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## PROCEDURE FOR THE EXPERIMENTAL DETERMINATION OF A FORMING LIMIT CURVE FOR USIBOR 1500 P

Y. Dahan <sup>\*†</sup>, Y. Chastel <sup>†</sup> , P. Duroux <sup>\*</sup>, J. Wilsius <sup>\*</sup>, P. Hein <sup>\*</sup> and E. Massoni <sup>†</sup>

<sup>\*</sup> ARCELOR Research Automotive Applications  
1, route de Saint-Leu, BP 30109  
60761, Montataire Cedex, France  
e-mail: yoann.dahan@arcelor.com, patrick.duroux@arcelor.com, joel.wilsius@arcelor.com,  
philipp.hein@arcelor.com, web page: <http://www.arcelor.com>

<sup>†</sup> CEMEF, Centre de Mise en Forme des Matériaux,  
Ecole Nationale Supérieure des Mines de Paris  
1, rue Claude Daunesse, BP 207  
06904, Sophia-Antipolis Cedex, France  
e-mail: yoann.dahan@ensmp.fr, yvan.chastel@ensmp.fr, elisabeth.massoni@ensmp.fr,  
web page: <http://www.cemef.ensmp.fr>

 LIM, Laboratoire d'Ingénierie des Matériaux  
Ecole Nationale Supérieure d'Arts et Métiers  
151, Boulevard de l'Hôpital  
75013, Paris, France  
e-mail: yvan.chastel@ensma.fr - Web page: <http://www.ensma.fr>

**Key words:** Formability, hot stamping, forming limit curve, high strength steel

**Summary.** *USIBOR 1500 P<sup>®(1)</sup> is a coated C-Mn steel, micro-alloyed with boron, with excellent processing properties in hot stamping, both in terms of formability, quenchantability and surface protection, and leading to superior mechanical properties on the formed part. Arcelor Research is developing a numerical tool to support the feasibility analysis and to optimize the design of hot stamped parts made of USIBOR 1500P<sup>®</sup>. Among the numerous bricks of such a simulation methodology, formability data of the material are of primary importance as the forming analysis relies on them to make a decision in terms of feasibility. Up to now, there was no experimental procedure available in literature to determine the forming limits of hot stamping material, taking into account the specificities of this process. This paper reports about the research performed in this field.*

*First, an efficient experimental set-up which allows varying all the desired process conditions has been developed. Several hundred Nakazima hot stamping tests have been carried out for various process parameters (stroke, velocity, friction and heat exchange) and blank parameters (temperature, thickness and shape). The third step consisted in developing and validating an accurate analysis scheme to determine the critical strain values based on the Bragard method. Finally, the critical strain values have been confirmed and comparisons with industrial parts for various process conditions have been performed. In this paper these two last steps are mainly presented.*

(1) USIBOR<sup>®</sup> is a registered trademark belonging to the Arcelor Group and protected throughout the world. Furthermore, Arcelor Group has filed numerous patents covering the principle of direct or indirect hot-stamping process of either aluminized-coated steel sheets and zinc or zinc-alloy coated steel sheets, and of the issued parts.

## 1. INTRODUCTION

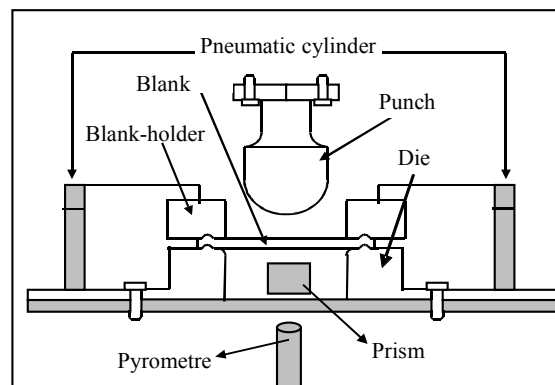
Safety improvement, weight reduction and cost saving are the major objectives of automotive manufacturers in the design of new bodies-in-white. Compared with several others industrial solutions [1], hot stamping of a quenchant steel comes out as a quite novel process which is increasingly used for automotive applications and intensive research is conducted to support this growth [2]. It allows producing thinner parts which display higher mechanical properties. The principle of hot stamping is intimately linked with the opportunities offered by the chemical composition of the quenchant steel, namely a robust process window for martensitic and bainitic transformation.

