Evaluation of the feasibility of the hole-flanging process using a multiple criteria method

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Abstract. Software dedicated to simulating the hole-flanging process has been developed for the sheet metal forming profession. This software innovates by providing companies in this sector with an alternative, which is easier and less expensive than existing, more general, software. The hole-flanging process can be applied in various ways. The software uses the most known method in the profession to manufacture a flanged hole, which is based on expanding a hole with or without ironing. This study focuses on evaluating the feasibility of the hole-flanging operation. Three fracture criteria have been used for this purpose: Rice & Tracey, Latham & Cockroft and the Hole Expansion Ratio (HER). The first two criteria apply an uncoupled approach and the values of the criteria are compared with the corresponding thresholds post-process. The third criterion is used either as input data or as a test to determine thresholds for the first two criteria. The fracture thresholds are determined from experimental trials on press and from hole-flanging simulations based on the same configurations. Various hole-flanging trials with or without ironing have been carried out. Comparing the results of experimental trials and simulations highlights similar flange geometries and forming forces. The simulation shows that the locations of fracture areas on the flange are accurately modelled. However, differences appear regarding the sensitivity of the criteria to the process parameters. In particular, the fracture thresholds for the criteria may vary according to whether the flanging is carried out with clearance or with ironing. For this reason, the software allows the user to view the two criteria and choose the best one for their configuration. The HER test is used to determine thresholds for the fracture criteria and seems to be suitable for subsequently evaluating the feasibility of new flanging configurations.

1. Introduction

Flange forming by hole-flanging is widely used in sheet metal forming presses. The most known method consists of forming a flange starting from an initial hole in a metal sheet, with the help of a punch, to expand the hole [1]. The flanging punch can take various shapes, the most frequently used shapes are (in order): conical as depicted in figure 1, flat (flat-bottomed) and hemispherical [2]. The need to obtain a high flange often leads to ironing during the flanging operation. The flanges thus formed are mainly used to provide additional support for bolt joints, solder connections with tubes, etc.

Analysing the feasibility of such flanges remains a major problem for sheet metal forming companies.

Rp = punch radii
Rd = die radii
Rh = hole radii
j = clearance
t = sheet thickness
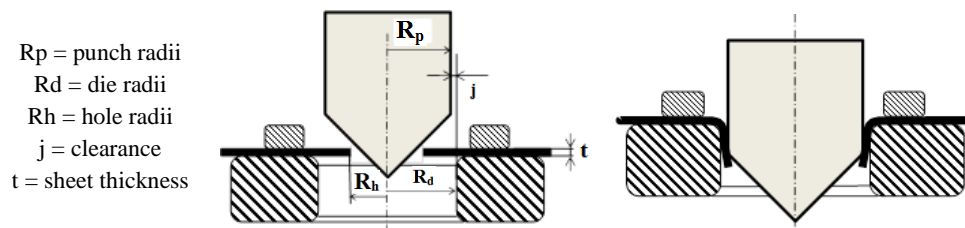
Figure 1. Schematic description of hole flanging.

In fact, requests from business providers are increasingly demanding, particularly with the arrival of sheets which are ever harder to form [3], with a known cut edge sensitivity [4]. Software dedicated to expansion flanging operations has been developed to allow companies in the sector to improve their predictions of the feasibility of such flanges. The aim is to be able to propose cost effective prediction software, which is easier to use than existing software in the sheet metal forming segment, to companies. The study presented focuses on evaluating the feasibility of the flange in terms of the fracture risks faced in forming with clearance and with ironing. The software allows for the use of different fracture criteria in order to evaluate this risk. This software has an original feature: the user can calibrate criteria based on previous experimental testing and define thresholds above which the fracture risk is evaluated and also define the most appropriate criterion or criteria in each case. The use of experimental tests as a reference makes it possible to take into account the process of punching the hole (type of clearance, wear of punch ...) and its final state (cut edge, quality …). After reiterating the characteristics of the calculation model developed, the criteria entered in the dedicated software are presented. Different simulations are performed and the predictions are compared with experimental results, and in some cases, with Abaqus software. The fracture criteria used are then analysed.

