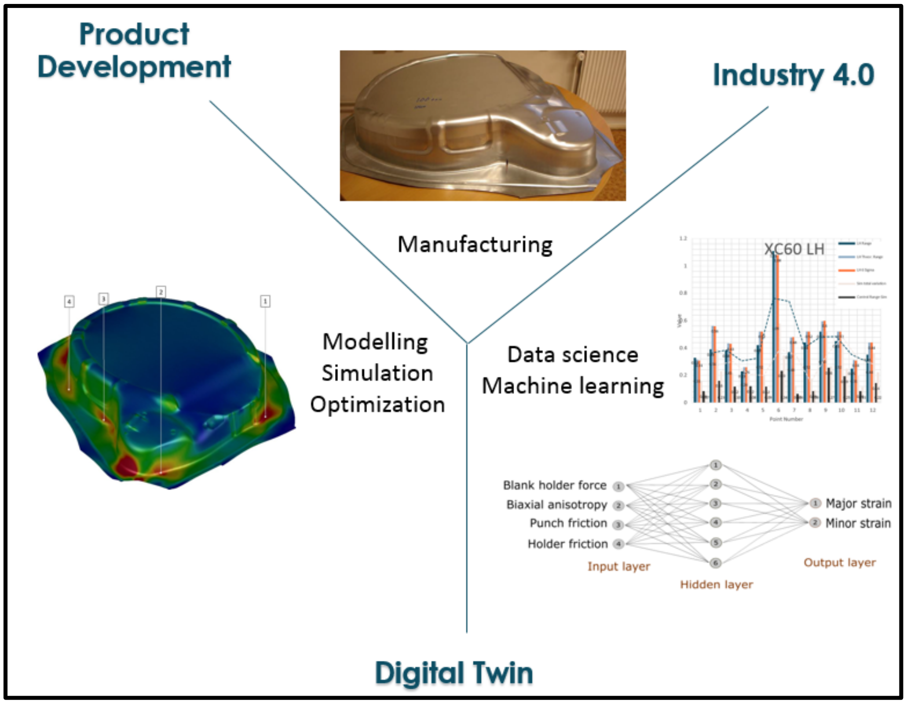
Prediktering av försträckning och brott för komplexa lastfall inom plåtformning

(PREDICT: Failure prediction for complex load cases in sheet metal forming)

Public report



Project within Hållbar produktion
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FFI Fordonsstrategisk Forskning och Innovation

Content

1. Summary

PREDICT has generated results and tools that are used to increase reliability of failure prediction of sheet metal forming simulation in finite element models (FE-model). The work in this project was focused to accurately model the effect of complex load cases like non-linear strain path (NLSP), stretch-bending and presence of edge crack in the formability of sheet metals like steel and aluminum alloys.

The effect of bi-linear strain path was experimentally performed on mild steel formability and findings were used to verify forming simulation of a critical automotive part. To bypass the NLSP effect on formability evaluation of sheet metal in FE-models, a strain path independent forming limit criterion was utilized. Outcome of NLSP study is published in two conference papers.

The strain localization during forming in shell element subjected to combined stretch-bend loads was successfully implemented in AutoForm FE-solver to evaluate risk on failure in automotive sheet metal stamping simulations. Studied results on a dual-phase steel and aluminum alloy showed that the forming limit is a function of the “stretching-to-bending ratio” and are published in a Journal.

Edge formability is often studied by sheet metal suppliers and automotive users through the hole expansion test (HET) in terms of hole expansion ratio (HER). The HER for a selected sheet metal usually varies in a wide range challenging its reliability. In PREDICT, HET was studied in a dual phase steel with modified boundary condition and full field strain measurement of the test samples and was concluded that restraining force of the sample during the test is not the primary cause of HER scatter. Similar scatter or uncertainty was numerically found in HET edge fracture strain. A systematic uncertainty quantification of HER in FE-model was studied and key factors effecting the scatter of HER and failure were identified, and the results are submitted for a journal publication.

During the project investigation, it was found that the failure/ necking in the sheet metal under forming has ambiguous definition among practitioners. The neck detection methods can be different and can depend on evaluator’s bias. Several works in PREDICT investigated and proposed a new/ modified neck detection method for defining the forming limit of the sheet metals and results are published in one journal and two conference papers.

To demonstrate the maturity of forming simulation which was further improved through PREDICT and a use case of implementing machine learning to achieve forming process robustness, FE-simulation prediction and measurement data based meta-model was developed using Artificial Neural Networks for quality assurance in the sheet metal forming process. The forming operation of the front door (inner) of a Volvo XC60 vehicle was selected in the case study and the predictions from the developed meta-model agreed well with FE-model prediction of deformation and failure.

In total, the project has resulted in one Licentiate thesis, three Journal articles (2 accepted and 1 under review), 6 conference papers and 6 master's theses. The project duration was extended by one month and 100% of the initial planned project budgets was utilized.

2. Sammanfattning på svenska

PREDICT har genererat resultat och verktyg som kan användas för att öka tillförlitligheten av prediktering av försträckning och brott vid plåtformningssimulering med finita elementmodeller (FE-modeller). I synnerhet fokuserades arbetet i detta projektet på att noggrant modellera effekten av komplexa lastfall såsom icke-linjära töjningsvägar (NLSP), sträckning-böjning och närvaro av kantsprickor som påverkar formbarheten hos plåt tillverkad av stål och aluminiumlegeringar.

Effekten av bi-linjär töjningsväg på påtmaterialets formbarhet studerades och utfördes experimentellt på ett mjukt stål och resultaten användes för att verifiera formningssimuleringen av en kritisk fordonskomponent. För att kringgå NLSP-effekten på formbarhetsutvärdering av metaller i FE-modeller, användes ett töjningsvägsoberoende formningsgränskriterium. Resultatet av NLSP-studien har publicerats i två konferensartiklar.

Töjningslokaliseringen under formning modellerad med skalelement som utsatts för kombinerad sträck ochböjbelastningar implementerades framgångsrikt i AutoForm FE-solver för att genom simulering utvärdera risken för försträckning och brott vid formning av plåtkomponenter för bilindustrin. Studerade resultat på tvåfas DP-stål och aluminiumlegeringen visade att formningsgränsen är en funktion av "förhållandet mellan sträckning och böjning". Resultaten har publicerats i en vetenskaplig tidskrift.

Risken för kantsprickor tuderas av materialleverantörer och inom bilindustrin oftast genom hålexpansionstest (HET) som ger ett hålexpansionsförhållande (HER- hole expansion ratio). HER för en utvald plåt varierar vanligtvis inom ett brett intervall, vilket ifrågasätter provets tillförlitlighet. I PREDICT studerades HET i ett DP- stål med modfierade randvillkor och fullfälts-töjningsmätning (DIC-Digital Image Correlation) av testprovet. Slutsatsen drogs att bromsningen av plåten inte är den primära orsaken till HER-spridning. Liknande spridning eller osäkerhet återfanns numeriskt vid HET-brottöjning. En systematisk osäkerhetskvantifiering av HER i en FE-modell studerades och olika nyckelfaktorer identifierades. Resultaten har skickats in för en tidskriftspublikation.

Prediktering av risk för lokalisering: Under projektets gång fann man att risken förtöjningslokalisering och/eller spricka i plåten under formning har en tvetydig definition bland utövare. Detekteringsmetoderna för töjningslokalisering (necking) kan vara olika och kan bero på utvärderarens partiskhet. Flera aktiviteter i PREDICT har undersökt och föreslagit nya/modifierader detekteringsmetoder för lokalsiering i syfte att definiera formgränsen för plåten. Resultaten har publiceras i en tidskrift och två konferensartiklar.

För att demonstrera mognaden hos formningssimulering som ytterligare har förbättrats genom PREDICT och ett exempel på användningsfall för att implementera maskininlärning i syfte att uppnå en robust formningsprocess, utvecklades artificiella neurala nätverk och FE-simuleringsbaserad metamodell för kvalitetssäkring av plåtformningsprocessen.

Totalt har projektet resulterat i en licentiatuppsats, tre tidskriftsartiklar (2 antagna och 1 under granskning), 6 konferensbidrag och 6 masteruppsatser.

3. Background

The automotive industry is entirely dependent on maintaining and improving competitiveness to stay relevant in the car market. This in turn, forces the Swedish automotive industry to rapidly adapt, develop, and identify new solutions. Moreover, the climate challenges and the current pandemic situation will further influence legislation, customer desires and future trends.

The focus of this project was sheet metal forming (SMF) used to create car body components like door panels, structural beams, and trunk lids, among other parts. One large obstacle to implementing new component design measures or introducing a new lightweight sheet material is the cost and lead time of stamping dies. For each new car model, a new set of stamping dies is designed and manufactured at a cost of around 550 MSEK, which is a major part of the investment. Moreover, the total lead time is more than two years. Setbacks during the tryout process of dies in the tool shop are contributing to higher lead time which is often followed by subsequent rework steps in the production press. The process is highly manual, time-consuming and thus costly. It can require up to five weeks per iteration loop for a single die and hundreds of dies are manufactured worldwide in each car project. One way forward to reduce cost and lead time is to finalize new die designs entirely based on finite element simulations that can model the stamping process with very high accuracy to reduce number of iterations and thereby the lead time and cost.

The SMF process has been simulated for the past couple of decades using FE-models, whereby one can predict factors such as shape, strains, thickness, springback, risk of failure, and wrinkles. Although FE-model predictions have benefited from advanced material characterization techniques, anisotropic plasticity, hardening models and advanced friction models, one bottleneck to reliable simulation result is the decade old failure models. This limitation of the current ‘industry standard’ failure models has been identified during several interactive workshops arranged by “The Stamping & Forming Center of Excellence”. Solving this research question can enable accurate FE-model based die designs which will reduce tryout time as well as the need for rework. An improved failure predictability could additionally enable the designers to be more aggressive in their geometrical shaping of new products since the safety margin when analyzing FE-models could decrease. This will also fast-track the introduction of new lightweight and sustainable materials to reduce body weight and minimize environmental impact.

Moreover, the variation in sheet metal thickness, material properties, lubrication and initial and boundary conditions have major influences on the formed part. Due to this, even an ideally designed die will not always avoid failure for every metal sheet in every batch. This is especially true if the formed part is aggressive in geometrical shaping which uses the formability to its limit.

PREDICT aimed to achieve increased accuracy in failure predictions by developing advanced material model calibration, and effective finite element simulations, which can enable unambiguous and reliable formability predictions. Specially, simulation failure predictions of phenomena such as non-linear strain paths, effect of strain rate, anisotropy and presence of edge cracks were studied. Finally, FE-simulation driven metamodels based on artificial intelligence were developed to predict formability based on supplier data to make process adjustments for failure prevention. This was an important step towards Industry 4.0 for the industry partners.

4. Purpose and research questions

The purpose of PREDICT is to achieve increased accuracy in failure predictions by developing advanced material models, calibration techniques and effective finite element simulations, which can enable unambiguous and reliable formability predictions. Specially, simulation failure predictions of phenomena such as non-linear strain paths, effect of strain rate, anisotropy and presence of edge cracks is studied, and understanding has been improved. More accurate failure prediction under these complex load cases during sheet metal forming simulation will increase trust on FE-model prediction. With high prediction accuracy of FE-models, the number of rework loops on the forming surfaces of die will be reduced. This will prevent component failure, need for additional rework as well as fast-track the introduction of new lightweight materials that minimize the environmental impact. This has the potential to significantly reduce cost and lead time and increase the Swedish automotive industry competitiveness.

