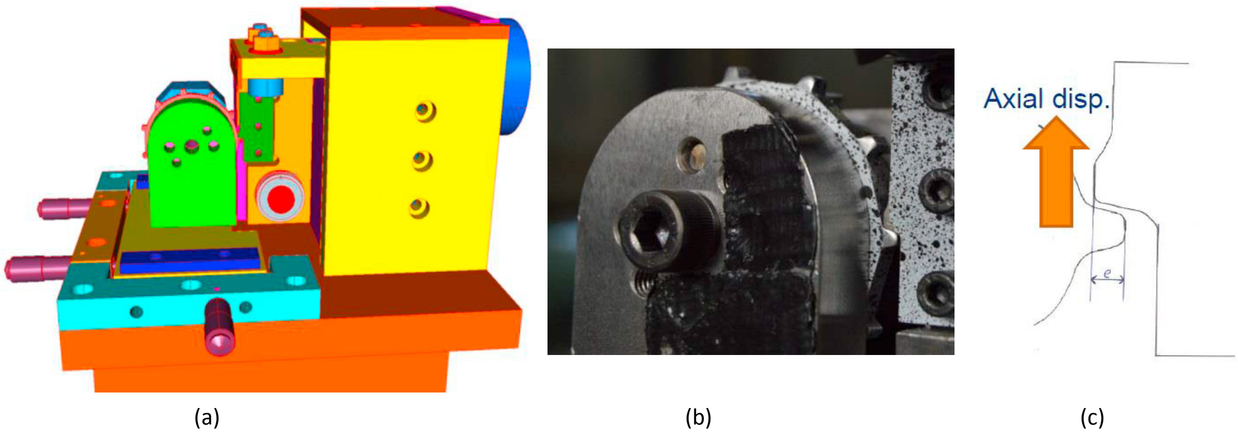

Fig. 2. (a) Schematic view of the semi-industrial test-bench; (b) close-up view of the loaded tooth; (c) definition of engagement depth *e*.

A comparison between carbonitrided pinions (CN), and pinions made out of the core material only[1] (CMO) is carried out. Results, detailed in [1], show only a slight force and toughness increase for the CN pinions compared to the CMO ones. Carbonitriding is indeed interesting in terms of contact properties for such components, and the benefits in terms of failure resistance remains small. The engagement depth analysis shows that higher engagement depth leads to higher sustained load before failure.

Regarding failure mechanism (see Fig. 3.), the initial crack (purple arrow) appears below the contact surface with the tool indicated by a green arrow in Fig. 3. The CN layer is brittle and multiple superficial cracks initiate and propagate in the CN layer perpendicularly to the maximum principal stress. In the depth, these cracks usually stop in the transition area. Final failure is due to a main shear crack in the core material.

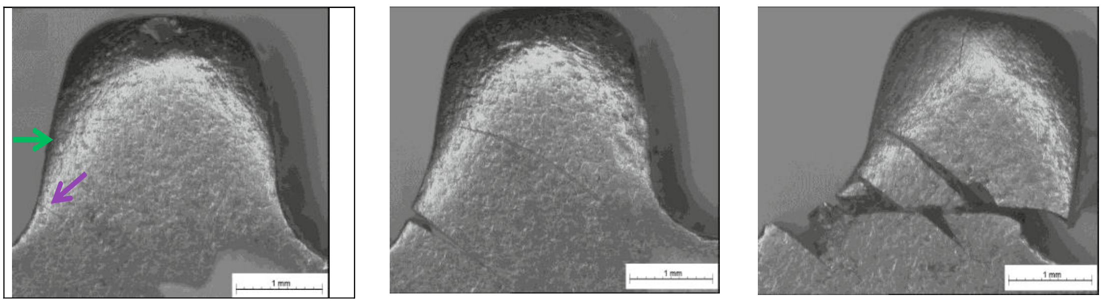

Fig. 3. Failure mechanisms observed on a carbonitrided pinion tooth.

[1] An anti-carbonitriding paint is used to obtain pinions with the same core microstructure as the CN pinions and without any superficial CN layer.