The hot stamping process consists first in heating a blank until complete austenitization. The hot blank is then moved quickly into a stamping press where it is simultaneously stamped and quenched by the cold tools. To predict part feasibility and perform process layout, Arcelor Research is developing a numerical tool to support the feasibility analysis and the design of hot stamped parts made of USIBOR 1500P®. This task is challenging because of the large number of process parameters, and of the thermo-mechanical and metallurgical interactions which influence formability [3-5].

Formability is the ability of the material to be strained without necking and fracture. For a coupled thermo-mechanical process, formability is a function of several parameters such as temperature, strain rate, strain path, thickness. An accurate experimental methodology has been defined to determine a failure criterion. This methodology is divided into 4 steps. The first step consists in the development of a robust experimental set-up which allows varying the process parameters. Several hundred hot stamping tests have been carried out following this procedure for various process parameters (stroke, velocity, friction and heat exchange) and blank parameters (initial temperature, thickness and shape). These steps have already been presented by the authors in [6]. Then, an analysis scheme has been developed to determine the critical strain values. The last step consists in the validation and comparisons with industrial parts for various process conditions. In this paper we will mainly focus on these two last steps.

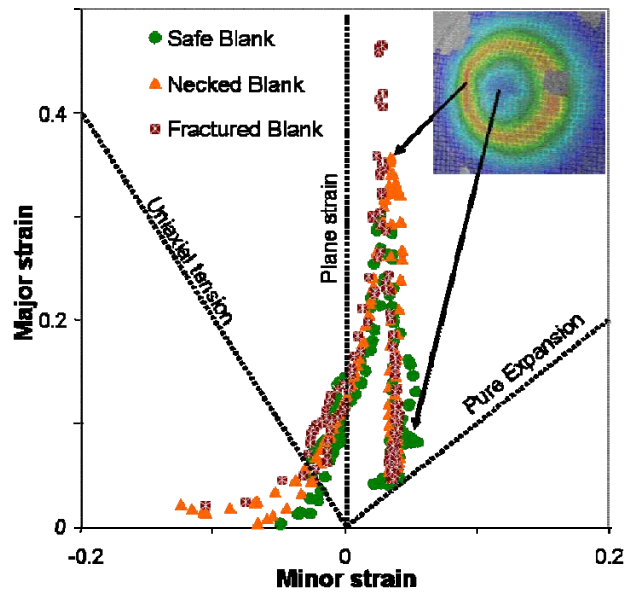
## 2. NAKAZIMA HOT STAMPING TESTS

The Nakazima and the Marciniak tests are two usual experimental tests which provide information on formability of sheet material. The main difference between these tests is the shape of the punch which is respectively hemispherical or flat. The Nakazima set-up has been selected for a straight-forward reason: it is much simpler to perform than the Marciniak test. The Nakazima set-up is made of a hemispherical punch, a die, a blank-holder and a draw-bead which prevents any sliding motion (see Figure 1).



*Figure 1. Set-up for the Nakazima hot stamping tests*

Several sensor data are recorded during the test, such as the punch load and local temperature histories. A grid is etched on the blank and allows determining the strain distribution by *a posteriori* analysis using pattern recognition systems. Thanks to this set-up, it is possible to vary several parameters of the blank and of the tools (punch temperature, punch velocity, friction). More details on the set-up and on the test protocol are available in [6] and similar approaches are reported in [7]. In [6], the authors show that necking occurs in a zone of nearly homogeneous temperature and obtain several strain distributions as functions of punch stroke, temperature, strain mode and thickness. Strain distributions of safe, necked and fractured specimens are presented in Figure 2 for given process conditions (blank thickness, initial blank temperature, punch velocity). These results are then used to determine the critical strain values.



*Figure 2. Influence of the punch stroke on the strain distribution*

### 3. DETERMINATION OF THE CRITICAL STRAIN VALUES

A methodology has to be defined to determine the critical strain values. The history and the available techniques for the determination of Forming Limit Curves (FLC) can be found in [6]. Different FLCs can be given for a single material using various criteria. And very different FLCs can be obtained from different experimental methods for a same material specimen. As a result, establishing a reference method to determine FLC still remains an issue in sheet metal forming [9, 10]. For hot stamping in particular, there is up to now no consistent testing procedure available in literature.

