The forming limit curve as a measure of formability – Is an increase of testing necessary for robustness simulations?

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Abstract: The concept of forming limit curves (FLC) is widely used in industrial practice. The onset of necking data should be delivered for typical material properties by the material suppliers. Providing experimentally determined forming limit curves for the variety of scattering in the mechanical properties is impossible. Therefore a forecast of the expected limit strains without expensive cost and time-consuming experiments is necessary. In the paper the quality of a regression analysis for determining forming limit curves based on tensile test results is presented and discussed. It is shown that the practical forecast is successful for the traditional visual definition of necking as well as for the new definition of forming limits according to ISO12004. The applied data base consists of 150 experimental FLCs. The quality of the regression FLCs is demonstrated by applying them to different forming parts.
Keywords: Failure, forming process, forming limit curve, regression

1. INTRODUCTION

With the development of new steel grades and the requirement of a better material utilization, the forecast of failure in forming processes becomes even more important. In industrial practice forming processes are designed using numerical simulation tools. Although nowadays there are many theoretical models of failure prediction the FLC is the most widely criterion. Especially in press shops the comparison of measured strains and their plot in a Forming Limit Diagram is applied to define a safety margin and gives an approximation of the expected robustness of the forming process.

2. EXPERIMENTAL DETERMINATION OF THE NECKING STRAINS

In general, forming limits in plasticity are path dependent, which means that pure knowledge of the strain state cannot be used for a failure forecast. The simplest way for a strain path dependency is a linear strain path with constant ratios of strains in the sheet plane. These limit strains are converted to a forming limit curve. Although there are several experimental procedures [Hasek, 1978] to determine failure with respect to linear strain paths two main experimental setups are widely used in practice. These are the so called Marciniak and the Nakajima test which differ in the loading conditions. For academic reasons the strategy of Marciniak can offer some advantages as there is no superposition of bending effects. Owing to the fact that normal forming processes change sheet metal blanks into various curved parts, failure values based on Nakajima results including bending effects are often used. An increasing width of the sheet samples allows a transition from a negative to a positive ratio of minor and major strains and thus leads to the determination of failure at different linear strain paths.

In general, forming limits are not defined using splits; already an onset of (visual) necking indicates unsafe processes. Therefore the forming limits should correspond to the beginning of the necking phenomena. Different strategies for the detection of the onset of necking are used in practice:

- Visual method: The last state before onset of visual necking is selected to determine limit strains. This means it is necessary to repeat the experiment at a punch stroke where no necking occurs (If there is a visual recording of the experiment, search for the last time state without necking and determine the limit strains at this time state).
- Definition of the forming limits using strain distribution at split samples. Here mathematical algorithms allow the extrapolation of measured spatial strain distribution to the desired onset of necking [ISO/FDIS12004, 2008].

Note that the different definitions of onset of necking can result in different numerical values for limit strains.

To sum up it can be stated that a variety of practicable experimental methods exist (extremely time and cost intensive with respect to tensile testing) for determination of limit strains following linear strain paths. To reduce the efforts these methods are applied to typical material properties of certain steel grades (If we assume a normal distribution of the mechanical properties the typical material should be inside a tolerance band of +/- one times the standard deviation). If one considers the huge number of the steel families /ThyssenKrupp Steel Europe AG, 2009/ with up to 6 members of each family and takes into consideration the different alloying concepts for several surface treatments, it becomes apparent that these demands for material characteristics can no longer be guaranteed purely by experiments. Therefore, theoretical methods have to be developed to determine material failure.

3. DEFINITION OF THE COMPLETE FORMING LIMIT CURVE

To fit the experimental true strains ε_1, ε_2 which define the onset of necking ThyssenKrupp Steel Europe AG uses a combination of two specific mathematical functions, one linear and one exponential function, with additional constraints. The unknown parameters a_0, b_0, b_1, b_2 and transition point ε_0 are determined by the minimum of least squares.

$$
\begin{aligned}
&\varepsilon_1 = a_0 + a_1\varepsilon_2, && \varepsilon_2 < \varepsilon_0 \\
&\varepsilon_1 = b_0 + b_1 \exp(-b_2\varepsilon_2), && \varepsilon_2 > \varepsilon_0 \\
&a_1 = -1, \;\; \varepsilon_1^{'}(\varepsilon_0) = c && \\
&Q\left(a_0, b_0, b_1, b_2, \varepsilon_0 \mid \varepsilon_2\right) = \sum_{j=1}^{n} \left(\varepsilon_1 - \varepsilon_{1\ calculated}\right)^2 \overset{!}{\rightarrow} Min. &&
\end{aligned}
\tag{1}
$$

In a second step the variance between the measured and calculated values is determined and the whole curve is transformed to lower values with k times for the standard deviation. The factor k exhibits a quantity for safety and is set to 1.96 in our practical work, figure 1. The resulting graph is defined as the forming limit curve (FLC) of the specific steel grade representing the onset of necking. Some additional aspects of the transformation are discussed more in detail in /Gerlach et al., 2007/.