Finally, FE-simulation-driven metamodels based on AI are developed to predict formability based on supplier and measured data to make process adjustments for failure prevention. This is an important step towards Industry 4.0 for the industry partners.

In summary the research question is:
Which aspects within material and process are of most significance to accurately predict formability, damage, and failure during forming in steel materials subject to non-linear straining, combined stretch-bending, and edge defects?

5. Objective

Competitiveness is largely about quickly moving from product idea to market and enabling efficient and reliable production. The objectives of this PREDICT project resonate with these requirements in the sheet metal forming industry. The main objectives are to:

- Achieve increased accuracy in failure predictions by developing advanced material models, calibration techniques and effective FE-simulations, which can enable unambiguous and reliable forming limit predictions.
- PREDICT process adjustment to prevent failure in a formed part as a result of material parameter variation.

To increase prediction capability of current failure models three failure effecting phenomena are studied experimentally and incorporated in FE-models:

1. Non-linear strain paths
2. Combined bending and stretching
3. Edge cracks

Another objective of PREDICT is to develop a metamodel using machine learning-based AI that can reduce the failure ratio of failure-prone parts. This is a pre-study that combined the accurate failure models developed in this project and variation of material properties provided by the supplier from their coupon tests. A failure-prone material and part was selected for this study by Volvo Cars who also provided a large amount of material property data from one of their suppliers. The output of this objective is a demonstrator desktop application that can predict process adjustments for the selected part which can then be used for manual process adjustments to reduce the risk of failure.

The proposed project contributed to several of the overarching FFI objectives. First, it has increased the Swedish capacity for research and innovation, thereby ensuring competitiveness and jobs in the field of automotive industry.

Second, this project promoted cooperation between industry, universities, and research institutes. The Region Blekinge has a large share of automotive suppliers with stamping and forming as core business. The local industry needs a supply of competence to ensure competitiveness and jobs. Consequently, Volvo Cars, RISE IVF, and BTH have strengthened the research area which has led to several master’s thesis works and one licentiate thesis from a PhD student. PREDICT is a strategic continuation of these efforts which has strengthened the competence network of the stamping industry in Sweden by co-financing a new PhD in the formability area.

Third, the addressed need for improved failure models is a common desire for Volvo Cars, Volvo Trucks and Scania. Thereby, the project has promoted cooperation between Swedish

OEM´s. Moreover, it has strengthened SSAB´s position as a material supplier in the automotive industry. Finally, PREDICT has also promoted cross-sectoral cooperation by participation of Alfa Laval, a company with advanced competence in press technology, thus creating a mutual and fruitful exchange of technology transfer.

Key PREDICT objectives are summarized in table Obj. and comments are made on the achievement of these objectives.

Objective (O)	Description	Realization
O1	SMF simulation will capture the effect of non-linear strain path in failure prediction.	Partial
O2	FE-models predicting failure for combined stretching and bending phenomena during forming operation.	Realized in DP800 and AA60xx
O3	Effect of edge crack sensitivity in blanks can be simulated as in a forming process.	Realized in DP800
O4	Strain rate dependence of failure will be integrated in the material model.	Realized experimentally in two AA60xx
O5	Testing for characterization of failure will be simplified to aid FE-models.	Partially realized by using FEMU and MT2.0
O6	Developed simulation driven metamodels will be able to optimize process settings to avoid failure.	Realized by artificial neural network based metamodel
O7	Three master's thesis projects. One or two students per thesis.	Six theses worked on PREDICT topic
O8	One Licentiate thesis	Realized
O9	Knowledge transfer for robust sheet metal forming operations at participating partners.	Realized through visits, meetings, workshops, co-production of scientific publications etc.

The original objectives in the project application did not change in any significant way.

6. Method, results and deliverables

A range of dual phase steels, mild steel and Aluminum alloys were studied in PREIDCT.
With the objective to achieve increased accuracy in failure predictions by developing advanced material models, calibration techniques and effective FE-simulations, which can enable unambiguous and reliable forming limit predictions, several studies in PREDICT were on how sheet metal formability is affected by (1) Non-linear strain paths (2) combiner stretch-bending load (3) presence of edge crack (defect) and investigated to incorporate these effects in FE-simulation models. Other than these, (4) strain rate effect on formability was experimentally evaluated in aluminum alloys, (5) method of neck detection and prediction of FLC was proposed. In the development of a FE-model of high accuracy, a

considerable amount of time and resources are spent on accurate material characterization. (6) Simplified material calibration techniques were investigated in this project. The method and results of these studies (1-6) are documented in good detail in this section. Most of these results are peer-reviewed and published in journals, conferences or theses; and for clarification of the method and results presented, the authors have been directed to the relevant publications resulting from PREDICT.

Finally, to predict corrective process adjustment to prevent failure in a formed part as a result of material parameter and some process parameter variation, ML-based metamodel has been studied and the method and results are presented in this section.

Non-linear strain path

The Forming Limit Diagram (FLD) has for the past many years been the industry standard within the automotive industry for predicting failure in sheet metal parts. The FLD consists of a Forming Limit Curve (FLC) and the predicted or measured major and minor strains in each point of the part. The determination of the FLC is usually carried out by Nakajima[1] or Marciniak tests[2]. The FLD does however require proportional loading i.e., linear and unbroken strain paths to be applicable. These proportional loading conditions are unlikely to occur in many forming processes with changing loading directions such as two-step forming operations or in parts exposed to combined tension. Examples presented by e.g. Affronti and Merklein[3] and Suttner and Merklein[4] illustrate the ending effects and pre-straining on the ductility properties and material behavior under bi-axial and in-plane shear loading.

To study the effect of non-linear strain paths on the formability of a few sheet grades, several studies were carried out in PREDICT. This topic was rather delicate and due to this a lot of efforts were put on where in many cases conclusions were made that the proposed or available methods were less effective to capture the effect of strain path non-linearity on formability. The first investigations were to design a small test-forming tool that can generate non-linear strain paths until failure[5] and then check the available methods in the literature to evaluate such tests for estimating the effect of arbitrary strain paths on forming. The designed tool was not very useful, and attention was paid to “strain-path independent” FLC. Generalised Incremental Stress-State damage Model (GISSMO) or the studied

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[1] Nakazima, K., Kikuma, T., & Hasuka, K. (1968). Study on the formability of steel sheets. YAWATA TECH REP, SEPT. 1968,--264--, 8517-8530.

[2] Marciniak, Z. (1978). Sheet metal forming limits. In Mechanics of Sheet Metal Forming: Material Behavior and Deformation Analysis (pp. 215-235). Boston, MA: Springer US.

[3] Affronti, E., & Merklein, M. (2018). Analysis of the bending effects and the biaxial pre-straining in sheet metal stretch forming processes for the determination of the forming limits. International Journal of Mechanical Sciences, 138, 295-309.

[4] Suttner, S., & Merklein, M. (2015). Characterization of the shear stress state under non-proportional strain paths realized by biaxial stretching in the Marciniak Test. Materials Today: Proceedings, 2, S98-S106.

[5] Eriksson, A. (2021). Non-Linear strain paths in Sheet Metal Forming.

material was calibrated and incorporated in FE-model but concluded to be ineffective capturing effect of NLSP[6].

A mild steel component from Volvo Cars, shown in figure NLSP-1 (a) was chosen that showed failure due to non-linear straining, although the strains did not reach the conventional forming limit. The FLC, which is in major and minor principal strain plane, was transformed to material flow direction α at the end of forming and the effective plastic strain plane. Here α is the ratio of minor and major principal strain rates at the last increment of deformations. It is worth noting that for an associated flow rule, α is related to the principal stress ratio and this is in called stress based FLC. For this transformation, BBC05 and Hill48 yield criteria were used. It was determined that the criterion for the transformation could not be decoupled from the material model used for the simulation[7].
In the FE-model of the Volvo Cars component, 4 arbitrary control elements in areas with high plastic strain were evaluated shown in figure NLSP-1 (b). The strain path of these 4 critical elements of FE-model together with a conventional FLC is presented in figure NLSP-2 (a). The path in black color is near the point where failure occurred in the component and surely is non-linear with a 90 degree right turn of path. Clearly, FLC does not predict failure here as the final strain is under the red FLC. Strain of the end of forming operation of the same 4 critical elements in the transformed evaluation plane is shown in figure NLSP-2 (b). Although, failure is not predicted either in this case, the most critical black dot in the plot is located away from the transformed FLC. It was concluded that his approach should be further investigated.

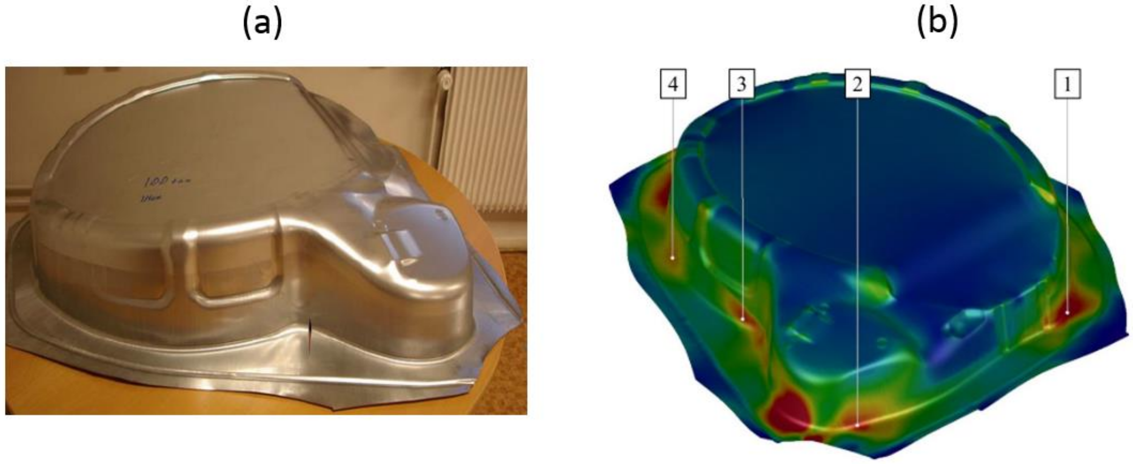

Figure NLSP-1: (a) A Volvo Cars component experiencing failure during forming due to non-linear strain path (b) FE-model of the same component showing 4 arbitrary control elements in areas with high plastic strain.

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[6] Aisvaran, C. (2021). Study of non-linear strain path in sheet metal forming.

[7] Barlo, A., Sigvant, M., Manopulo, N., Islam, M. S., & Pilthammar, J. (2022). Failure prediction of automotive components utilizing a path independent forming limit criterion. Key Engineering Materials, 926, 906-916.