#### 3.1. Bibliography

The Hecker and Bragard methods are well-known experimental techniques.

The Hecker method is quite easy to implement since tests series with varying punch strokes are sufficient to determine the critical strains. The blank with the highest punch stroke without any visible necking or fracture is selected. The maximum strain given by the analysis of this specimen is set as the critical strain value.

The Bragard method is based on the analysis of a blank with necking or fracture. Once the strain distribution is determined, the major strain evolution along a section normal to the fracture is drawn [10]. At this stage, a zone has to be defined around the fracture where the strain distribution will be not considered. Two variants may be used to define this region.

The first technique is based on an optical observation of the necking or the fracture. All measured cells which overlap the necking or fracture are deleted. For the USIBOR 1500 P sheets, the detection of necked and fractured cells is not always possible because of the damaging of the grid. In addition, this method is highly subjective since it is quite depended on the user's interpretation.

A second method, called "2<sup>nd</sup> derivative", uses the extrema of the second derivative of the major strain function [10]. All points between the extrema of the second derivative are deleted from the curve. The next step consists in an interpolation by a polynomial function (6<sup>th</sup> degree) of the remaining strain points. The highest value reached by this polynomial function is considered as the critical major strain value and thus one point of the FLC.

### 3.2. Application of the Bragard method to the Nakazima hot stamping test

Using the 2<sup>nd</sup> derivative Bragard method, a critical value in plane strain is estimated on a necked sample. The critical value in plane strain is referred as  $FLC_0$ . This value of  $FLC_0$  is used with the well-known Maximum Modified Force Criterion (MMFC) prediction model which assumes the coefficient of strain hardening  $n$  is equal to  $FLC_0$  [11]. This criterion has been used so far in this study for first shape representations of the FLC and needs further theoretical consideration in the specific context of hot stamping. This calculated FLC and the results of the Nakazima hot stamping tests are superimposed in Figure 3. The 2<sup>nd</sup> derivative Bragard FLC is relatively low and several tests reach higher strain values without visible damage. We conclude that the FLC obtained by this method is too conservative.

This is probably due to the fact that in hot Nakazima tests, the strain distribution is quite heterogeneous even on specimens well before necking (straining mainly in the moving punch nose area). For this kind of configuration, high order derivatives of the strain distribution seem too conservative to define the area affected by local necking.

This is the reason why a novel analysis procedure has been developed; it is derived from the 2<sup>nd</sup> derivative Bragard variant and is consistent with the analysis of the Nakazima tests. This method is referred to as the 1<sup>st</sup> derivative Bragard method.

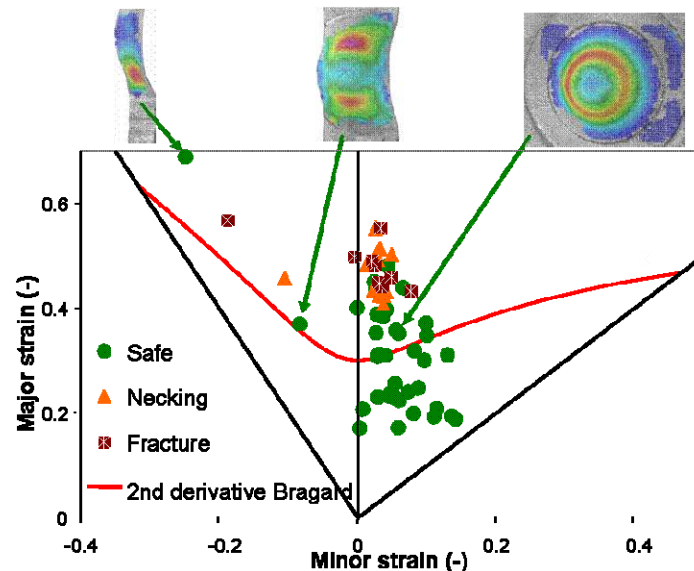


Figure 3. 2<sup>nd</sup> derivative Bragard FLC and results from the Nakazima hot stamping tests

### 3.3. The 1<sup>st</sup> derivative Bragard method

In the proposed exploitation procedure, the deletion zone is defined between the extrema of the 1<sup>st</sup> rather than the 2<sup>nd</sup> derivative. For given process conditions, the critical strain is for example found to be 0,40 instead of 0,31 with the 2<sup>nd</sup> derivative Bragard variant: see Figure 4.