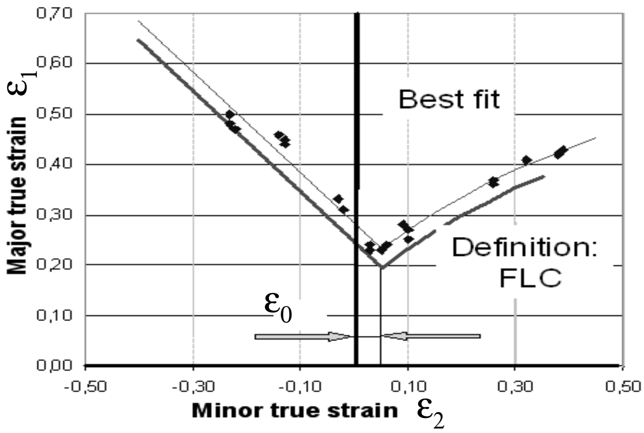

Figure1: FLC Definition using a best fit and an additional transformation

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4. APPROXIMATE PREDICTION OF FORMING LIMITS

The experimental procedure of the determination of FLCs is time consuming end relative expensive. Especially for press shop applications it is necessary to have a forecast of the forming limits because FLCs will not be available for every coil. In practice only tensile test results can be a reasonable basis which will be used for quality assurance and approval. Depending on different steel grades the quality standards can include the yield strength (YS), tensile strength (TS), total elongation (TE), as well as r- and n-values. An estimation of the expected FLCs is also helpful to assess the robustness of forming processes by means of numerical simulations.

4.1 Basic idea and used data base

The idea for a practical prediction of FLCs is described in figure 2. By means of a linear regression using mechanical properties and thickness, three characteristic necking points are approximated. With the help of these points the forming limit curve can easily be calculated as a combination of a linear and an exponential function according to the previously described definition of the FLC. Because of the importance of the so-called plane strain range in press shop applications the forecast of FLC should cover especially this area.