2. Numerical aspects

The finite element package named SIREL, dedicated to hole-flanging simulations [5], was developed in view of the high levels of non-linearities associated with process simulation. An explicit dynamic load stepping algorithm was used. In addition, the problem is considered as axisymmetric and a 4-node solid axisymmetric finite element, with physical hourglass stabilisation, is developed. The tools are considered as rigid and plate/tool contact is taken into account using a penalty method and Coulomb's law is used to incorporate friction. An elastoplastic model with a Von Mises threshold function and isotropic hardening is used to describe the behaviour of the sheet. The hardening curves for the two materials studied were modelled using Krupkowski's law:

$$\sigma = K \left(\overline{\varepsilon}^{\,p} + \varepsilon_0 \right)^n \quad (1)$$

σ represents the yield stress, $\overline{\varepsilon}^{\,p}$ represents equivalent plastic strain, K, ε_0 and n are the characteristic parameters of the material. The data for the materials used in this study are given in table 1.

Table 1. Data for hardening laws for the materials used.

Material	K (MPa)	ε_0	n
HCT600X	1267	0.0016	0.210
X2CrNi18-09	1442	0.0252	0.404

Predicting the fracture of the sheet during flanging is a key point for the process [6]. Damage criteria must also be integrated in the tool developed. However, several approaches can be used to model damage. The models proposed for this purpose range from the simplest to the most sophisticated, requiring significant material characterisation input. Considering the type of tool developed and its purpose, we opted for uncoupled damage models. In order to simplify use, we adopted three criteria, described below.

2.1. HER criteria

This criterion is frequently used in the sector and is very simple. It involves calculating the expansion ratio and comparing this value with a limiting value established based on tests [7]. The criterion can be written as:

$$\lambda < \lambda_l \quad \text{where} \quad \lambda = \frac{D_f - D_0}{D_0} \times 100 \; (\%) \tag{2}$$

D0 and Df are the initial and final hole diameters respectively. In the proposed approach, this criterion is used prior to the simulation to determine the feasibility of flanging. When combined with simulation, it is also used to identify the threshold values for the other two criteria described below.

2.2. Rice-Tracey (R&T) criterion

The Rice-Tracey criterion is developed based on the growth of a spherical cavity in an infinite elastoplastic solid [8]. Fracture occurs when the radius of the cavity reaches a threshold value. For growth in the radius of such a cavity, the authors of the criterion have established the following approximation:

$$\frac{\dot{R}}{R} = \alpha \exp\left(-\frac{3}{2}\eta\right) \dot{\bar{\varepsilon}}^p \tag{3}$$

R is the cavity radius, α is a coefficient equal to 0.283 and η is the triaxiality factor defined by:

$$\eta = \sigma_H / \bar{\sigma} \tag{4}$$

σ_H represents the hydrostatic stresses and represents the equivalent Von Mises stress.

2.3. Cockroft-Latham (C&L) criterion

The Cockroft-Latham criterion [9] stipulates that fracture occurs when:

$$\int_0^{\bar{\varepsilon}_f} \sigma^* d\bar{\varepsilon}^p = C \tag{5}$$

$\bar{\varepsilon}_f$ represents equivalent plastic strain at fracture and C represents the threshold value.

$$\sigma^* = Max(\sigma_{Imax}, 0) \tag{6}$$

σ_{Imax} represents the maximum main stress.

3. Experimental aspects

The experiments were carried out on a 200 kN hydraulic sheet metal forming test machine, with instrumentation to obtain the load curve of the punch (figure 2a). Only a conical punch was used to perform the flanging experiments (as shown in figure 2b). The burr formed in the blank hole was always positioned on the outside of the flange (die side). The process was lubricated using neat oil, brushed onto the sheet samples. The die radius (rd) was equal to 1 mm and the blank holder force was set to 15 kN (figure 2c) and punch displacement speed was set to 12 mm/min.

A map experiment was carried out, varying the following parameters:

- 2 materials were tested: high strength steel HCT600X and stainless steel X2CrNi18-09, with 1 mm thickness.
- 1 flange diameter: 20.8 mm.
- 4 tool configurations: one with positive clearance (without ironing) and three with negative clearance (with ironing).
- Two hole diameters leading to fracture.

The experimental map is shown in Table 2.

Flange condition was determined (fracture or not), flange geometry was measured and the flange curve was analysed to obtain force curves according to displacement, in each configuration. Flanging was also performed according to the standardised test (ISO 16630) with grade HCT600X.