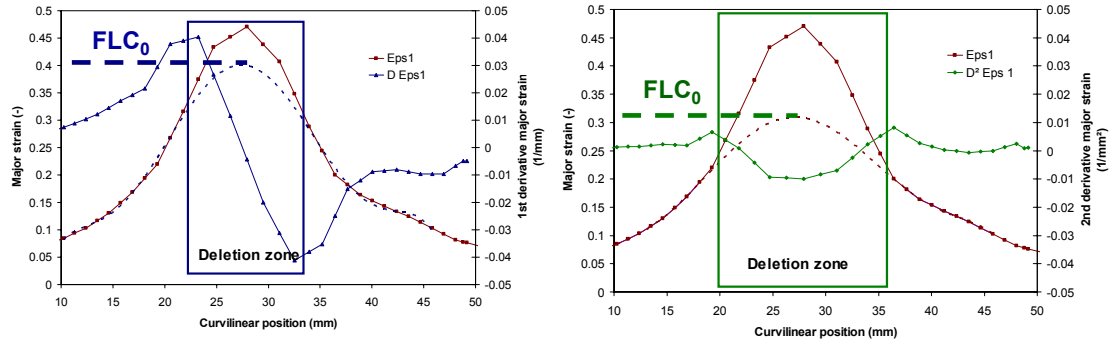


Figure 4. 1<sup>st</sup> derivative Bragard (left) and 2<sup>nd</sup> derivative Bragard (right) methods

This alternative method leads to higher values of  $FLC_0$ . This result is more reasonable since all safe and damage points fit respectively under and above the FLC in Figure 5.

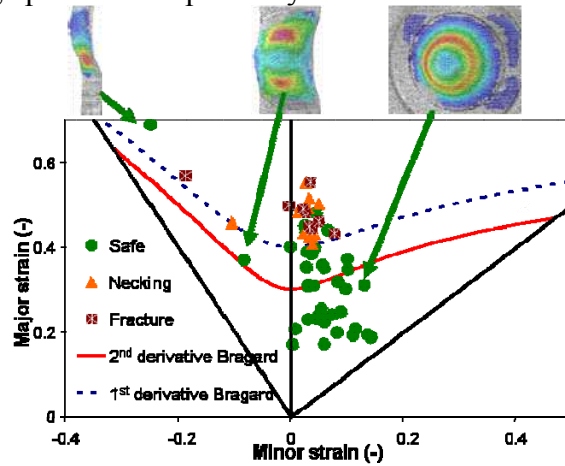


Figure 5. 1<sup>st</sup> derivative Bragard FLC and results from the Nakazima hot stamping tests

### 3.4. Thickness and temperature influence

The 1<sup>st</sup> derivative Bragard method has been applied to several specimens with different initial thicknesses and temperatures and which displayed cracks in an area deformed in plane strain. In order to write the critical strain values in plane strain  $FLC_0$  as a function of these two parameters ( $t$  for thickness and  $T$  for temperature), a multiple regression has been carried out using all specimens analysed with the 1<sup>st</sup> derivative Bragard method:

$$FLC_0 = function [t(mm), T(^{\circ}C)] . \quad (1)$$

The higher the initial blank temperature (or thickness), the higher the critical strain. The influence of the initial blank thickness on  $FLC_0$  is shown in Figure 6 for a given temperature.

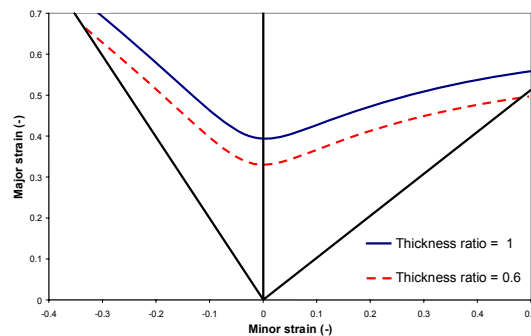
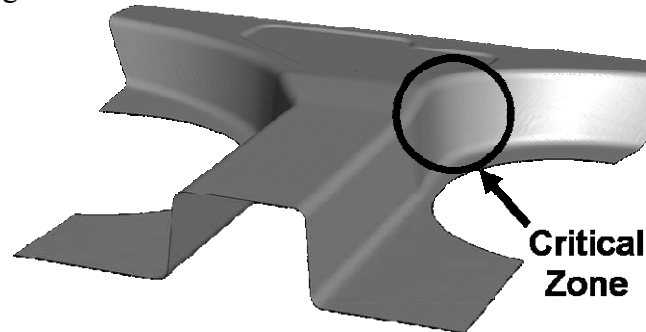