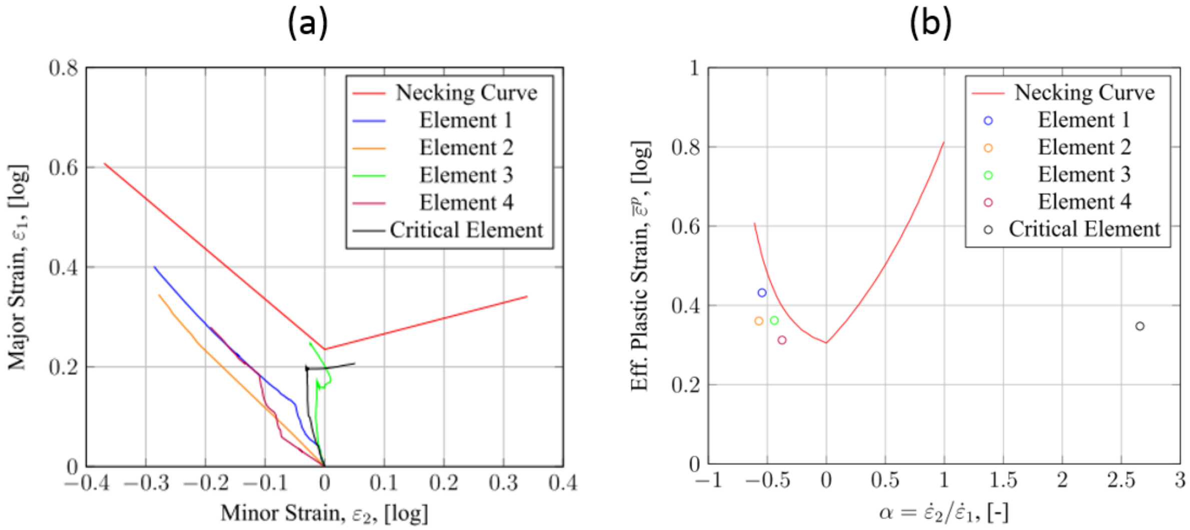

Figure NLSP-2: (a) strain paths of the 4 critical elements marked in figure NLSP-1 (b) strain of the end of forming operation of the same 4 critical elements in the transformed evaluation plane.

As by-passing the effect of strain path dependence was found to be difficult, the mild steel in the above complement was experimentally tested in newly designed pre-straining tool of 598×398 [mm] dimension[8]. In this large tool, mild steel plates could be pre-strained in uniaxial tension at about 25% and 50% of forming limit which is shown in the left-hand side of figure NLSP-3.

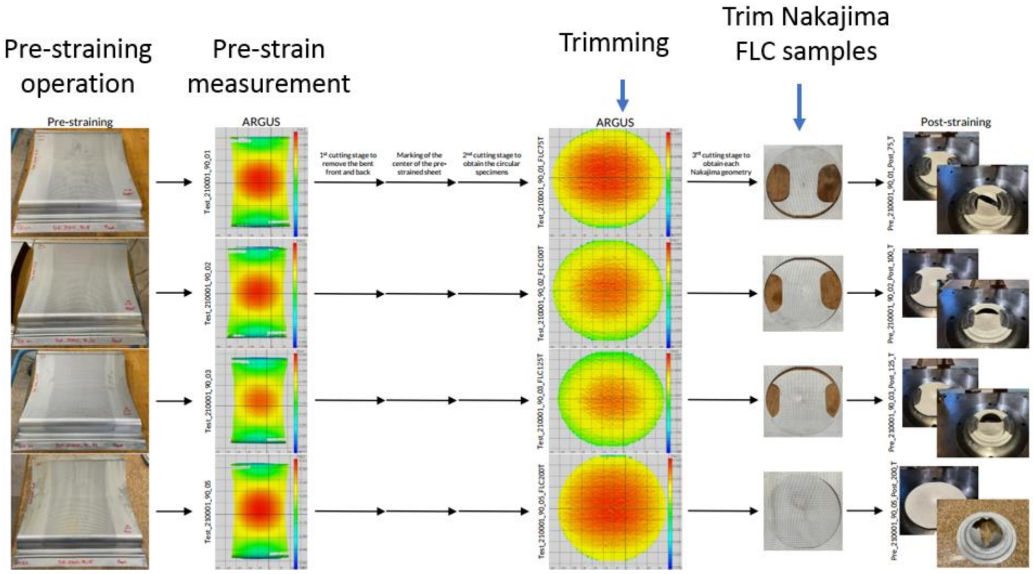

Figure NLSP-3: Uniaxial pre-straining operation followed by trimming FLC specimens and evaluation of FLC tests at 4 points.

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[8] Barlo, A., Sigvant, M., Islam, M. S., Pérez, L., Olofsson, E., Al-Fadhli, M., ... & Odenberger, E. L. (2023, June). Proposal of a New Tool for Pre-Straining Operations of Sheet Metals and an Initial Investigation of CR4 Mild Steel Formability. In IOP Conference Series: Materials Science and Engineering (Vol. 1284, No. 1, p. 012079). IOP Publishing.

Table NLSP-1: Test matrix of uniaxial and plane-strain pre-straining operation of different levels followed by post straining in Nakajima FLC tests.

Specimen	FE simulation			Experiment					Experiment	
	Pre-strain level	Draw depth [mm]	Major and minor strains [log]	Etched	Pressure gas springs [bar]	Draw depth [mm]	Major and minor strains [log]		Post-strain geometry	Major and minor strains [log]
Pre_210001_90_UT_25_01	25%	42.8	0.152, −0.0925	Yes	90	43.07	0.1492, −0.1178		FLC75	
Pre_210001_90_UT_25_02				No	=100	42.99	---		FLC100	
Pre_210001_90_UT_25_03						43.14	---		FLC100_L	
Pre_210001_90_UT_25_04						43.00	---		FLC125	
Pre_210001_90_UT_25_05						43.09	---		FLC125_L	
Pre_210001_90_UT_25_06						43.18	---		FLC200	
Pre_210001_90_PS_25_01	25%	30.0	0.0587, 0.0000	Yes	90	30.27	0.0199, −0.01508		---	---
Pre_210001_90_PS_25_02	25%	29.83	0.0587, 0.0000	Yes	150	30.35	0.0423, −0.01531		FLC75	
Pre_210001_90_PS_25_03	15%	26.0		Yes	150	25.75	0.0311, −0.0179		FLC100	
Pre_210001_90_PS_25_04				No		25.89	---		FLC100_L	
Pre_210001_90_PS_25_05						25.89	---		FLC125	
Pre_210001_90_PS_25_06						25.91	---		FLC125_L	
Pre_210001_90_PS_25_07						25.88	---		FLC200	
Pre_210001_90_UT_50_01	50%	59.6	0.304, −0.185	Yes	90	56.19	0.268, −0.192		FLC75	
Pre_210001_90_UT_50_02				Yes	=100	56.27	0.2774, −0.195		FLC75_L	
Pre_210001_90_UT_50_03				No		56.28	---		FLC100	
Pre_210001_90_UT_50_04						56.28	---		FLC125	
Pre_210001_90_UT_50_05						56.24	---		FLC200	
Pre_210001_90_UT_50_06						56.25	---		FLC200_L	
Pre_210001_90_PS_50_01	50%	36.61	0.1175, 0.0000	Yes	=100	36.14	0.0383, −0.01347		FLC75	
Pre_210001_90_PS_50_02	50%	36.61	0.1175, 0.0000	Yes	150	36.17	0.05616, −0.01277		FLC75_L	
Pre_210001_90_PS_50_03	50% (25%)	39.86		Yes	150	39.86	0.05826, −0.01280		FLC100	
Pre_210001_90_PS_50_04	25%			No		39.68	---		FLC125	
Pre_210001_90_PS_50_05						39.68	---		FLC200	
Pre_210001_90_PS_50_06						39.69	---		FLC200_L	

A similar levels of plane-strain pre-straining were performed using the same tool on another set of samples. All pre-strained specimens were trimmed to 4 different Nakajima geometries ranging from uniaxial, plane-strain to biaxial straining and tested to evaluate post-FLC. These two straining operations generated bi-linear strain paths in the failed specimens. These operations are shown for uniaxial case in figure NLSP-3 and some details on all the NLSP testing are presented in table NLSP-1. Non-proportional bi-linear strain path effect on the FLC is depicted in figure NLSP-3.

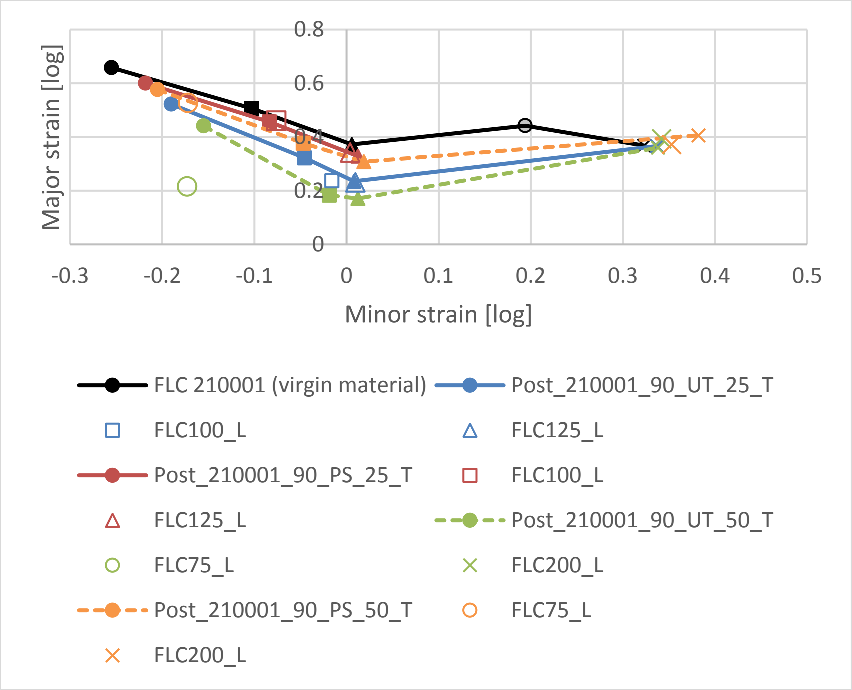

Figure NLSP-3: Forming limit curve effected by pre-straining in different strain-paths.

Stretch-bending

At combined stretch and bending load cases, sheet metal formability in aluminum alloy and DP steel were observed to increase at various levels in plane-strain conditions which were confirmed earlier by some of the PREDICT participating researchers[9]. These claims were based on experimental investigation of sheet metals in a combined stretch-bending setup shown in figure S-B 1. Details of the test and evaluation can be read in a PREDICT-related publication[10]. Here a modeling approach was introduced to predict strain localization during sheet metal stamping processes undergoing such loading. There is a proposal for using the “stretching-to-bending ratio,” to characterize the loading conditions experienced by an element in FE-model during stamping. Necking strain is suggested to be a function of this “stretching-to-bending ratio”.