2a   2b   2c
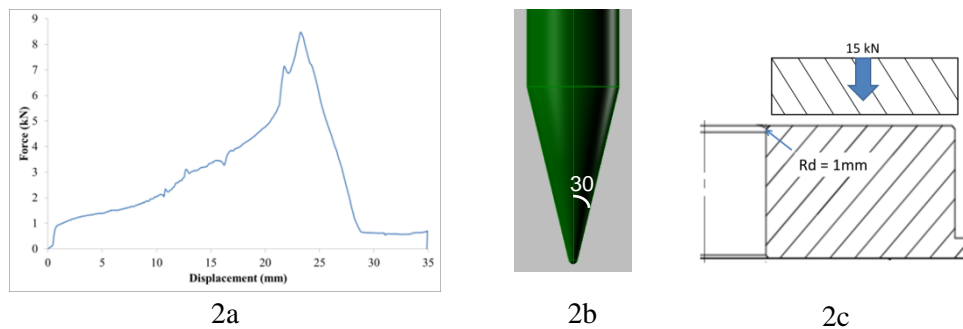
**Figure 2a.** Sample acquisition curve / **Figure 2b**. Punch shape / **Figure 2c**. Die shape and blank holder

Table 2. Experimental map.

Configuration	Materials	Thickness (mm)	Punch ϕ (mm)	Clearance (% thickness)	Die ϕ (mm)	Hole ϕ (mm)
1	HCT600X			c = + 10	23	15
2				c = - 30	22.20	13.23
3	X2CrNi18-09	1	20.8	c = - 5	22.70	13.23
4				c = - 20	22.40	13.23

4. Results

Simulations were carried out with the dedicated software and the results were compared with the experimental results (geometric profiles, forces and fracture). The results obtained using Abaqus are compared in configurations 1 and 2 for fracture criteria values. Tables 3 and 4 show the geometries and forces obtained. The flange profiles calculated with the dedicated software generally agree with experimental results. A slight flare in the flange is visible in configuration 1 and particularly highlighted in the simulation. However, in configuration 3, a difference appears for the tilted wall, probably caused by the generic hardening law applied. Forming forces are similar to experimental values. The strong oscillations towards the end of the calculated force curves relate to the contact management mode. This set of results confirms the good quality of the results obtained with the dedicated software [5].

Table 3. Geometry results.

Configuration 1

Configuration 2

Configuration 3

Configuration 4
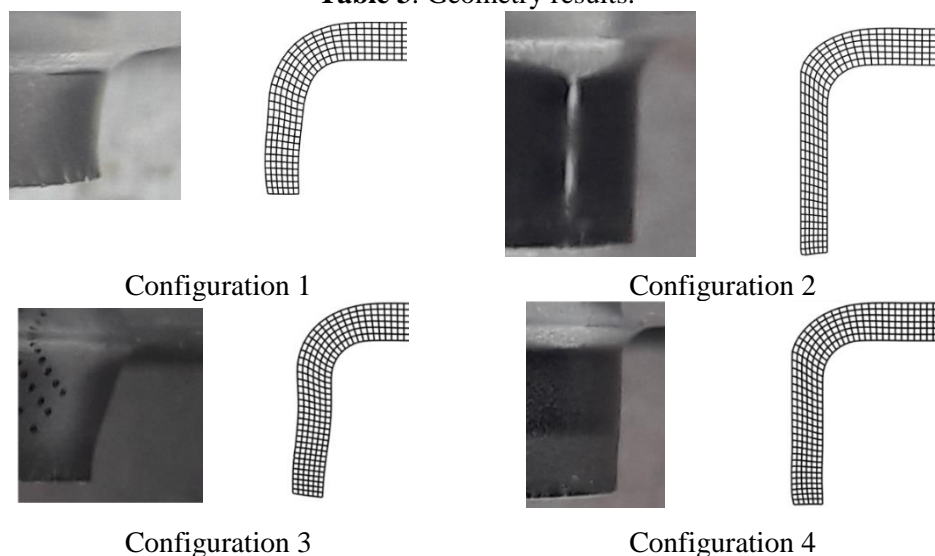
Table 4. Force results - Dedicated software and Measurements.