The analysis of the full carbonitrided material is detailed in [1]. However, as final failure is essentially due to shear ductile fracture of the core material, this paper will concentrate on the behavior and failure properties of the core material only.

3. Calibration of material behavior and failure criteria

Ten characterization tests with different stress states (tensile (T), tensile notched (TN7 and TN9) and grooved (TG1 and TG7), butterfly specimens for dominant shear (but-10, but-S, but-+5) or tension (but-T)) were performed and parameters identified through numerical simulation and inverse analysis. See [1] for more details.

Regarding material behavior, isotropic von Mises plasticity and a modified Voce law ([1, 2]) were chosen for the core material and a good match was obtained for the ten tests.

Regarding ductile fracture, it was decided to use failure criteria accounting for both the stress triaxiality ratio and the Lode parameter. The damage variable, *D*, is defined by Eq. 1, where $\overline{\varepsilon_p}$ is the equivalent plastic strain and $\overline{\varepsilon_f}$, the plastic strain at failure, is a function of the stress triaxiality ratio η and the Lode parameter $\bar{\theta}$.

$$D\left(\overline{\varepsilon_p}\right) = \int_0^{\overline{\varepsilon_p}} \frac{d\overline{\varepsilon_p}}{\overline{\varepsilon_f}(\eta,\bar{\theta})} \qquad (1)$$

Many functions $\overline{\varepsilon_f}$ were proposed in the literature (See [1, 2] for some of them). The parameters of these functions need to be identified with experimental tests with different values of stress triaxiality ratio and Lode parameter. The 10 tests chosen for this study enable a range of stress triaxiality ratio $\eta \in [-1.2; 1.1]$ and of Lode parameter $\bar{\theta} \in [-0.5; 1]$. Identification of failure criteria parameters is achieved through a hybrid numerical-experimental analysis described in [3].

Several fracture criteria from the literature were tested, among which were the Bai & Wierzbicki criterion [4] and the Lou & Huh criterion [5]. None of them succeeded in representing correctly strain to failure for all 10 mechanical tests. An adapted criterion has therefore been proposed as an outcome of this extensive mechanical testing campaign. For this particular quenched steel, it suggests a quasi-independence on the Lode parameter except for very high values ($\bar{\theta}$ = 0.8 – 1.0) where the strain to fracture strongly increases. Stress triaxiality influence is represented by three branches of exponentials:

$$\begin{aligned}
\varepsilon_f(\eta,\bar{\theta}) &= (C_1 + C_2 * e^{-C_3*\eta}) * \left(1 + L_1 * e^{L_2*|\bar{\theta}|}\right) \quad for\ \eta \le 0.05 \\
\varepsilon_f(\eta,\bar{\theta}) &= (C_4 + C_5 * e^{-C_6*\eta}) * \left(1 + L_1 * e^{L_2*|\bar{\theta}|}\right) \quad for\ 0.05 \le \eta \le 0.8 \\
\varepsilon_f(\eta,\bar{\theta}) &= (C_7 + C_8 * e^{-C_9*\eta}) * \left(1 + L_1 * e^{L_2*|\bar{\theta}|}\right) \quad for\ 0.8 \le \eta
\end{aligned} \qquad (2)$$

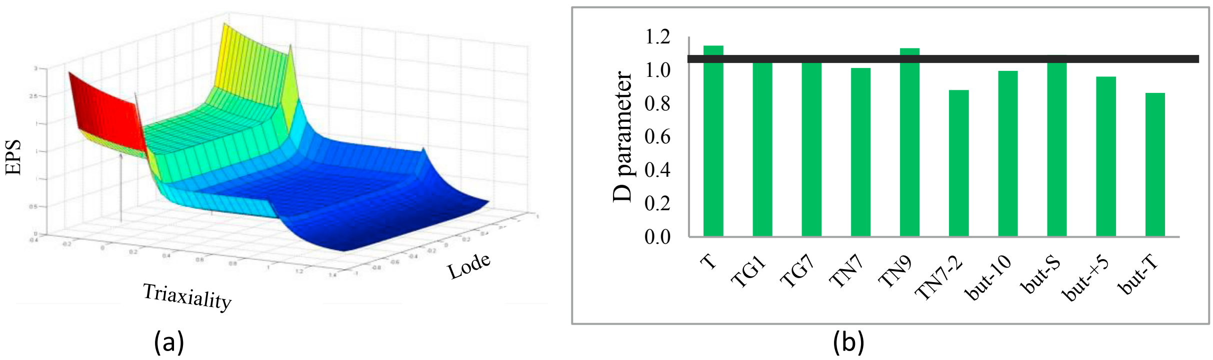

Fig. 4. (a) representation of the fitted failure surface (in the space of Lode parameter, triaxiality, and strain to fracture) of the new exponential failure criterion; (b) prediction of damage for the 10 experimental tests.