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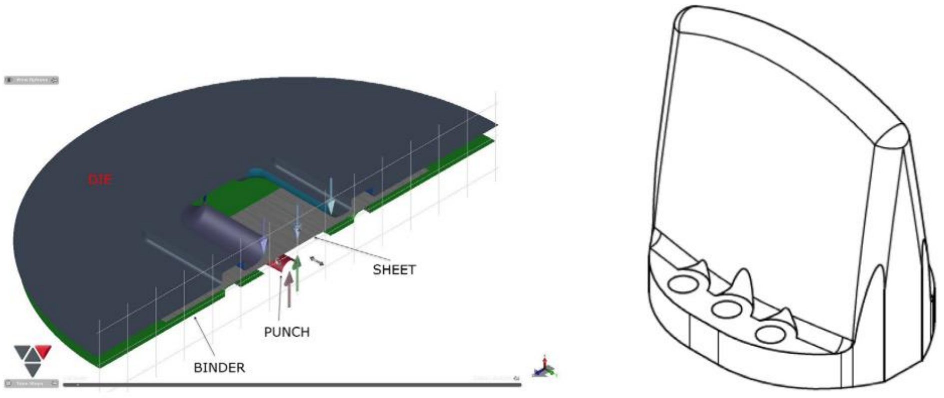
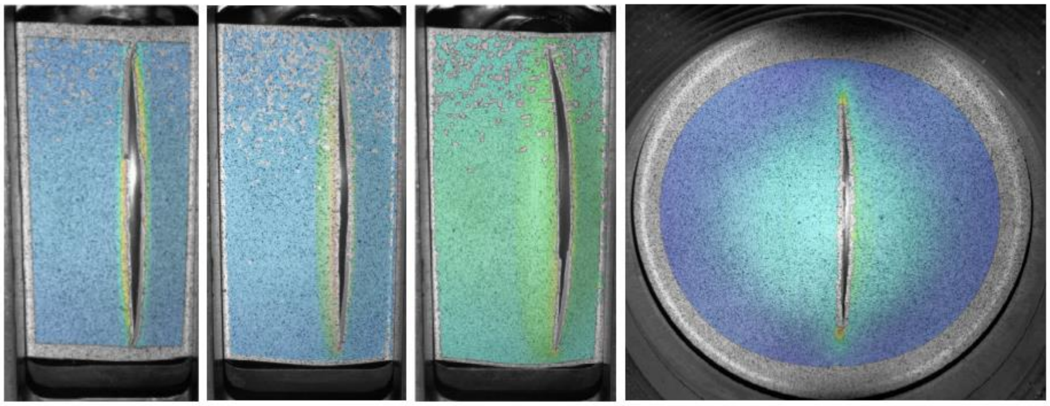
[9] Barlo, A., Manopulo, N., Sigvant, M., Endelt, B., & Trana, K. (2019). Investigation of a Bending Corrected Forming Limit Surface for Failure Prediction in Sheet Metals. In 12th Forming Technology Forum, Munich, Germany, September 19-20, 2019.

[10] Pham, Q. T., Islam, M. S., Barlo, A., Sigvant, M., Caro, L. P., & Trana, K. (2023). Modeling the strain localization of shell elements subjected to combined stretch–bend loads: Application on automotive sheet metal stamping simulations. Thin-walled structures, 188, 110804.



(a) A section view of the stretch-bend test (b) An illustration of the R6 punch

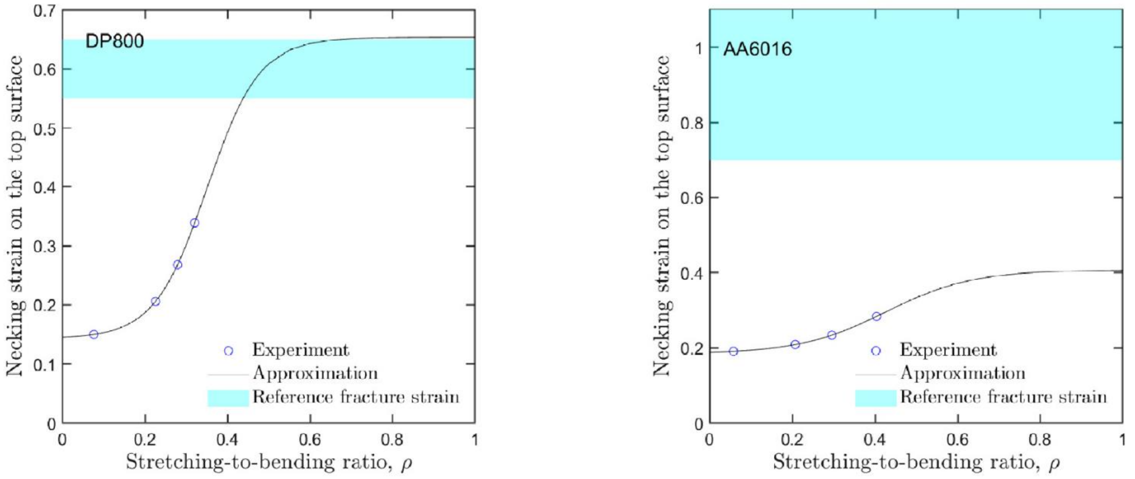
Figure S-B 1: Detail of stretch-bending test setup (a) section view of binder, punch, and sheet (b) enlarged R6 punch.



(a) R3 (b) R6 (c) R10 (d) R50-Nakajima test

Figure S-B 2: Fracture in DP800 specimens obtained from the stretch–bend tests with different punch radii.

To explore forming limits under different proportion of combined stretch–bend loads, four stretch–bending test types with different punching tool radii of R3, R6, R10, and R50 were performed on two automotive sheet metals: DP800 and AA6016. Full strain field at failure from digital image correlation (DIC) is used to find the failure strain at each stretching-to-bending ratio like that shown in figure (S-B 2). Based on these tests and a Boltzmann function, figure S-B 3 shows the identified necking limit curve of the tested materials[10].
The calibrated necking limit curve of the AA6016 sheet is then employed in AutoForm R10 software to successfully predict the necking and failure of a stamped panel[10]. To use the constructed necking limits in practice, a necking index was defined that updates the failure strain based on stretching-to-bending ratio and indicates how close the element under evaluation is to necking. The necking index is calculated using the maximum principal strains of the upper and lower layers of the element of interest[10]. The distribution of the index in some critical elements of the AA6016 panel used for validation of the proposed method is shown in figure S-B 4. Here an index equaling to or more than 1 means the necking limit has been reached. For FE-modeling, an advanced yield criterion i.e. BBC05 was calibrated for both materials, and the hardening curves were extrapolated using uniaxial tensile, viscous bulge test and then Swift or Hockett-Sherby laws that provided the cutting-edge simulation accuracy of forming deformations in this study.



(a) DP800 (b) AA6016

Figure S-B 3: Forming limit of the tested materials under combined stretch–bend loads.

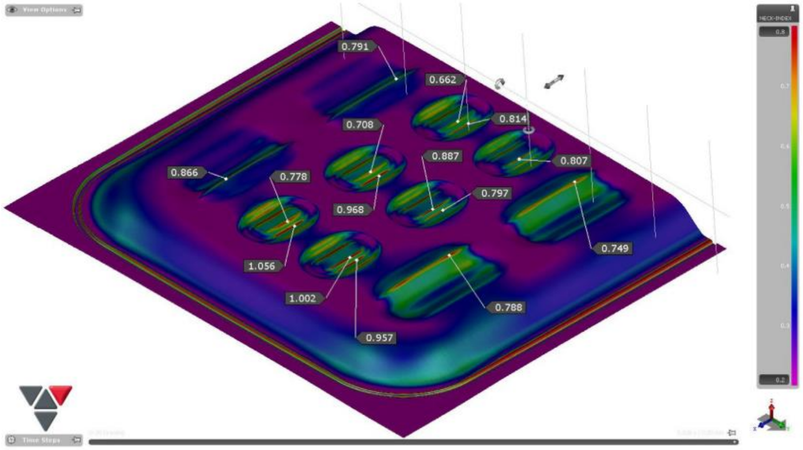


Figure S-B 4: A focused view of the simulated panel with the necking index distribution.

Edge Crack

The challenge with edge cracks is that the formability of sheet material is reduced due to unfavorable process conditions during the trimming of the part in the stamping process. Furthermore, this effect is more pronounced for the new lightweight materials, e.g., DP-steels and Aluminum alloys. Edge formability is commonly investigated using the ISO-16630 standardized hole expansion test (HET), which quantifies the hole expansion ratio (HER) for a given sheet metal. However, the HER values for specific sheet metal can exhibit considerable variation, posing challenges to its reliability. In the context of the project, researchers examined hole expansion testing (HET) on a dual phase steel samples. The boundary conditions (BC) in ISO-16630 don’t require to use of drawbeads to lock the test specimen more firmly. One HER study in PREDICT started with the hypothesis that the scatter in HER can be caused by a less-controlled blank holding method. So, the standard BC was modified, and Nakajima test setup was used for HET that clamps the specimen with drawbeads as shown in figure HET-1. To collect information on the time history of strain at the hole edge, DIC system was employed for full-field strain measurements during the test. Arguably, the proposed setup minorly improves the HER scatter situation (see the scatter in figure HET-2) yet shows the possibility of using a standard Nakajima test setup for HET[11]. The findings indicated that the restraining force of BC acting on the sample during the test is not the primary cause of the observed scatter in HER results.

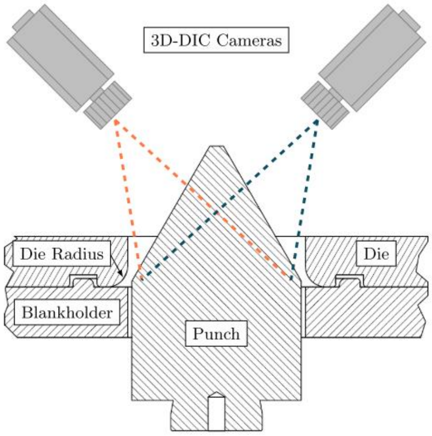


Figure HET-1: Cross-section view of the new experimental setup introducing draw beads and DIC system to the Hole Expansion Test.

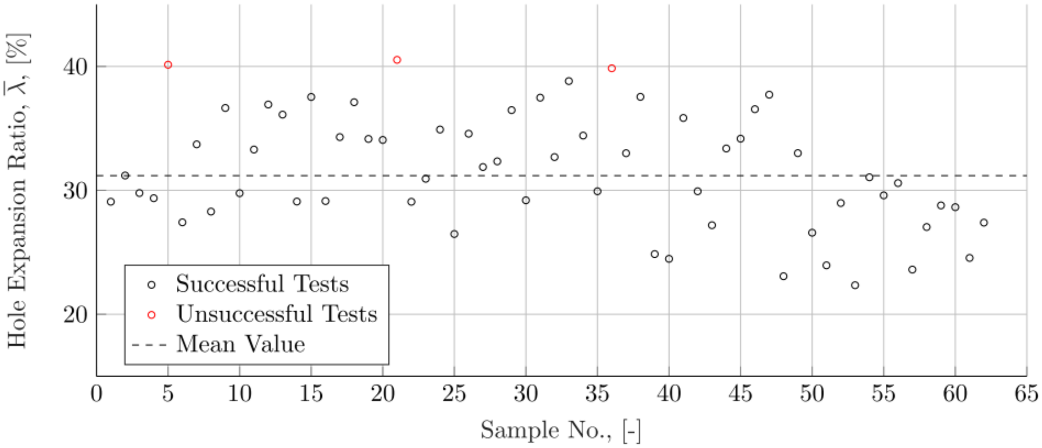


Figure HET-2: Hole Expansion Ratios of the 62 tests conducted. In total three tests were unsuccessful due to no presence of through-thickness cracks.