Configuration 1

Configuration 2

Configuration 3

Configuration 4
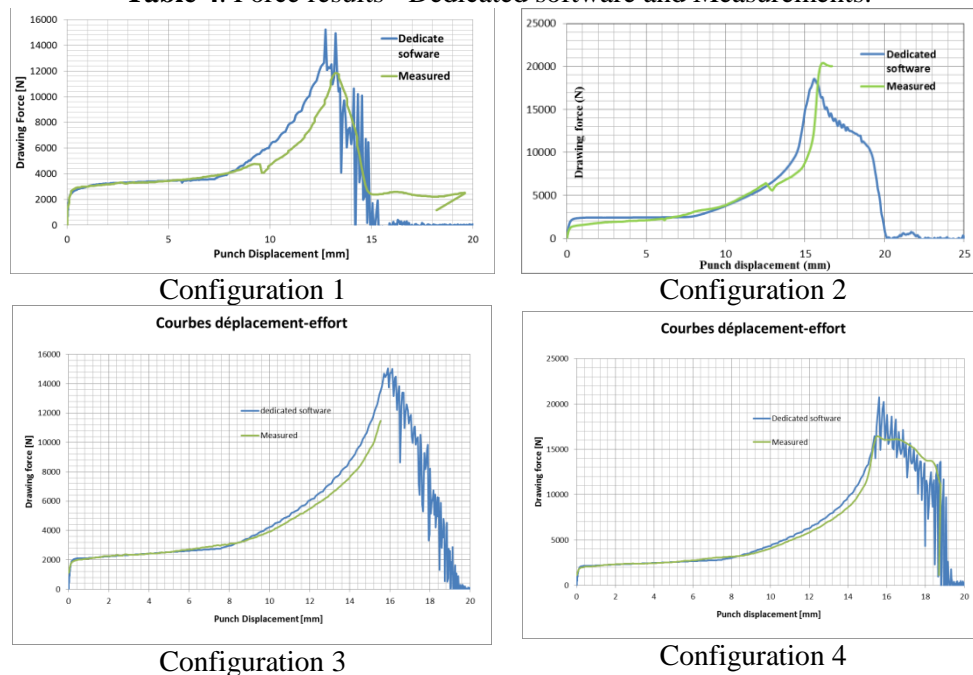
Table 5 shows the appearance of the fractures and the criteria values obtained with the dedicated software. Fractures initiating on the edge of the raised hole and running from the outer part of the flange towards the inner part were observed in all of the configurations studied. The two fracture criteria clearly demonstrate that this zone indeed has the highest hazard level, with a difference for the R&T criteria, which can also affect the base of the flange. These results were also found with the Abaqus software (configurations 1 and 2) and demonstrate the good numerical behaviour of the dedicated software. The threshold values were similar with the R&Tcriterion for flanging with clearance and flanging with ironing, while a significant difference appeared with the C&L criterion, particularly for grade HCT600X. These values are similar between the materials formed by ironing, if we consider configurations 2 and 4 as comparable. When considering the results recorded in table 5 and if we compare the threshold values for criteria in configurations 1 and 2, it appears that the R&T criterion only varies slightly when changing from flanging without ironing to flanging with ironing, while total plastic strain increases from 40% to 85%. This minor variation in the threshold value for the criterion is probably caused by the triaxiality factor, which is lower if the wall is ironing. This trend does not appear with the C&L criterion, which does not involve the triaxiality factor, but rather the largest main stress, if positive.

The fracture criteria threshold values depend on precision when determining the fracture. In configuration 4, the fracture can appear when the flange is complete or when the flange is only partial (table 6). This shows the wide range of experimental results which must be taken into consideration when analysing fracture thresholds. Case B with the partial penetration of the punch was simulated in order to better evaluate this influence. Case C does not seem acceptable to serve as a reference case because of the too large rupture obtained. The results obtained (table 7) show that the fracture threshold is, in this case, similar to case A with an identical value for R&T (0.25) and a similar value for C&L (420 versus 440).
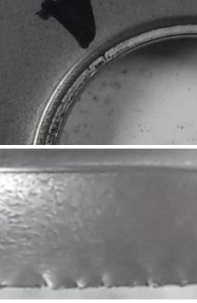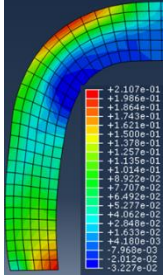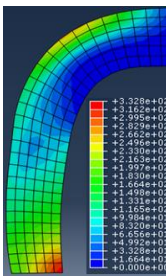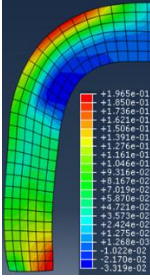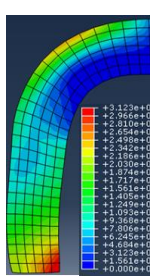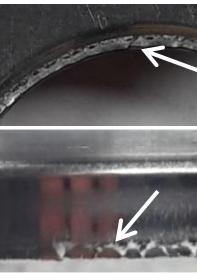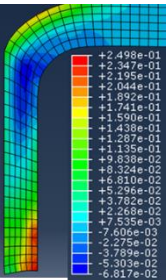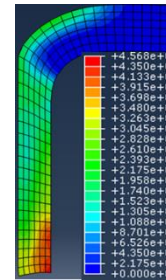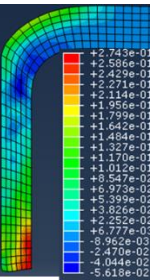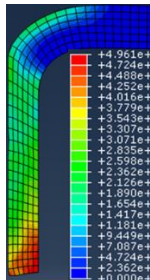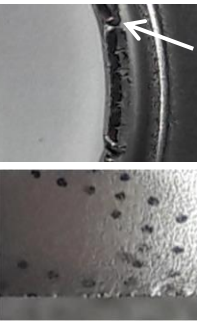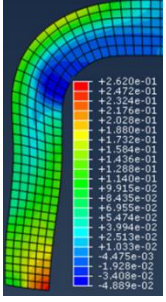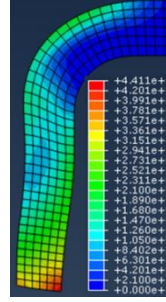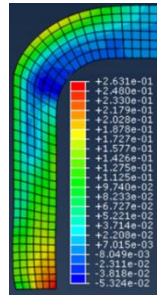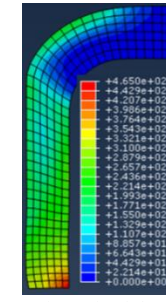
The approximation of the fracture using experimental results would not appear to significantly modify the fracture thresholds in the configuration studied. The fracture criteria thresholds can be determined based on testing specifically carried out using other tools and using other flange geometries or different hole edge states before flanging potentially from past experiments.