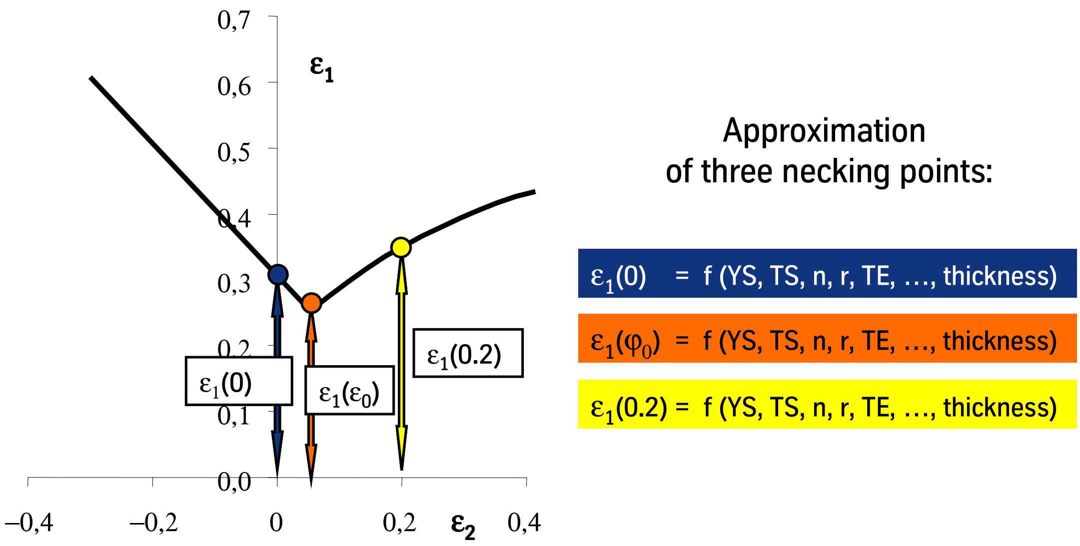


Figure 2: Method of a FLC forecast using three characteristic points

During our research work we found some surprising but very helpful results. Already the assumption of a linear function of the necking strains for all 3 points based on the mechanical properties was practically sufficient. Another favorable fact was that not all mechanical properties are significant in the regression analysis but only the tensile strength, total elongation and sheet thickness. These values are always available and also given in material specific standards for each steel family. This advantage of the FLC forecast for press shop applications is associated with the disadvantage that the total elongation is no input value in numerical FE codes. Because of the fact that the minimum total elongation however always defined in the material standards an estimation of the FLC can also be reached.

The final formula for the three characteristic points is very simple. Each point can be calculated using a linear function of sheet thickness, tensile strength and total elongation with the coefficients K_t, K_{TS}, K_{TE}, and K which are determined in a linear regression analysis. The necking points are based on the best fit of equation (1) without applying a transformation.

$$
\begin{aligned}
\varepsilon_1(0) &= K_t t + K_{TS} TS + K_{TE} TE + K \\
\varepsilon_1(\varepsilon_0) &= K_t t + K_{TS} TS + K_{TE} TE + K \qquad (2) \\
\varepsilon_1(0.2) &= K_t t + K_{TS} TS + K_{TE} TE + K
\end{aligned}
$$

The applied data base consists of 150 experimental determined FLCs for the whole product range of ThyssenKrupp Steel Europe AG. Here we find mild steels as well as high strength steels with a tensile strength of about 1200 MPa in a thickness range from 0.6 to 3.0 mm, figure 3.

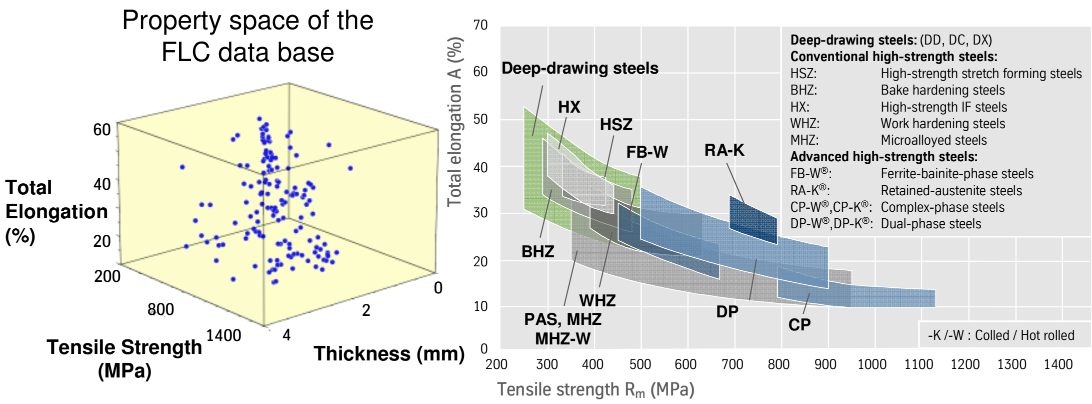


Figure 3: Mechanical properties for different steel grades used in the FLC data base

4.2. Forecast of the FLC using the visual definition of necking and the ISO12004 definition

In table 1 the coefficients of the regression analysis for the FLC forecast based on the visual definition of necking as well as on the new ISO12004 proposal are given. It should be noted that for the FLC regression according to ISO12004 up to now 116 of the 150 experiments using the Nakajima test setup were evaluated. It can be seen that the coefficients of determination are in a range of 90% for both definitions for the onset of necking. The standard deviation of the forecast of the characteristic points differ only little. In tendency it can be pointed out that the accuracy of the approximation is slightly higher in the left side of the FLC. However the mean standard deviation of about 0.02 in the regression is in the same range as the standard deviation in the approximation process of the linear and the exponential function using the individual measured necking strains.