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[11] Barlo, A., Sigvant, M., Pérez, L., Islam, M. S., & Pilthammar, J. (2022, May). A Study of the Boundary Conditions in the ISO-16630 Hole Expansion Test. In IOP Conference Series: Materials Science and Engineering (Vol. 1238, No. 1, p. 012031). IOP Publishing.

Interestingly, a similar degree of scatter or uncertainty was also observed in the HET edge fracture strain shown in figure HET-3 obtained through inverse finite element modeling[12].

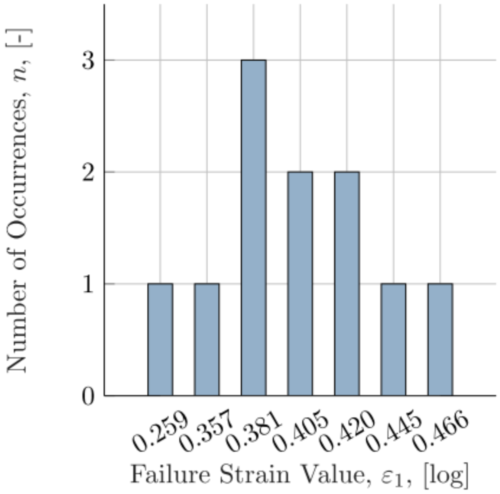
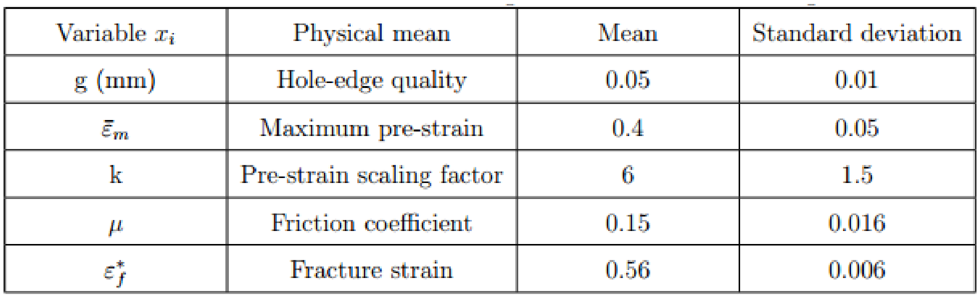


Figure HET-3: Number of occurrences for each failure strain for the surface layer.

To address this unwanted scatter, the researchers in PREDICT conducted a systematic uncertainty quantification study using the FE-model shown in figure HET-4. They identified five key factors contributing to the HER variability and are listed in table HET-1.

Table HET-1: Five variables observed during a HET and their variation range.



Variable x_i	Physical mean	Mean	Standard deviation
g (mm)	Hole-edge quality	0.05	0.01
$\bar{\varepsilon}_m$	Maximum pre-strain	0.4	0.05
k	Pre-strain scaling factor	6	1.5
μ	Friction coefficient	0.15	0.016
ε_f^*	Fracture strain	0.56	0.006

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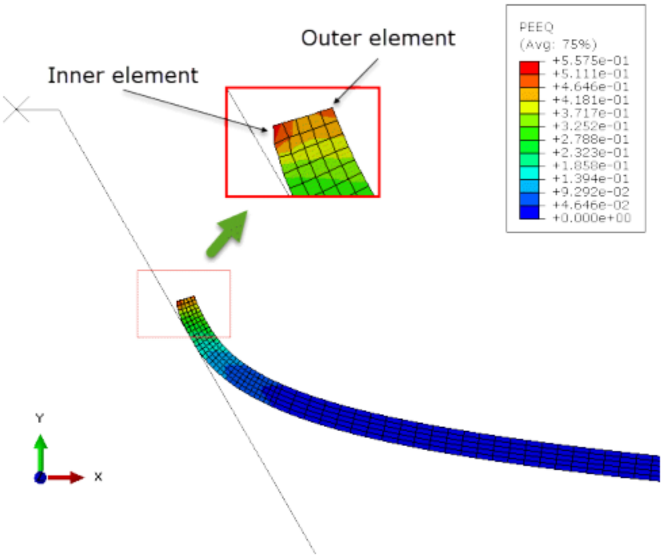
[12] Barlo, A., Sigvant, M., Kesti, V., Islam, M. S., Pham, Q. T., & Pilthammar, J. (2023, June). Determination of Edge Fracture Limit Strain for AHSS in the ISO-16630 Hole Expansion Test. In IOP Conference Series: Materials Science and Engineering (Vol. 1284, No. 1, p. 012027). IOP Publishing.



FigureHET-4: Determination of edge crack in a FE simulation using limiting equivalent plastic strain values.

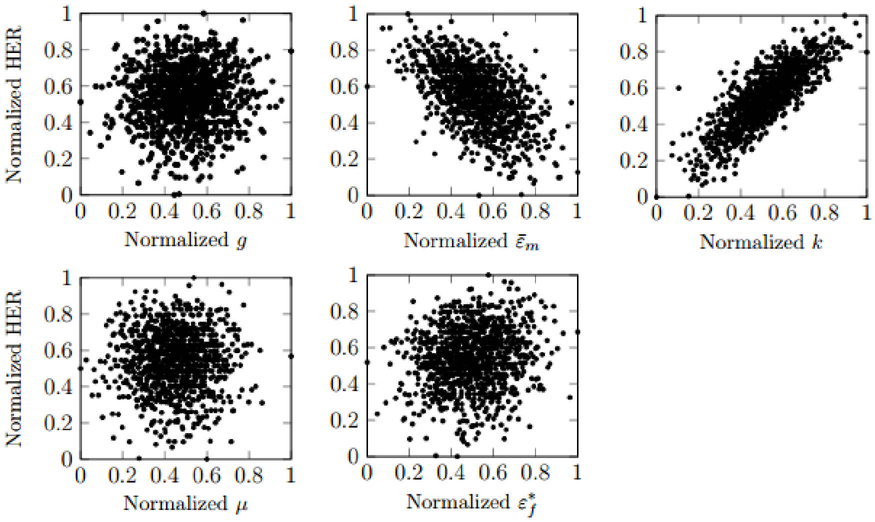


Figure HET-5: Correlations between the output normalized HER and input variables examined from simulations.

figure HET-5 presents the correlations between the output and input variables examined from simulations. It is seen that the HER has a degree of correlation with the pre-strain scaling factor, k and hence the most significant. In a nutshell, here k determines how fast the pre-strain from hole punching operation in HET decreases from the shear cutting edge to away of the edge. One way of determining pre-strain distribution around the hole is to perform hardness tests in a grid within a few millimeters of the hole edge. Histogram of the HER measured from HET experiment and simulations are compared in figure HET-6 showing good agreement. The detail of this study is documented in a journal article currently under review for publication[13].

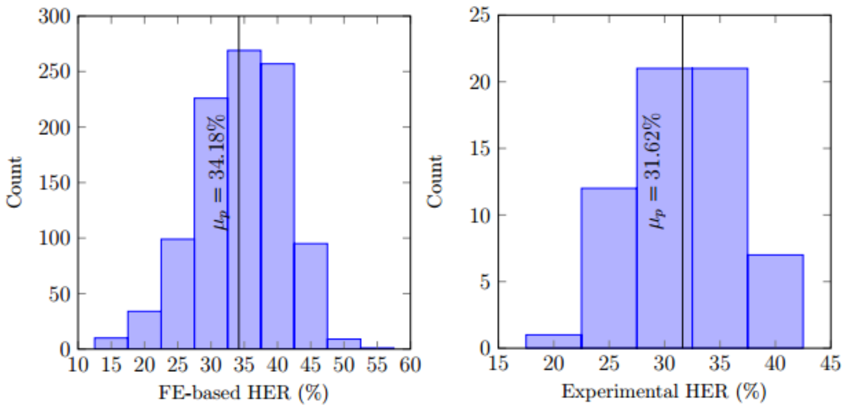


Figure 10: Histogram of the HER examined from the developed database.

Figure HET-6: Histogram of the HER examined from the developed database.

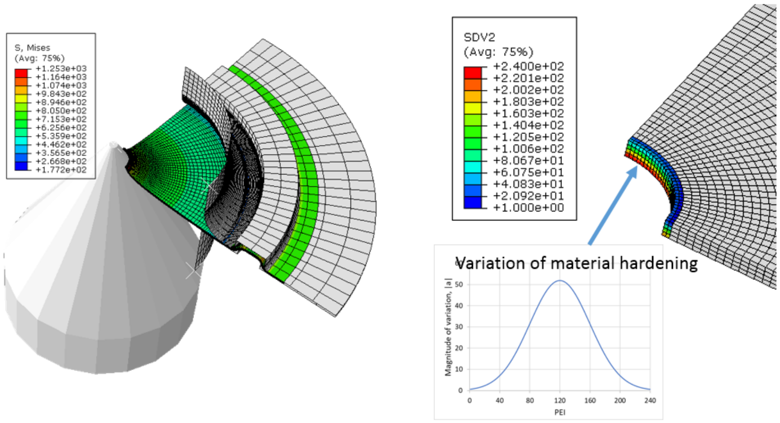


Figure HET-7: Material variation as a measure of uncertainty quantification of hole expansion ration in HET.

A separate pre-studies of stochastic material property distribution were made where the hardening curve was normally scaled and assigned to elements near the hole edge of HET 3D simulation model as shown in figure HET-7. The spread of simulated and experimental HER is shown in figure HET-8. Although the modeling needs more maturity, nevertheless, this showed promising result of using such stochastic modeling for uncertainty quantification.

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[13] Pham, Q. T., Barlo, A., Islam, M. S., Sigvant, Pilthammar, J., M., Pérez, L., & Kesti V. (2024, Uncertainty quantification for conical hole expansion test of DP800 sheet metal (Submitted for journal publication)

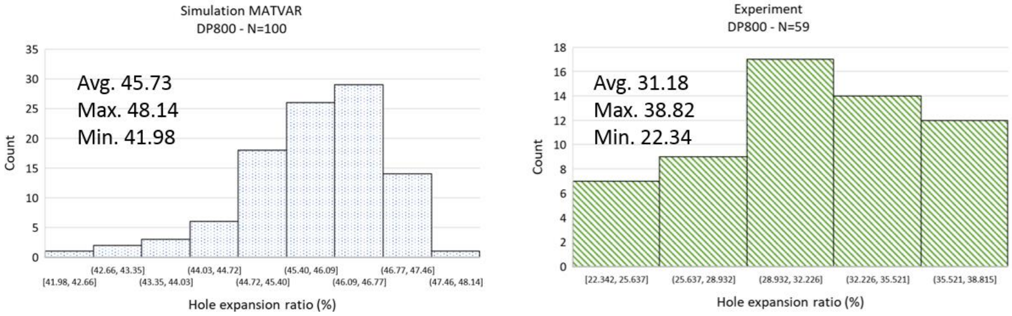

Figure HET-8: Simulated scatter of HER by material property variation near hole edge vs the experimental HER

Strain rate

The effect of strain rate together with natural aging on two grades of aluminum alloy was studied. It is concluded that increased strain rate has a minor negative effect on formability (figure SR-1) and hardening of the studied alloys.

