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# Comparison of reduction ability between multi-stage cold drawing and rolling of stainless steel wire – Experimental and numerical investigations of damage

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ABSTRACT

The present paper deals with the comparison between two multi-stage cold forming processes on an austenitic stainless steel, wire drawing and wire rolling, in terms of reduction ability. In the first step, experimental tests are carried out and reveal that, starting from an identical initial wire, higher reduction can be obtained with the drawing process. In the second step, numerical simulations are employed to investigate ductile damage in these two processes, using the phenomenological fracture criterion proposed recently by Bai and Wierzbicki (2008) and the coupled Lemaitre model in the framework of continuum damage mechanics (CDM). For the applications to forming processes, the models' parameters are identified first based on different mechanical tests at different loading configurations. Applications to wire drawing and rolling processes show the validity of these two models in fracture prediction both quantitatively and qualitatively. These two damage models are capable of predicting accurately the instant of fracture and also confirm the experimental comparative results between the reduction abilities of the two processes. Between the two studied forming processes, the results suggest the use of the drawing process instead of the rolling process to reduce wire section with minimum damage. It also shows that numerical simulations with the two developed damage models could be an effective tool to investigate ductile damage in other forming configurations or processes.



## 1. Introduction

For all industrial cold forming processes, understanding and modeling ductile damage mechanisms remain a major issue in view of obtaining defect-free products. In addition, significant costs can be saved if the failures are predicted and eliminated in the "prototyping" phase. The ability of numerical modeling to predict ductile fracture is indeed crucial, but it is still limited in the case of complex loading paths (multi-axial and non-proportional loadings). In particular, important shear effects exist in several forming processes, where the stress triaxiality ratio is nearly zero, and their impact on damage and fracture is still poorly known.

Regarding the wire drawing process, defects in drawn wire come from both the initial defects from the preform and the deformation process itself. The common defect observed in drawing is chevron cracking or central burst (also called "cupping" – cup and cone fracture), which were early studied by Avitzur (1968). Venkata Reddy et al. (2000) compared three ductile fracture criteria for the prediction of chevron cracks in axisymmetric drawing: hydrostatic stress criterion, the Thomason's fracture criterion (Thomason, 1968) and the critical damage criterion.[1] Among these criteria, the hydrostatic stress criterion (proposed by Venkata Reddy et al., 1996) was found best adapted to central burst prediction during drawing. McAllen and Phelan (2007) analyzed the occurrence of central burst defects in single and multipass wire drawing by using a modified damage work model and the Gurson–Tvergaard–Needleman (GTN – Gurson, 1977 and Tvergaard and Needleman, 1984) model to define the flow rule and the yield function. With this approach and using the element removal technique (i.e. the element is removed when its damage variable reaches a critical value), the authors investigated the influence of central burst formation on the distribution

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[1] This criterion is a modification of the Lemaitre model to account for "*void nucleation*" as proposed by Dhar et al. (1996).

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of die pressure, hydrostatic pressure and the effective stress along the central line. The results showed a fluctuation of these parameters along the central line, with the "wavelength" equal to the distance between two consecutive central bursts. This oscillation came from the fact that fracture relaxes the tensile stress, which takes a certain distance to recover. Moreover, the die land was demonstrated to have a negligible effect on damage and mechanical properties such as stress and strain state. Tang et al. (2011) used the GTN model for the numerical simulation of damage evolution in multi-pass drawing. An optimization procedure, based on least damage accumulation principle, was proposed to define an optimal area reduction in a single pass drawing, with a constant semi-angle ($\alpha = 4^{\circ}$). The authors then proposed a potential replacement of the standard 8-pass process with a 7-pass one, for the same total area reduction through the following drawing schedule: reduction should be low in the first pass, then increase in second pass and gradually decrease in the following passes. Although successful applications were obtained with above-mentioned studies, few of these results were validated by experiments. Massé et al. (2013) performed an optimization on a single drawing pass to deduce an optimal die angle to minimize drawing force and damage using the Latham–Cockcroft fracture criterion (Cockcroft and Latham, 1968). Based on multi-objective optimization, the authors showed that for the range of industrially used angles, a strong decrease of damage could be obtained at the expense of small increase of drawing force. However, this conclusion was obtained qualitatively with a simple damage model (which can only indicate the maximum damage location, but cannot predict the instant of fracture). Furthermore, it was not compared with experimental results. It should be emphasized that numerous studies have been performed in the literature on the influence of the cold drawing process on materials properties. One can cite the effect of cold drawing on susceptibility to hydrogen embrittlement of prestressing steel (Toribio and Lancha, 1993), or on microstructure and corrosion performance (Toribio and Ovejero, 1997). In the present study, only the damage accumulation during the process is investigated, interested readers can refer to the aforementioned references for other aspects.