The resulting function (Fig. 4.a) representing strain to fracture as a function of stress triaxiality ratio and Lode parameter differs from the functions usually seen in the literature. Fig. 4.b shows the prediction of the failure criteria for the 10 calibration tests. Green columns correspond to the damage value given by the criterion when the experimental displacement to fracture is reached. This value should therefore be as close as possible to 1 to predict failure correctly. The average discrepancy for this criterion is 8% whereas the discrepancy for the Bai & Wierzbicki criterion and the Lou & Huh criterion are respectively 24% and 21%.

4. Failure modeling of carbonitrided pinions

Simulations are carried out using the finite element software LS-Dyna with 8-nodes hexahedral elements and reduced integration. Only one sector of the pinion corresponding to one tooth is modelled and displacements are applied based on DIC measurements on the test bench. Failure criteria are implemented through the GISSMO model in LS-Dyna and failure is modelled using the element erosion technique. This is the only technique available in LS-Dyna for modelling such 3D ductile fracture.

Simulations presented here were carried out on pinions made out of the core material only. These pinions exhibit ductile failure. Fig.5 shows the load-displacement comparison between experimental tests and numerical simulations for three different engagement depths. The maximum load reached is in very good agreement whereas the displacement to failure is slightly overestimated. However, the analysis after experimental failure must be taken with care since boundary conditions adopted for numerical simulations come from DIC measurements, which are not reliable beyond the onset of fracture if fracture did not already occurred numerically. Fig.6 shows the tooth failure for the medium engagement and its comparison with experimental observations. The shear-based failure mechanism is well predicted, and it can be concluded that the new proposed failure criterion is well-suited for the modelling of pinions made out of core material only.

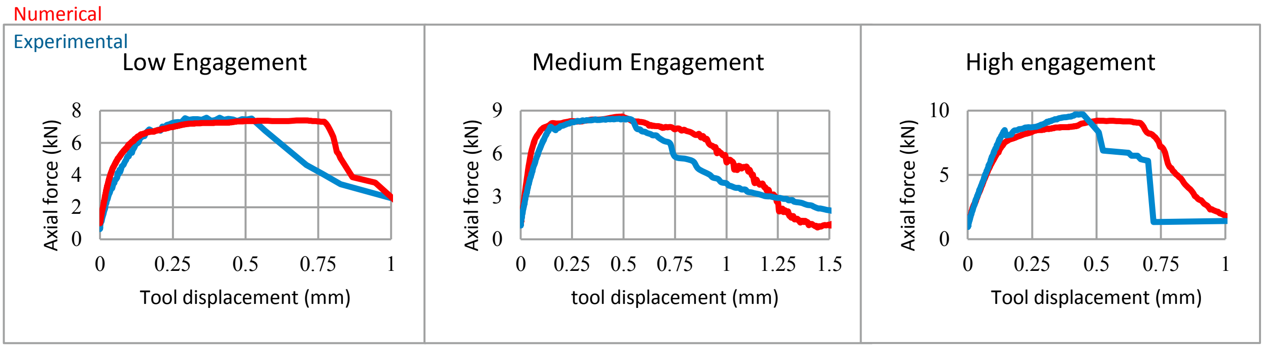

Fig. 5. Comparison of experimental and numerical load-displacement curves for 3 different engagement depths and for the core material only