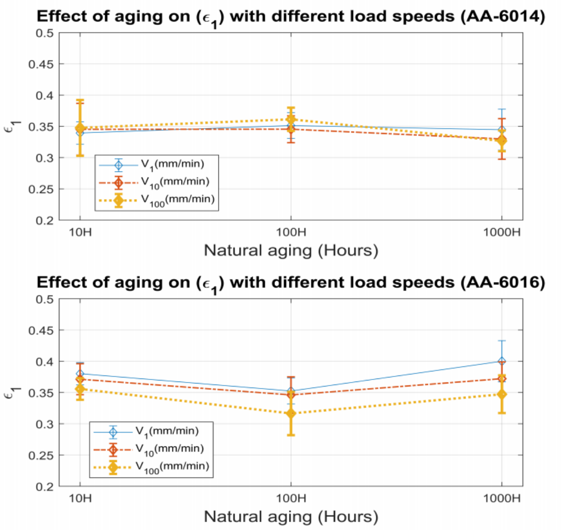

Figure SR-1: localized necking major strain at different strain rates during natural aging for AA6014 andAA6016.

Neck detection

In sheet metal stamping, the occurrence of strain localization in a deformed sheet is considered a failure. Disagreements exist among experts in the field on the method defining the limit strain from experimental observation resulting different research group evaluating very different FLC from the exact same set of tests. A new evaluation method for experimentally detecting strain localization of sheet metals is proposed in PREDICT[14]. The method seeks the minimum of the Coefficient of Variation (CoV) observed in the major

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[14] Tuan Pham, Quoc, Md Shafiqul Islam, Mats Sigvant, and Perez Lluis Caro. "Prediction of forming limit diagram of automotive sheet metals using a new necking criterion." In International ESAFORM Conference 2023, pp. 705-710. 2023.

strain rate field spreading in a region of interest, which makes its implementation programmable. The proposed method is applied to determine the FLC of AA6016 and DP800 sheets, of which the derived FLCs are significantly lower than that of the ISO 12004:2-2008 standard method. Compared to an industrial used curve, the VCBC-FLC[14], the former presents closer results than those of the latter. The performance of the CoV method is compared with two other popular necking detection methods in figure FLC-1.

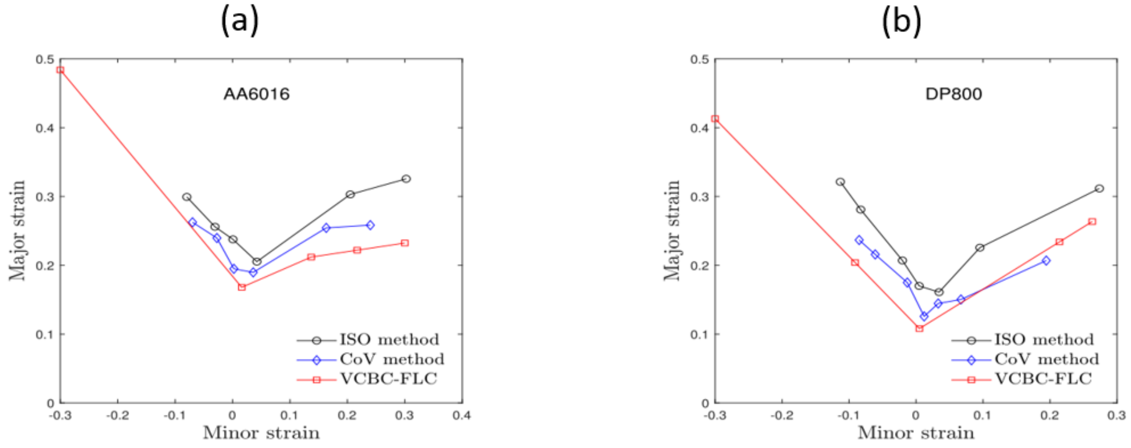

Figure FLC-1: Comparison between predicted FLCs of sheet based on different methods (a) AA6016 and (b) DP800.

In addition, improvement of modified maximum force criterion (MMFC) for forming limit diagram prediction of sheet metals was proposed and validated within PREDICT and the results are published in a journal article[15].

Simplified material calibration

Testing and calibration of failure is expected to be simplified during PREDICT. It is an urgent demand to develop new testing methods and characterization procedures that are able to produce a huge amount of meaningful data within a few numbers of material tests. In a PREDICT study, a calibration method based on machine learning techniques to identify parameters of a Swift type hardening law of two dual-phase steel sheets was carried out. The Swift hardening law for the curve is given by the Eq. MT-1 that has three material parameters C, ε_0 and n.

$$\sigma = C(\bar{\varepsilon} + \varepsilon_0)^n \qquad \text{(MT-1)}$$

Accurate extrapolated hardening curve is fundamental to accurate deformation under forming operation. Especially, hardening response around defused necking is relevant to failure by necking. The current identification procedure of hardening curve parameter, when done at high accuracy, requires in-plane and biaxial tests and finite element model updating. In the study, the framework in figure MT-1 was adopted. At the first stage, three material parameters' design spaces were identified, and a set of virtual material was selected. These virtual materials are simply sets of different combinations of the three

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[15] Pham, Q. T., Islam, M. S., Sigvant, M., Caro, L. P., Lee, M. G., & Kim, Y. S. (2023). Improvement of modified maximum force criterion for forming limit diagram prediction of sheet metal. International Journal of Solids and Structures, 273, 112264.

hardening parameters within the design space. A dogbone tensile specimen FE-model was virtually tested to generate the database for feed forward artificial neural network (FFNN). Six key features from the resulting force-displacement response were the selected.

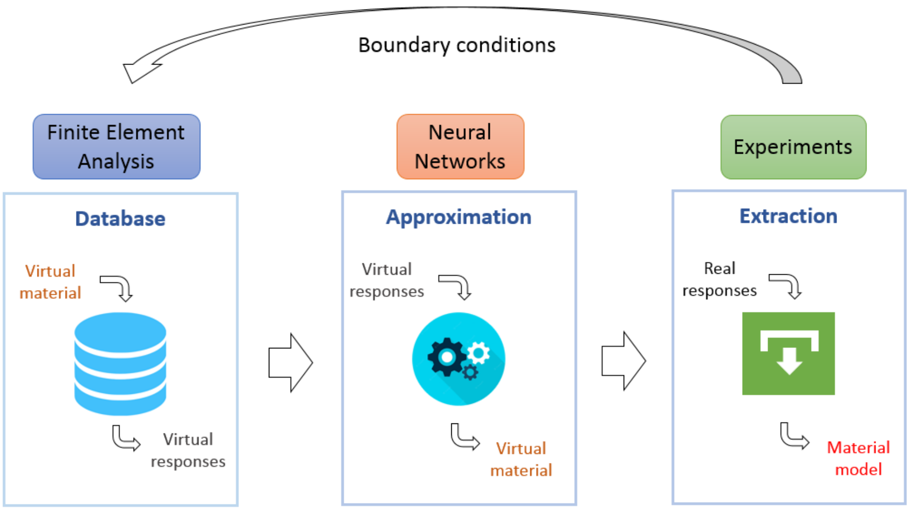

Figure MT-1: Framework for identification of material properties using feed-forward neural networks.

In the next step, the virtual material parameters and features from the associated simulated response were used to train two FFNNs with variation in the features. The performance from both FFNN predictions is compared in figure MT-2.

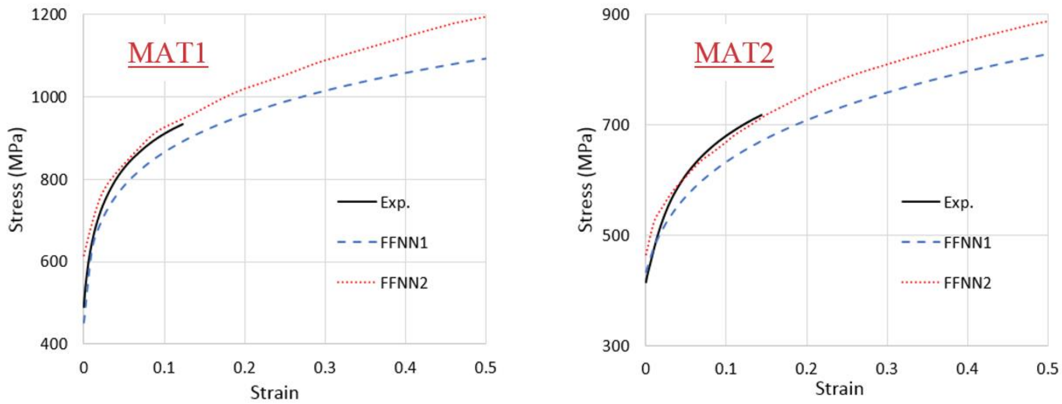

Figure MT-2: The performance from both FFNN predictions in two steel grades.

The so-called Material Testing 2.0 (MT 2.0) is a promising proposal in which the full- field measurement via digital image correlation (DIC) is becoming mainstream[16]. The richness of the full-field measurement with its kinematic information opens possibility to design and use more complex, potent, statically indeterminate test configurations than standard ones. MT2.0 has huge potential of simplifying the material characterization procedure.

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[16] Pierron, F., & Grédiac, M. (2021). Towards Material Testing 2.0. A review of test design for identification of constitutive parameters from full-field measurements. Strain, 57(1), e12370.

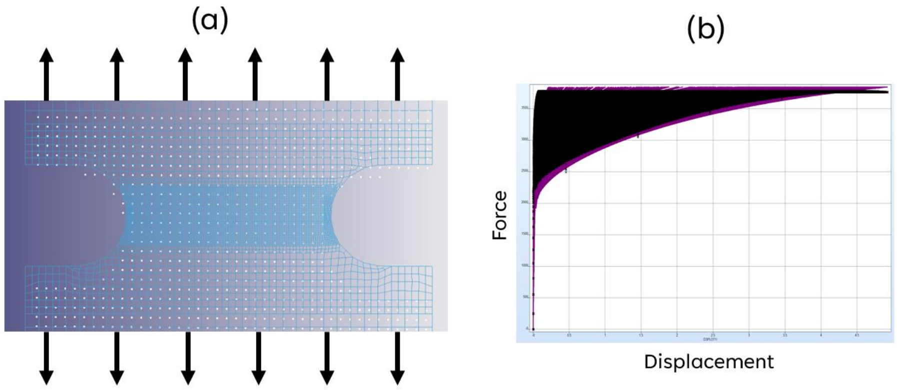

Figure MT-4: Mt 2.0 (a) Overlapping DIC and FE-model nodal responses and (b) the nodal force-displacement responses comparison after optimization of Swift hardening parameters.

In a similar PREDICT study, the Swift hardening parameters were identified using inverse-FEA methodology, where the full field strain were measured using DIC system together with force and displacement response from tensile test of a plane-strain specimen of mild steel (figure MT-4 (a)). Nodal force-displacement values of experimental DIC mesh were compared with FE-model response of the same test at many deformations increments. The Swift hardening parameters were updated in LS-OPT and until these responses were close enough as shown in figure MT-4 (b).

In both simplified characterization cases, the obtained hardening parameters were comparable with those identified traditionally showing the potential of using these methods.