	$\varepsilon_1(0)$		$\varepsilon_1(\varepsilon_0)$		$\varepsilon_1(0.2)$	
	visual	ISO 12004	visual	ISO 12004	visual	ISO 12004
K_t [1/mm]	0,0771	0,0577	0,0719	0,0518	0,0640	0,0448
K_{TS} [1/MPa]	-0,000192	-0,000127	-0,000148	-0,000111	-0,000152	-0,000119
K_{TE} [1/%]	0,00428	0,00582	0,00422	0,00502	0,00301	0,00360
K	0,219	0,121	0,154	0,098	0,295	0,254
standard deviation	0,022	0,017	0,022	0,017	0,027	0,022
coefficient of determination	0,940	0,959	0,923	0,948	0,849	0,887

Table 1: Regression coefficients for the forecast of the three characteristic points

A typical plot of the prediction of the FLC using different methods of necking definition is given in figure 4. For the definition of the FLC on the basis of the regression analysis an analogous transformation with the mean standard deviation was applied (see chapter 3). Beside the quality of each regression it is observable that the FLC according to the ISO12004 is characterised by a lower level of major strain in general. Another interesting aspect is that the regression based on the visual necking definition provides a consistently conservative prediction for the family of complex phase steels.

	Thickness	YS	TS	UE	TE	r	n
Grade	mm	MPa	MPa	%	%	-	-
DP-K34/60	1,50	392	641	19,1	26,5	0,82	0,203

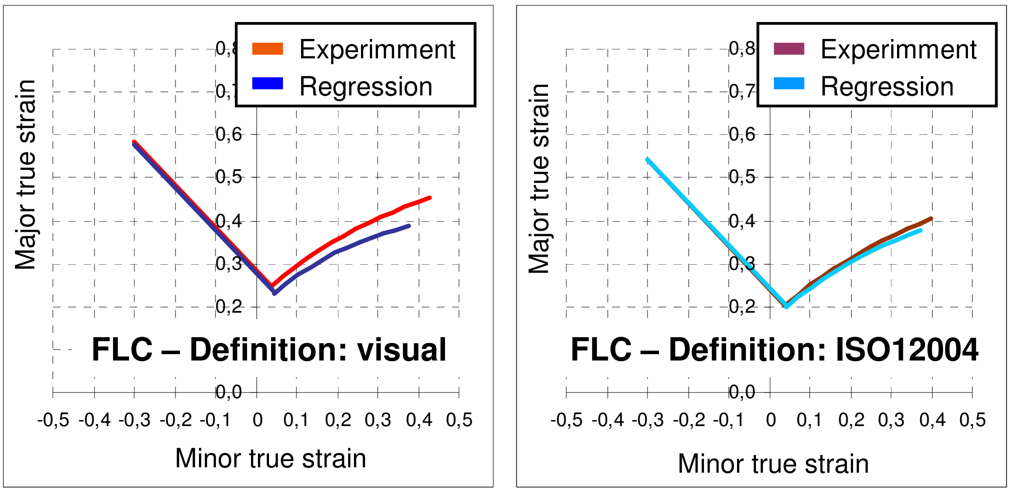


Figure 4: Experimental and predicted FLCs for a dual phase steel grade

5. VALIDATION OF THE DIFFERENT FLC FORECASTS

In press shop applications tools will be released when the measured strain distribution is below a certain safety margin. A common margin is 10 % engineering strain. This is based on experience and represents a compromise between the utilization of materials and the desire for robust forming processes. It is obvious that the transition to a new definition for the onset of necking the practical experience of the safety area must be re-examined. This should be demonstrated with an example. In figure 5 the measured strain distribution of two areas of a reinforcing part are shown. No visible necking was observed. To assess the practical robustness of the expected forming process the strain distribution of the non-cracked part will be compared with the FLC. However in the press shop only the tensile test results of the coil are available and therefore the FLC has to be approximated with the help of the regression formula and the mechanical properties. In the example given the safety requirement did not exist.