5. Conclusion

In this work, the failure mechanisms of carbonitrided pinions made out of 20MnB5 steel was studied. A test bench was designed so as to analyze these failure mechanisms in terms of load-displacement curves together with local observations of failure on the pinion's tooth. Due to the small influence of the carbonitrided layer in terms of maximum load and toughness of carbonitrided tooth, it was decided to concentrate here on the core material only. The identification of material behavior and of failure criteria parameters was based on 10 experimental tests with significant variation of stress triaxiality ratio and Lode parameter. As failure criteria from the literature were unable to predict correctly failure for the 10 tests, it was decided to define a new failure criteria with a quasi-independence on the Lode parameter except for very high values ($\bar{\theta}$ = 0.8 – 1.0) where the strain to fracture strongly increases. Simulations were carried out with LS-Dyna and for three different engagement depths. The overall results are in good agreement with the experimental ones both in terms of load-displacement curves and failure pattern.

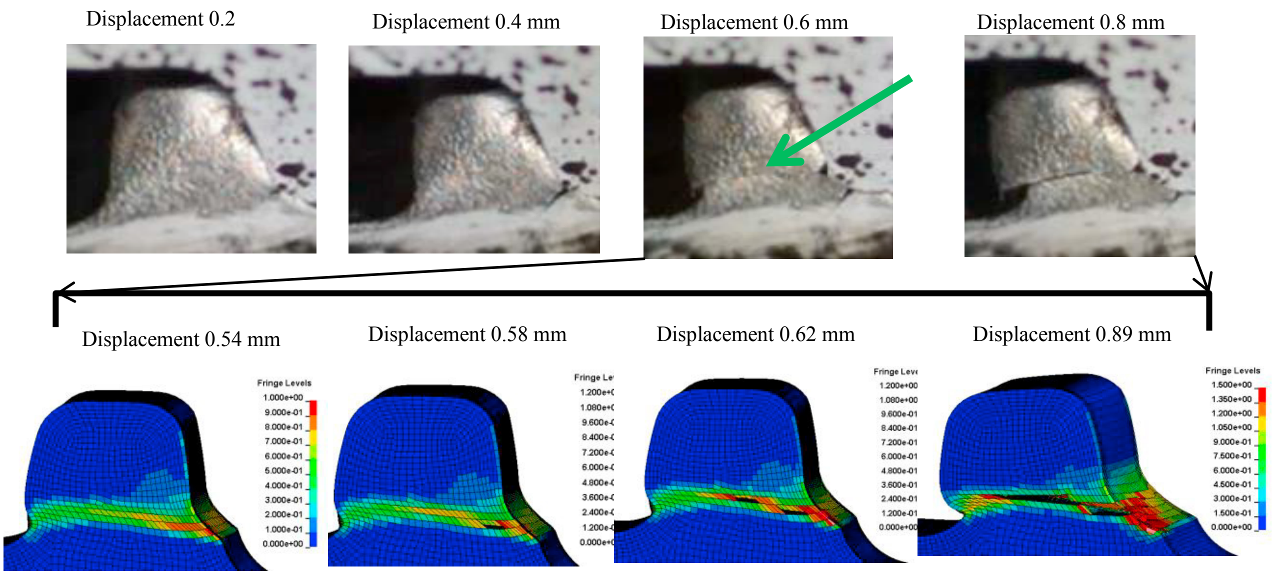

Fig. 6. Shear failure of the tooth made out of core material only for the medium engagement depth

The same analysis was conducted for carbonitrided pinions. The CN layer was represented by 3 elements with a thickness of 0.2 mm. Brittle failure of this CN layer was considered using a stress-based criterion detailed in [1]. The overall failure pattern was in reasonable agreement with experimental observations. However, failure tends to occur too fast in the CN layer, which led to an underestimation of the maximum load and of the displacement to fracture. This is due to the element erosion technique which leads to significant volume loss and which does not allow controlling failure energy properly. In addition, it was shown that simplifying the modeling of this carbonitrided material with only two different behaviors (CN layer and CMO) was not accurate enough to describe properly the transition from brittle to ductile fracture and the crack arrest observed in the transition zone.

In the future, more efforts should therefore be spent on a better understanding, characterization and modeling of the transition area. In addition, the use of more advanced numerical failure-modeling techniques (such as discrete crack propagation or cohesive zone models) would definitely improve the accuracy of carbonitrided pinions failure modeling.

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