ML based process adjustment to prevent failure

The variation of geometry, material properties and required initial and boundary conditions in this application area is one of the key issues having a major influence on the numerical results. Generally, the numerical simulation of sheet metal forming is based on the nominal values of appropriate parameters, or a particular design setting, which are essential for the process, e.g., material properties, friction condition between different contact areas, initial thickness of specimen, draw bead conditions, blank holder and press forces, position of the specimen, etc. However, there is no guarantee that the conclusion or results from one deterministic simulation can be extended over the entire design space[17].

A virtual twin of the manufacturing process was created using accurate FE-model prediction of metal forming and machine learning algorithms. For this case study, the Volvo XC60 front door (inner) was relevant to select due to its complex geometric features and some critically formed regions. With this aim, data was collected from press line measurement of cushion force and lubrication migration in the sheet, a range of material properties characterized form laboratory testing by sheet metal suppliers and PREDICT

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[17] Chen, W., Baghdasaryan, L., Buranathiti, T., & Cao, J. (2004). Model validation via uncertainty propagation and data transformations. AIAA journal, 42(7), 1406-1415.

consortium. Some of the above-mentioned data types (parameters) were observed to be varying in ranges that affect the quality of the formed part. Naturally, these parameters varying in observed ranges were selected to systematically change in a series of FE-modeling of the XC60 door forming process and predict formability or potential failure at critical regions of the part. The part geometry being complex, there could be no failure in case of favorable combinations of the above-mentioned variables. On the contrary, there can be some critical combinations of the parameters in the current production setting that can cause part failure, e.g., crack, excessive thinning, and wrinkle. To check if simplifying some geometric features can improve the number of successful parts, two geometric parameters i.e., bending radius at two critical regions were varied in the FE-model, and failure predictions were made as before. Data were collected from a total of 255 FE-simulations in AutoFrom and in each case, the strains in three critical points (3 outputs) were checked for failure which can be seen in figure (Twin-3). The list and range of a total of 16 variables (inputs) are depicted in figure Twin-1

Data Generation

Geometrical Parameters	
R_1:	5 – 10
R_2:	5 – 10
Material Parameters	
R-value:	1.429 – 1.747
R_p:	142.7 – 170.1
R_m:	286-9 – 314.3
Lubrication and Migration Parameters	
Lub. Amount (Upper):	0 – 0.8
Mig. Upper 1:	0 – 0.8
Mig. Upper 2:	0 – 0.4
Mig. Upper 3:	0 – 0.4
Mig. Upper 4:	0 – 0.8
Lub. Amount (Lower):	0 – 0.8
Mig. Lower 1:	0 – 0.8
Mig. Lower 2:	0 – 0.4
Mig. Lower 3:	0 – 0.4
Mig. Lower 4:	0 – 0.8
Press Line Parameters	
Cushion Force:	1030 – 1800

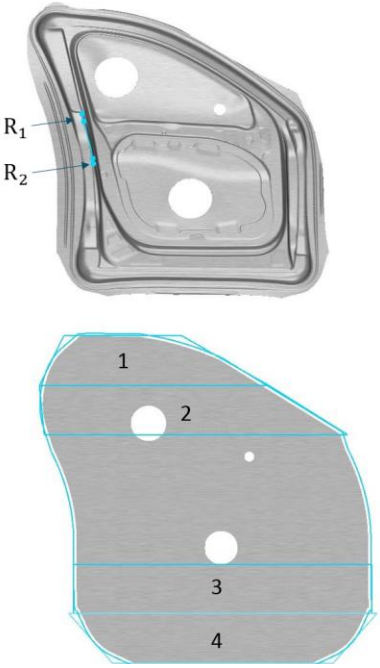
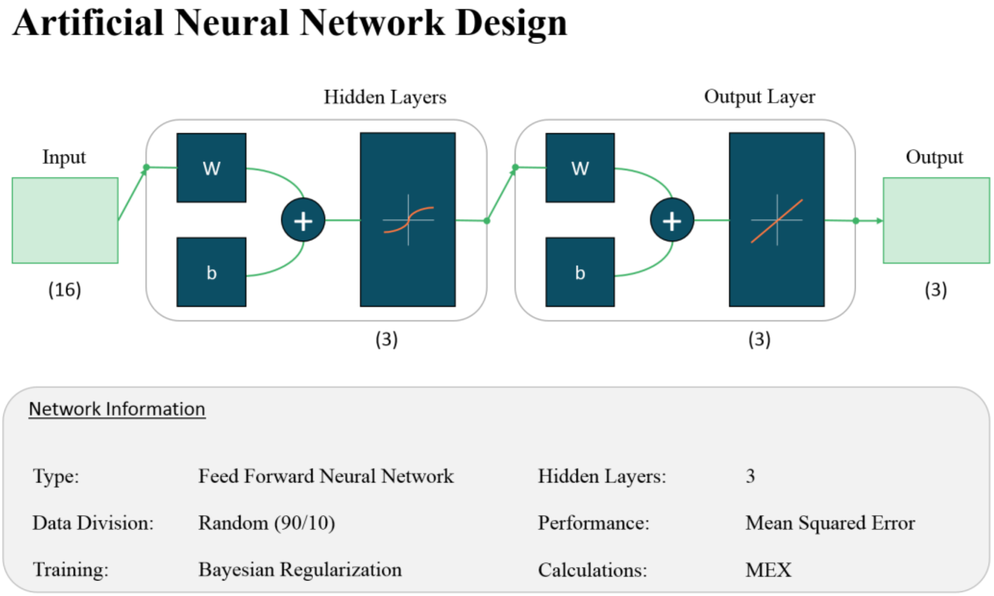


Figure Twin-1: Data generation: List and range of variables in the FE-simulation with geometric clarification.

The collected data set enabled the training of Artificial Neural Networks (ANN) with arbitrary input and output data. Arbitrary in the sense that depending on the controllable and uncontrollable parameters, the trained network can be used to suggest a preventive adjustment of the controllable parameters for a given press and available data. The ANN design is shown in figure Twin-2. Successful validation of the ANN was performed using FE-model prediction and a comparison was shown in figure Twin-3 for three given input data sets.



Network Information

Type:	Feed Forward Neural Network	Hidden Layers:	3
Data Division:	Random (90/10)	Performance:	Mean Squared Error
Training:	Bayesian Regularization	Calculations:	MEX

Figure Twin-2: Design of one of the ANN with 16 inputs and 3 outputs.

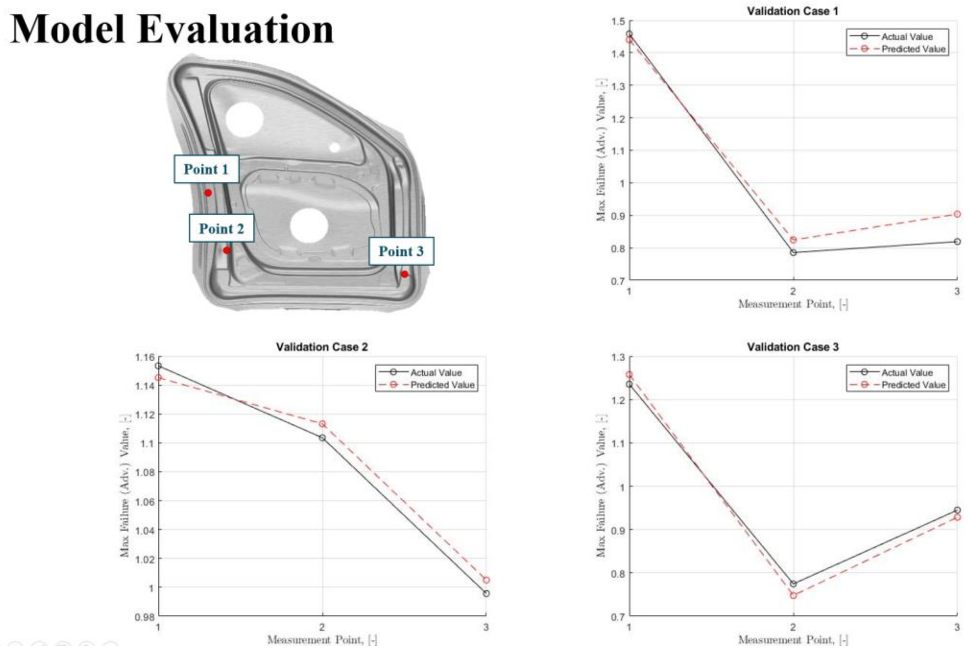
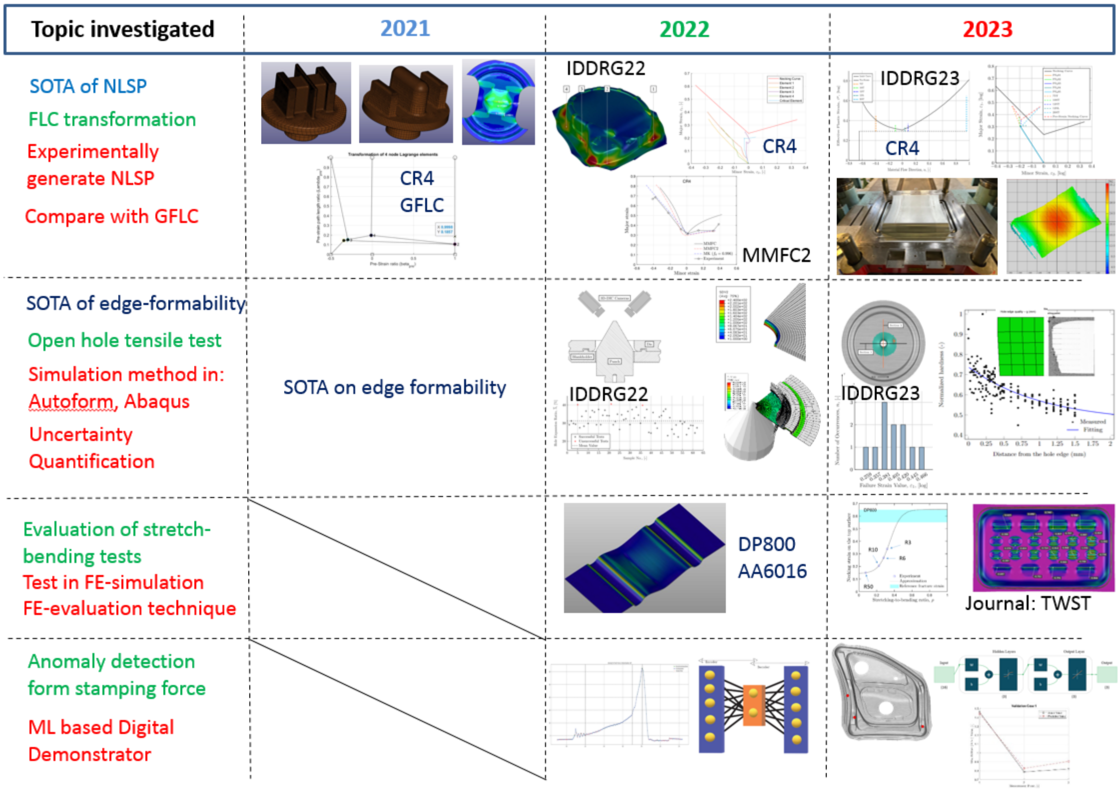


Figure Twin-3: Critical points for checking failure and FE-simulated and ANN predicted failure comparison at those 3 points for a given input data set.