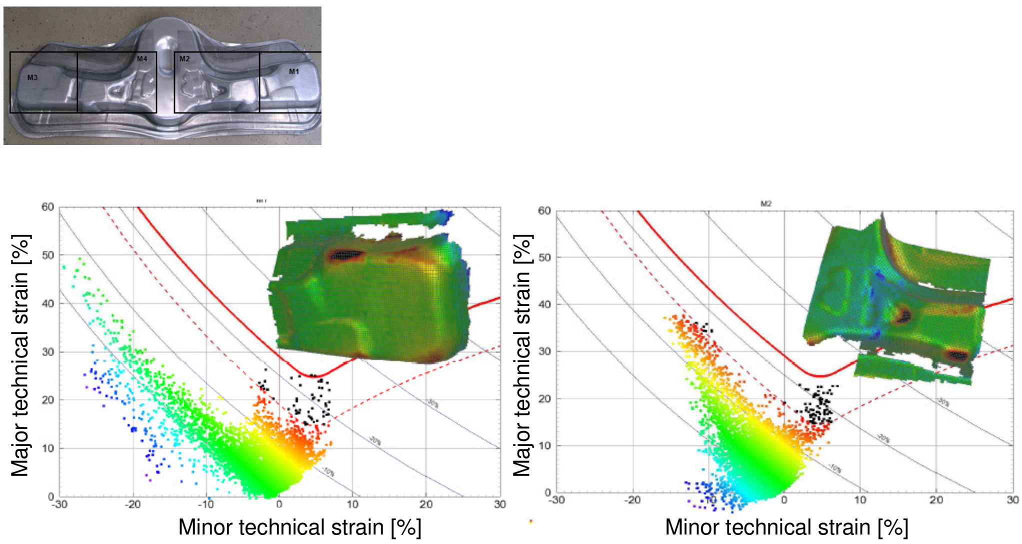
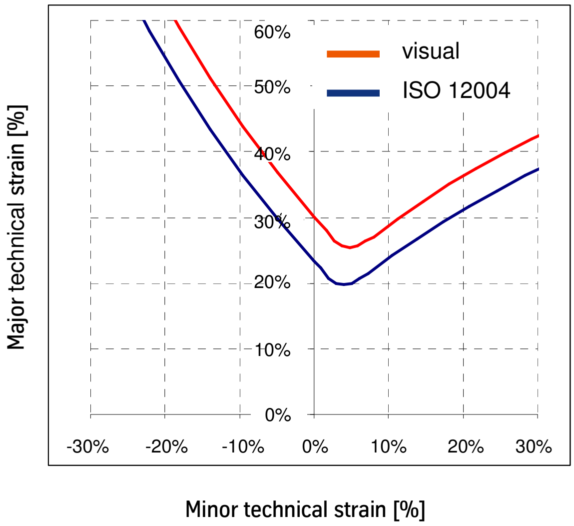


Figure 5: Strain distribution in two areas compared to the approximated FLC (visual) and the related 10% safety margin

In figure 6 it is shown that the practical safety margin of 10% is in the same order of magnitude as the difference of the FLCs due to their specific definitions. The FLCs are calculated using the regression formula as well as the mean standard deviation for transformation. It is therefore imperative to adapt practical experience in press shops when applying the new definition of the onset of necking to compare the strain distribution.



Grade
DP-K34/60

Thickness	TS	TE
mm	MPa	%
1,50	651	21,0

Figure 6: Visualisation of the FLC forecast depending on definition of necking

6. VARIABLE FLCs IN ROBUSTNESS SIMULATIONS

Using a regression formula it is possible to consider different formability limits in principle. Even if the elongation is not an input variable for the simulation an estimation of the change in the strain limits can be achieved using minimum values specified in the standards for certain steel grades. Nevertheless, the question arises if it is really necessary to consider the change of the FLC in robustness simulations. This will be illustrated briefly below by an example. A mild steel grade should be used for a door outer. Typical mean expected values used for the FLC calculation are a tensile strength of 295 MPa and a total elongation of 44%. In figure 7 the outer panel and the FLCs on the basis of mean values and the worst as well as best case are given for a sheet thickness of 0.8 mm. Note, there is nearly no difference in the forecast of the forming limits according to a visual or the ISO definition using the mean values of the mechanical properties, figure 7 left. The worst and best case FLCs regarding the ISO 12004 definition were calculated using the defined limits in the material standard of 270 < TS < 350 MPa and 38% < TE < assumed 51%, figure 7 right. These limits of the expected FLCs have a difference of about 0.04 from the FLC calculated with mean values. With reference to a real material scatter can be noted that the range of uncertainty in general is even smaller if the measured mechanical properties will not fulfil the entire range of the standard /Gerlach et al., 2010/.