In order to evaluate the pertinence of this method of using the software, criteria thresholds are determined for the flanging test scenario according to standard ISO16630 (figure 4) and are compared

to those obtained in configuration 1. The results obtained are shown in table 8. The threshold values obtained for the test according to the ISO standard and the test with the industrial tool in configuration 1 are very similar and show that this approach to using the software is coherent.
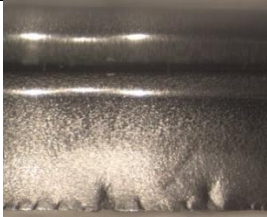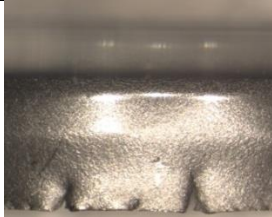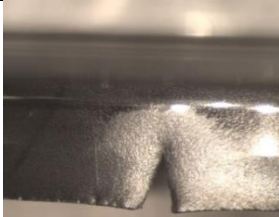
Table 5. Fracture results - R&T (Rice & Tracey) and C&L (Cockroft & Latham).

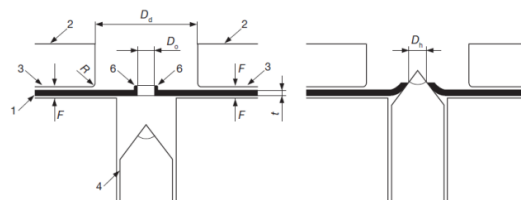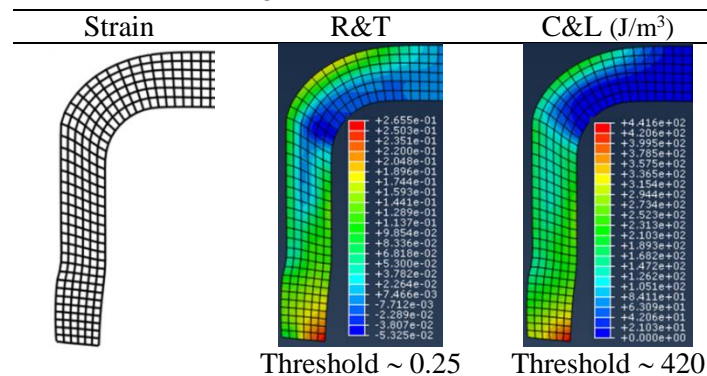| Conf	Fracturing	Fracture criteria values			
		Dedicated software		Abaqus	
		R&T	C&L (J/m^3)	R&T	C&L (J/m^3)
1		Threshold ~ 0.20	Threshold ~ 315	Threshold ~ 0.19	Threshold ~ 300
2		Threshold ~ 0.22	Threshold ~ 425	Threshold ~ 0.26	Threshold ~ 475
3		Threshold ~ 0.25	Threshold ~ 420		
4	Case A	Threshold ~ 0.25	Threshold ~ 440		

The criteria thresholds obtained can therefore apparently be used for other flanging configurations using the same material. For example, the analysis of the feasibility of a new flanging configuration is shown.