Some of the key results of PREDICT are summarized in project timeline in the figure result-summary.



Topic investigated	2021	2022	2023
SOTA of NLSP FLC transformation Experimentally generate NLSP Compare with GFLC	CR4 GFLC	IDDRG22 CR4 MMFC2	IDDRG23 CR4
SOTA of edge-formability Open hole tensile test Simulation method in: Autoform, Abaqus Uncertainty Quantification	SOTA on edge formability	IDDRG22	IDDRG23
Evaluation of stretch-bending tests Test in FE-simulation FE-evaluation technique		DP800 AA6016	Journal: TWST
Anomaly detection form stamping force ML based Digital Demonstrator			

Figure result-summary: A summary of key results created in PREDICT in the project timeline.

The significant goals (G) for expected results and goal fulfillment (GF) are as listed in table G&GF 1.

Table G&GF 1: List of the significant goals (G) for expected results and goal fulfillment (GF) in PREDICT.

Goal no.	Goal (G)	Goal fulfillment (GF)
G1	SMF simulation will capture the effect of non-linear strain path in failure prediction	Non-linear strain path effect on failure was evaluated in steel sheets. With the aim to gain a strain path-independence of failure criteria, forming limit diagram for mild steel was transformed into different planes and validated against a critical automotive part.
G2	FE-models predicting failure for combined stretching and bending.	An FE-modeling method is developed and validated on a dual-phase steel and an aluminum alloy showing that forming limit is a function of the "stretch-bending ratio".
G3	The effect of edge crack sensitivity in blanks can be simulated.	Hole Expansion Ratio (HER) as edge formability was studied experimentally and also simulated to check failure strain variation. In both cases significant variation was found, and measures were taken to reduce them. Uncertainty quantification of

		HER in FE-model was studied and key factors were identified and implemented.
G4	The strain rate effect will be studied.	The effect of strain rate on two grades of aluminum alloy was studied. It is concluded that increased strain rate has a minor negative effect on formability and hardening of the studied alloys.
G5	Testing for characterization of failure will be simplified to aid FE-models.	A simplified die-punch setup is designed to generate non-linear strain paths and measure its effect on formability. Pre-studies were done using full-field strain measurement to vastly simplify characterization of advanced material models.
G6	Predict process adjustment to prevent failure in a formed part as a result of material parameter variation.	A use case example of implementing machine learning to achieve forming process robustness, Artificial Neural Networks and FE-simulation based meta-model was developed for quality assurance in the sheet metal forming process.
G7	1 licentiate and 3 master’s thesis projects.	The project resulted in 1 Licentiate and 6 master’s theses.

Contributions to overall FFI goals

- Increase research and innovation capacity in Sweden in the field of sheet metal forming simulation by enabling accurate failure prediction.
- Promote collaboration between industries, university, and institutes by running part of the project as doctoral and master’s degree projects.
- Promote cross-industry collaboration, as vehicle suppliers, material manufacturers, research institute and education players actively participate.
- Work internationally through journal publishing, conferences, and exchanges of knowledge with researchers and companies abroad.

Contributions to Sustainable Production goals

- Improved material characterization and accurate simulations created the possibility to fast-track the introduction of new lightweight materials to reduce body weight and minimize CO_2 emissions in the vehicle life cycle.

- Reduction in die lead time can increase resource efficiency and reduce the environmental impact of the production system.
- Reduced component failure and the need for additional rework will reduce material waste.
- Artificial intelligent based demonstrator is developed that showed metamodel capability to prevent failure in formed parts. This will be a step towards industry 4.0 for the participating partners.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	Knowledge of failure prediction in FE-model has increased. New experimental and evaluation methos have been proposed and published in peer reviewed publications.
Be passed on to other advanced technological development projects	X	One national and one EU research project application was submitted that can further develop on PREDICT results.
Be passed on to product development projects	X	Some of the knowledge is passed to product development activities.
Introduced on the market		Not achieved.
Used in investigations / regulatory / licensing / political decisions		Not achieved.

A part of the PREDICT consortium is seeking future project funding on the topic of recycled sheet metals used in mass market applications. Such recycled materials have large performance property variation (spread in formability, strength, etc.) from batch to batch of the same material. Due to this, more frequent material testing and characterization is needed for quality control. The simplification of this process studied in PREDICT will be important. To model this spread of performance in FE-models different uncertainty quantification methods investigated in PREDICT will be useful. In general, the understanding of the failure prediction in this project and the achieved close collaboration of key partners in the industry will prove curtail for further study of the results.

7.2 Publications

The project results have been published in one Licentiate thesis, three Journal articles (2 accepted and 1 under review), 6 conference papers, and 6 master's theses. A list of the conference (C), Journal (J) articles, licentiate (L), and master's thesis (T) publications are presented next.

C1: Barlo, A., Sigvant, M., Pérez, L., Islam, M. S., & Pilthammar, J. (2022, May). A Study of the Boundary Conditions in the ISO-16630 Hole Expansion Test. In IOP Conference Series: Materials Science and Engineering (Vol. 1238, No. 1, p. 012031). IOP Publishing.
C2: Barlo, A., Sigvant, M., Manopulo, N., Islam, M. S., & Pilthammar, J. (2022). Failure prediction of automotive components utilizing a path independent forming limit criterion. Key Engineering Materials, 926, 906-916.
C3: Tuan Pham, Quoc, Md Shafiqul Islam, Mats Sigvant, and Perez Lluis Caro. "Prediction of forming limit diagram of automotive sheet metals using a new necking criterion." In International ESAFORM Conference 2023, pp. 705-710. 2023.
C4: Pham, Q. T., Islam, M. S., Barlo, A., & Sigvant, M. (2023, June). An evaluation method for experimental necking detection of automotive sheet metals. In IOP Conference Series: Materials Science and Engineering (Vol. 1284, No. 1, p. 012020). IOP Publishing.
C5: Barlo, A., Sigvant, M., Kesti, V., Islam, M. S., Pham, Q. T., & Pilthammar, J. (2023, June). Determination of Edge Fracture Limit Strain for AHSS in the ISO-16630 Hole Expansion Test. In IOP Conference Series: Materials Science and Engineering (Vol. 1284, No. 1, p. 012027). IOP Publishing.
C6: Barlo, A., Sigvant, M., Islam, M. S., Pérez, L., Olofsson, E., Al-Fadhli, M., ... & Odenberger, E. L. (2023, June). Proposal of a New Tool for Pre-Straining Operations of Sheet Metals and an Initial Investigation of CR4 Mild Steel Formability. In IOP Conference Series: Materials Science and Engineering (Vol. 1284, No. 1, p. 012079). IOP Publishing.

J1: Pham, Q. T., Islam, M. S., Sigvant, M., Caro, L. P., Lee, M. G., & Kim, Y. S. (2023). Improvement of modified maximum force criterion for forming limit diagram prediction of sheet metal. International Journal of Solids and Structures, 273, 112264.
J2: Pham, Q. T., Islam, M. S., Barlo, A., Sigvant, M., Caro, L. P., & Trana, K. (2023). Modeling the strain localization of shell elements subjected to combined stretch–bend loads: Application on automotive sheet metal stamping simulations. Thin-walled structures, 188, 110804.
J3: Uncertainty quantification for conical hole expansion test of DP800 sheet metal (Submitted for Journal publication)
L1: Barlo, A. (2023). Failure Prediction of Complex Load Cases in Sheet Metal Forming: Emphasis on Non-Linear Strain Paths, Stretch-Bending and Edge Effects (Licenciate dissertation, Blekinge Tekniska Högskola).

T1: Eriksson, A. (2021). Non-Linear strain paths in Sheet Metal Forming.
T2: Aisvaran, C. (2021). Study of non-linear strain path in sheet metal forming.
T3: Olofsson, E., & Al-Fadhli, M. (2022). Pre-Straining Operation: Prediction of Strain Paths Within a Forming Limit Diagram.
T4: Bayat, H., & Abbasi, M. (2023). Investigation of the basic mechanics of edge cracking in sheet aluminum forming.
T5: Palan, A. (2023). Analysis and Anomaly Detection in Sheet Metal Forming.
T6: Abedisamarin, A., & Gholami, A. (2024). Effects of natural aging and low strain-rate on mechanical properties of aluminium alloy sheets used in automotive industry.

8. Conclusions and future research

Conclusions

Three main complex load cases initially selected for the failure prediction study are non-linear strain paths, combined bending and stretching, and edge cracks. The studies showed that all these cases significantly affect the formability in sheet metals hence failure. From the research carried out on non-linear strain paths, it can be concluded that this is the most frequently occurring complex load case and at the same time most challenging to model. Non-linear strain path effect on failure was evaluated in several sheet metals. With the aim to gain a strain path-independence of failure criteria, forming limit diagram for mild steel was transformed into different planes and validated against a critical automotive part. The non-proportional bi-linear FLC is a rich experimental database resulted from PREDICT. BTH, RISE and Volvo Cars will continue to build further knowledge of failure prediction due to NLSP.

An FE-modeling method was developed and validated on a dual-phase steel and an aluminum alloy showing that the forming limit is a function of the “stretch-bending ratio”.

Edge formability is also a vast topic and is affected by load cases. A selection was made and the most popular edge formability test i.e., Hole Expansion Test (HET) was studied experimentally and also simulated to check failure strain variation. In both cases, significant variation was found, and measures were taken to reduce them. Uncertainty quantification of HER in FE-models was studied and key factors were identified and implemented in the FE-model.

FE-simulation and measurement databased meta-model was developed using Artificial Neural Networks for quality assurance in the sheet metal forming process. The success of this study was encouraging to the industry partners and for some, one step forward to Industry 4.0.

In conclusion, PREDICT has increased accuracy in failure prediction by developing advanced formability evaluation methods, calibration techniques and effective FE-models for simulations.

Future work

The experimental results from bi-liner FLC required a considerable amount of work in PREDICT, however, some potential evaluation of adopting the tested result can be excellent future work. The test data can be used with GFLC[18] or machine learning to create models that can predict the formability of the tested sheet metals under arbitrary non-linear straining. These results can be used to calibrate very accurate yield and hardening models that can indicate forming limit in simulation directly as strain localization.

The stretch-bending approach can be integrated as a feature in AutoForm post processing. This can increase failure prediction and also allow to use larger element i.e., faster simulation of loading case where combined stretch-bending type loading is significant. The effect of spread in HER needs to be further investigated both experimentally and in stochastic simulations in 3D model where HET specimen center hole imperfections, pre-strains, etc. are more carefully measured and considered in modeling. AI-based process adjustment applications can be developed and associated with press lines to check the effectiveness of the developed meta-model in actual production.

Material testing 2.0 (MT2.0) can be further studied for simplifying yield criteria and FLC determination. Stochastic modeling of uncertainty quantification showed great possibility of doing non-deterministic FE-modeling of forming deformations in the future.

A Vinnova project application was submitted to FFI-circularity for the continuation of PREDICT and a separate European Union research project is applied where findings from PREDICT are planned to be used.

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[18] Volk, W., & Suh, J. (2013, December). Prediction of formability for non-linear deformation history using generalized forming limit concept (GFLC). In *AIP Conference Proceedings* (Vol. 1567, No. 1, pp. 556-561). American Institute of Physics.

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