Figure 6. Influence of the initial blank thickness on FLC

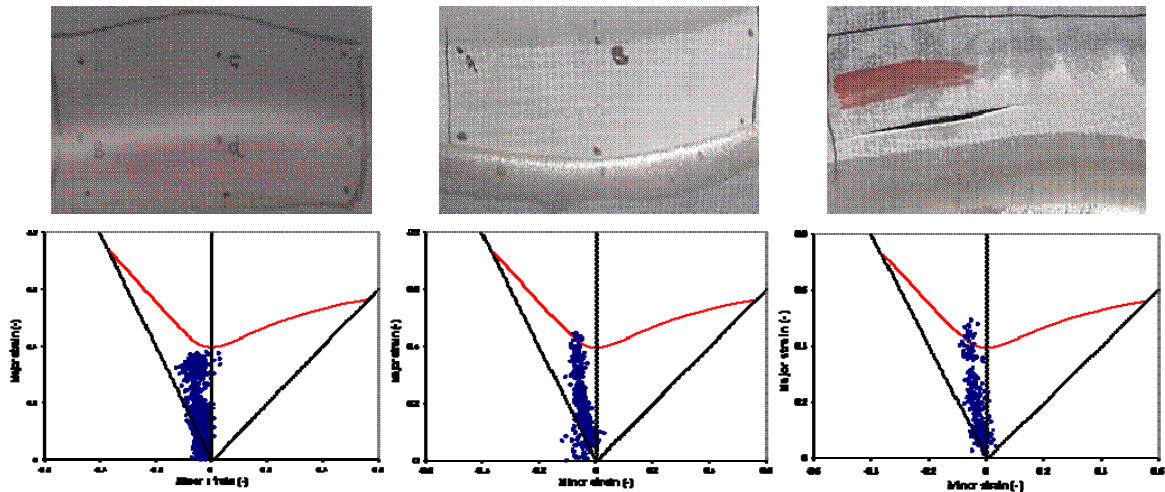
### 3.5. Confirmation on hot stamped parts

This proposed methodology and the measured formability data have been confronted with real size forming tests on the die of a lower B-pillar. Test parts have been stamped with varying process conditions in order to deliberately produce parts with necking or fracture in the zone shown in Figure 6.



*Figure 7. B pillar part and critical zone for given process conditions*

Using a pattern recognition system, the strain distributions of the three different specimens (safe, necked and fractured) have been plotted in the Forming Limit Diagram. These measurements are compared to the FLC given by the 1<sup>st</sup> derivative Bragard method for given values of initial temperature and thickness (Figure 8). For the safe specimen, the strain distribution is located under the FLC. Necking occurrence has been determined manually or optically. Samples with visible necking have strain distributions which reach the FLC. The strain range given by the fractured specimen confirms this trend, since it crosses the FLC. These observations confirm the  $FLC_0$  values expressed as a function of the initial thickness, temperature and strain path.



*Figure 8. Safe, necked and fractured test parts*

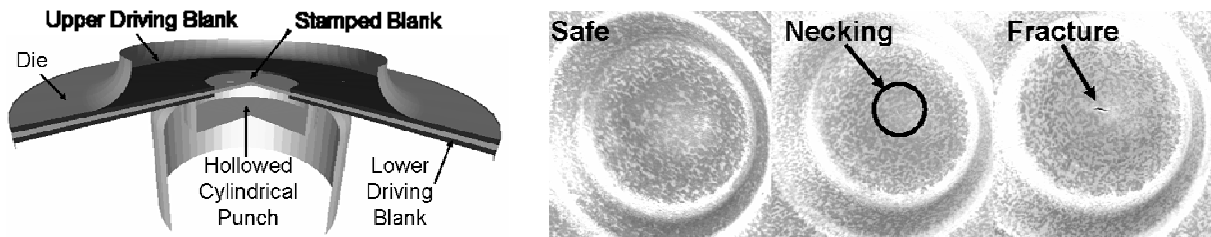
## 4. MARCINIAK HOT STAMPING TESTS

In [6], the authors show that pure bi-axial stretching can not be obtained with this Nakazima set-up. That's why another laboratory test based on the Marciniak set-up has been designed.