This refers to configuration 4 as described previously, but the conical punch has been replaced with a flat punch (table 9). When compared with the conical punch case (table 5 – configuration 4), the results obtained show (table 9) that the fracture risk is equivalent to, and even slightly below, that for the conical punch, with the benefit of creating a better calibrated flange wall.

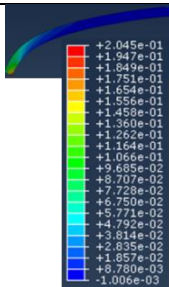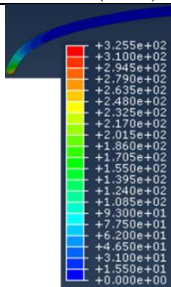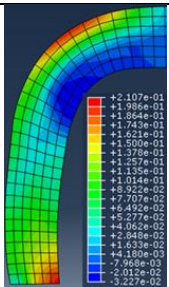**Table 6.** Configuration 4: Different possible crack conditions.
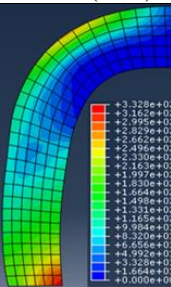
A - Crack initiated for the complete flange	B - Open crack with the partial penetration of the punch	C - Very open crack with the partial penetration of the punch

Table 7. Configuration 4: Simulation of case B.

Strain	R&T	C&L (J/m^3)
	Threshold ~ 0.25	Threshold ~ 420

Figure 4. Flanging test according to standard ISO16630.

Table 8. HCT600X fracture criteria values with flanging test according to ISO 16630.

Material	HER (%)	Flanging test - ISO 16630		Configuration 1	
		Fracture criteria values with Dedicated software			
		R&T	C&L (J/m^3)	R&T	C&L (J/m^3)
HCT600X 1 mm thickness	36				
		Threshold ~ 0.19	Threshold ~ 310	Threshold ~ 0.20	Threshold ~ 315

Table 9. Configuration 4 with flat punch – values of fracture criteria.

Flat punch	R&T	C&L (J/m^3)
	Threshold ~ 0.23	Threshold ~ 400
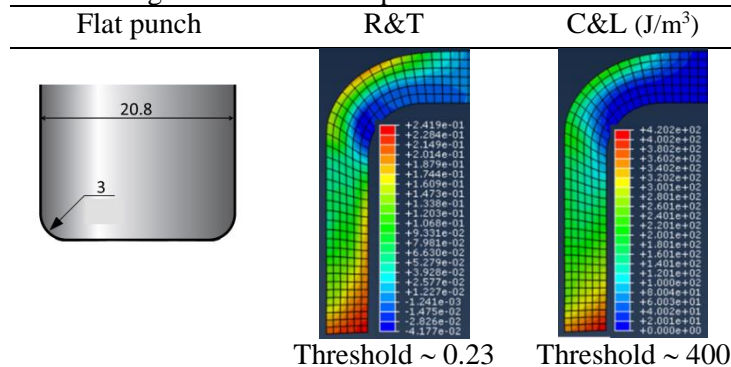
5. Conclusion

Software dedicated to simulating hole expansion flanging, with clearance and ironing, was developed to help sheet metal forming companies with designing and producing their parts. The software was purposely developed in order to simplify its use and provide rapid responses with minimal expertise and limited investment in terms of the characterisation of materials. Software evaluation demonstrated that its results are similar to experimental values and that it can be used to develop flange feasibility analysis based on two fracture criteria. Analysing these criteria demonstrated that the fracture area was accurately identified and that the risk could be predicted based on the fracture limit threshold determined. The threshold for the Rice & Tracey criterion would appear less sensitive to the forming mode (positive clearance or with ironing) than the Cockroft & Latham criterion. These thresholds, determined based on past experiments, can apparently be used for a new flanging configuration providing that the material worked (grade and thickness) and probably the type of flanging (with clearance or with ironing) are taken into consideration. The experimental calibration of the threshold of the rupture criterion also makes it possible to associate the state of the cut edge in the prediction of the rupture of the collar. The user can select the best criterion for representing the fracture faced and use the pre-identified criteria thresholds to evaluate the feasibility of new flanging cases. Fracture criteria will change with the upcoming introduction of a 3rd criterion, a modified Mohr-Coulomb type criterion, aiming to identify damage.

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