Concerning the wire rolling process, there are few studies in the literature dealing with the damage and fracture prediction in cold rolling of long products. The reason may be that few products are made by cold rolling and the simulation of such process is often 3D by nature, which has only been possible for the past twenty years. Recently, Massé and coworkers (Massé et al., 2012) performed SEM (scanning electron microscopy) observations of damage state in a wire flat rolling process. The authors reported a higher void density in the wire core and in the "blacksmith cross", which led them to a conclusion that these zones were the danger zones in such a process. They then used the Lemaitre damage model to study the localization of damage, but it failed to predict the above-mentioned danger zones. The reason is that these critical areas coincide with "sheared" zones, in which the stress-triaxiality based damage variable is nearly deactivated.

From the above results, it can be observed that numerous studies were carried out in the literature to analyze fracture in wire drawing process, principally to predict the central burst. However, few studies give quantitative results regarding the real instant of fracture and compare these results with experimental observations. Concerning the cold wire rolling process, limited studies were carried out and the ability of numerical simulation in predicting fracture observed in experiments is still questionable. Moreover, regarding damage models, those used were relatively simple, and sometimes could not describe the complex damage localization in such processes. In addition, it should be noted that the identification of damage models parameters plays an important role to obtain a reliable prediction, and few studies among the above-mentioned detailed the method used to obtain these parameters.

In the present study, the comparison of two multi-stage cold forming processes, namely wire drawing and wire rolling, in terms of reduction ability for a stainless steel is addressed. In the first part (Section 2), experimental wire drawing and rolling tests are presented, followed by mechanical tests used for material characterization and models' parameters identification (i.e. hardening and damage models). In order to investigate damage in the two above-mentioned forming processes, both the uncoupled damage model recently proposed by Bai and Wierzbicki (2008) and the coupled Lemaitre damage model (Lemaitre, 1986) are employed, which are recalled in Section 3. These models are calibrated via different mechanical tests for different loading configurations, using a hardening model calibrated from both compression and tensile tests (Section 4). In Section 5, experimental results on damage observed in the studied wire drawing and rolling processes are presented. Then, numerical simulations with the Finite Element (FE) method are performed to investigate ductile damage in these two processes. Numerical results of damage on 8-pass drawing and 5-pass rolling processes are compared with experimental results to validate the prediction ability of the two studied damage models (Sections 6 and 7). In addition, the results are also used to validate the experimental comparison of the reduction ability between these two processes.

## 2. Experimental techniques

The material used is an austenitic stainless steel (on the basis of 304 steel grade). The objective of the experimental test is to compare two different processes in terms of maximum safe reduction. Starting from the same initial wire ($D_i = 5.56$ mm), two processes, namely wire drawing and rolling, were used to reduce the wire section as much as possible, until final fracture. This experimental comparison helps choosing the most relevant process and also validating the ability of numerical simulation to predict failure with different damage models (see Section 6). Furthermore, mechanical tests were also performed to identify hardening model's parameters (see Section 4.1) and damage models' parameters (see Section 4.2) used for numerical simulations.

### 2.1. Experiments on forming processes

#### 2.1.1. Wire drawing

The studied wire drawing process consists of 8 passes, with the section area reduction varies from 26% (the first pass) to 11%.[2] The final wire diameter after 8 drawing passes is 2.7 mm. The drawing speed was about 1 $\mathrm{m\,s^{-1}}$. The strategy is a decreasing reduction ratio. Die geometries were also measured from experiments. These profiles are then used in the numerical simulation of the process (see Section 6.1).

#### 2.1.2. Wire rolling

The studied rolling process consists of 5 "passes", each pass involving 2 stands (3+3 rolls or 2+2 rolls). The first pass uses the 3+3 technology, where 2 stands of 3 rolls are set next to each other (see Fig. 1a). For each stand, one roll makes an angle of 120° with another. For the other four rolling passes, the 2+2 rolls are used, which consists of one horizontal stand and one vertical stand of 2 rolls (see Fig. 1b). This process can be considered as a 5 "double-passes" (or 10 passes) rolling process since the wire passed 10 rolling stands. Here, each "pass" corresponds to each overall

[2] The section reduction ratio for each pass is defined as: $(S_i - S_o)/S_i$, where $S_i$ and $S_o$ are respectively areas of the drawn wire before (input) and after (output) the studied pass.