### 4.1. Presentation of the Marciniak set-up

The major differences between the Nakazima and the Marciniak tests are in terms of the punch shape. The Nakazima test uses a punch and the Marciniak test a flat punch. Further-

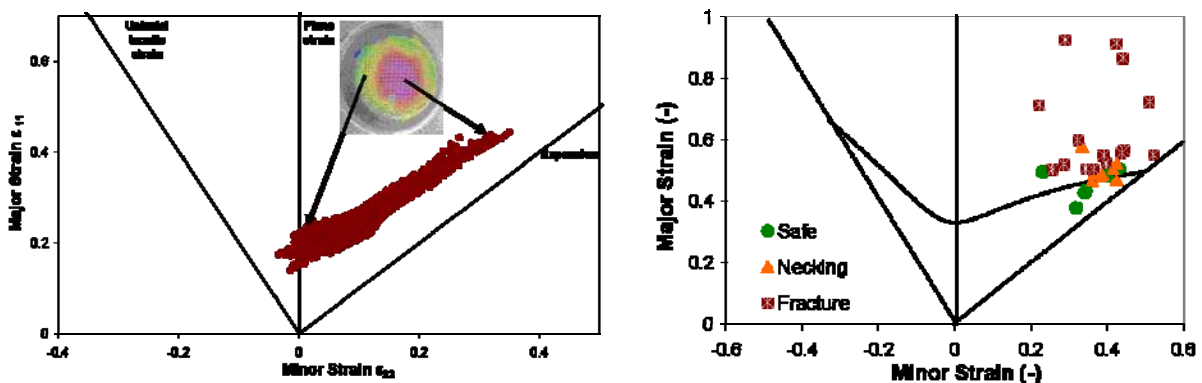
more, a specific design was defined for the Marciniak test: one or two additional rings of sheet metal, called carrier blanks, have been used to prevent the contact between the punch and the tested blank. Experimentally, this test is a real challenge since a hot blank has to be introduced from the furnace in-between two cold carrier blanks within a very short transfer time. This is the reason why a first finite element analysis has been carried out to check the strain distribution and to optimize the driving blank (material, diameter of the central hole). Figure 9 presents a numerical model of this experimental set-up (left) and shows the three types of specimens which can be obtained (right). It is confirmed that the strain localization appears in the central blank zone. Necking and fracture can also easily be detected.



**Figure 9.** Marciniak set-up (left) and experimental safe, necked and fractured blanks (right)

#### 4.2. Strain distribution and FLC prediction

The global analysis in Figure 10 confirms that positive  $\varepsilon_1$  and  $\varepsilon_2$  values can be achieved with this test. The closer to the blank centre, the higher the major and minor strains, the closer to an equi-biaxial strain state. In the outer areas of the blank (close to the punch radius), the strain distribution tends towards a plane strain state. The results of the Marciniak hot stamping tests and the FLC given by the MMFC and the 1<sup>st</sup> derivative Bragard method are superimposed in Figure 10. No points corresponding to tests with necking and fracture lie below the FLC. Therefore, the shape and the level of the FLC are globally confirmed. Further experiments are in progress to fully exploit this second test set-up.



**Figure 10.** Strain distribution and prediction of the FLC for Marciniak hot stamping tests

### 5. CONCLUSION

The results of this investigation are the following:

- Two experimental tests, based on Nakazima and Marciniak tests, have been specifically developed to study the formability of USIBOR 1500 P at high temperature for the hot stamping process.
- A robust method has been developed to determine the critical strain and to build a FLC from the Nakazima hot stamping tests.
- This method has been applied for various process conditions: temperature, thickness



and strain path. The influences of thickness and temperature on  $FLC_0$  have been determined.

- A preliminary FLC has been deduced from the experimental  $FLC_0$  values using the MMFC. Results from Marciniak tests are consistent with these data.
- These forming limit data have been checked on several laboratory tests and a few industrial parts. So far, all cases have confirmed the accuracy of the derived FLCs for the industrial hot stamping conditions.

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