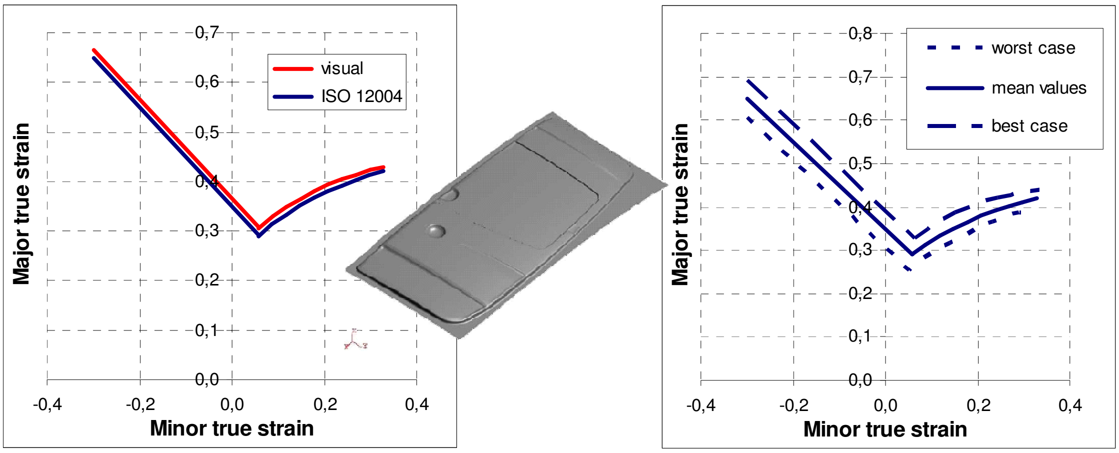


Figure 7: FLC forecast using the regression formula for an outer panel application of mild steel

In our numerical experience, not robust processes are characterized by extremely high volatility in the strain distribution. In addition to the variations in the material properties the friction often plays a crucial role especially using thin sheets with low strength. If the formability assessed by means of the distance to the FLC, the influence of a possible shift of the FLC itself often is small in contrast to the forced strain distribution. Therefore it does not seem absolutely necessary to cover the phenomenon of variable FLCs in robustness simulations. This aspect is visualised using the strain distributions according to the best/worst material parameter combinations and the lowest/highest friction coefficients compared with a constant FLC, figure 8.

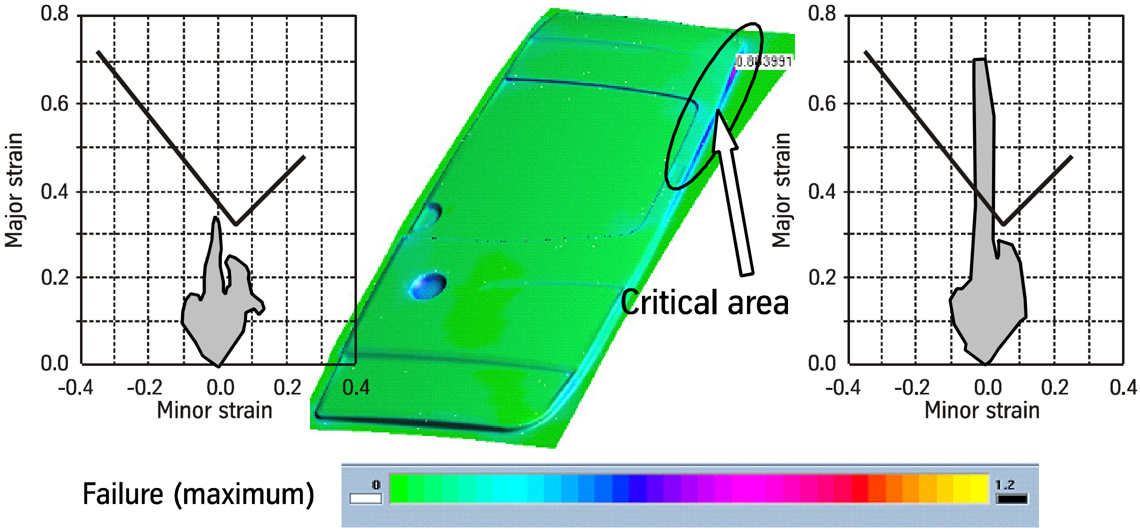


Figure 8: Strain distribution depending on scatter of mechanical properties and friction for the panel application

7. CONCLUSIONS

For practical applications it is possible to calculate the FLC from the mechanical properties with sufficient accuracy. For both definitions of failure according the traditional visual onset of necking and the new definition included in the ISO12004 proposal the sheet thickness, tensile strength and total elongation are the significant values. The forecast of the FLCs differs however when using various definitions for onset of necking especially for thicker sheets. This has an impact on the classical definition and interpretation of the safety margin in press shop applications.
Applying the regression formula, it is also possible to consider a variation of the forming limits in robustness simulations. However an absolute necessity for the consideration of the variability of the FLCs could not previously be detected.

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