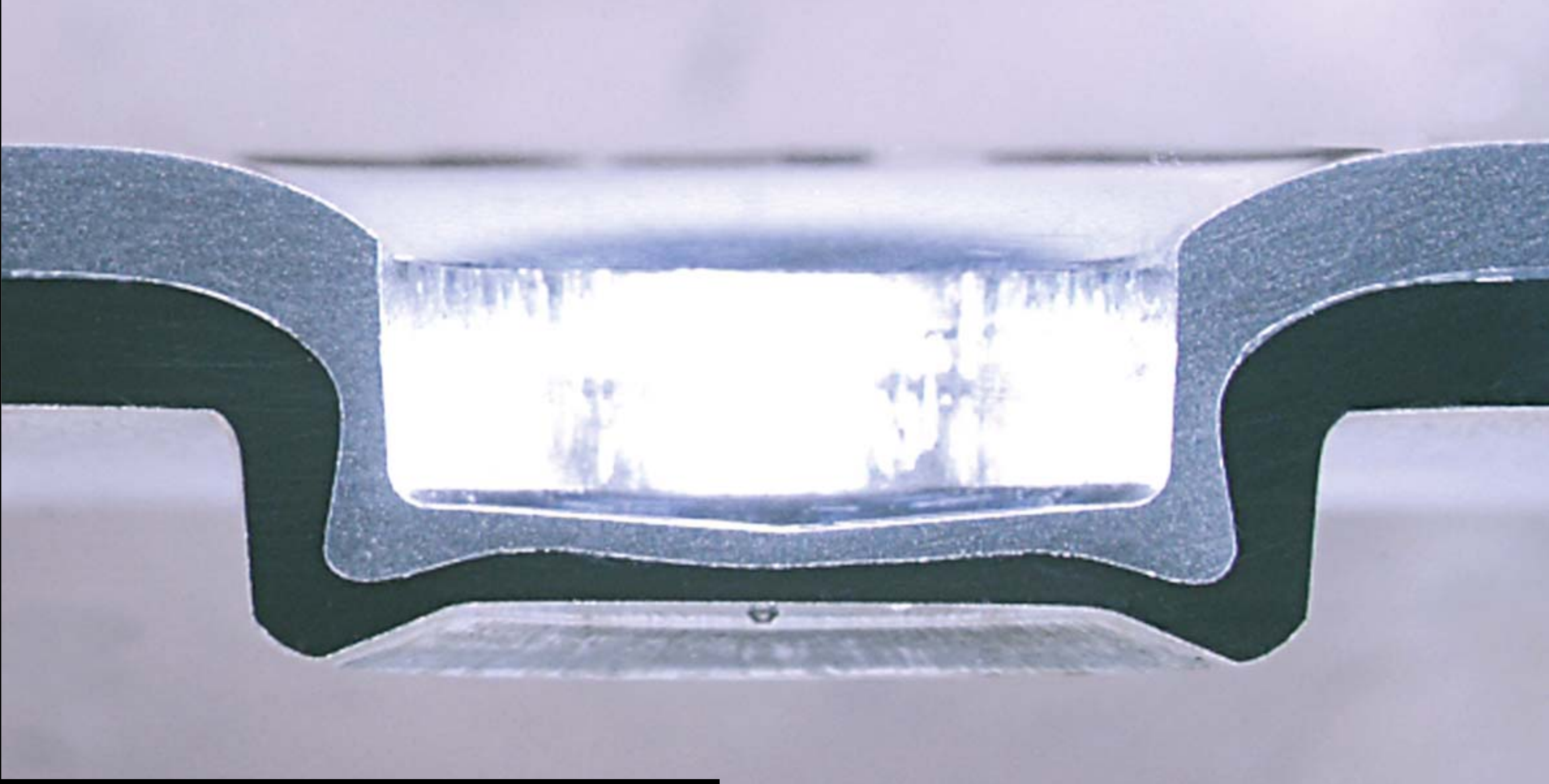


EVALUATION OF SCATTERING PARAMETERS IN MECHANICAL JOINING TECHNOLOGIES

A sensitivity analysis optimizes the design of forming dies by determining the most relevant joining parameters. Furthermore, methods to increase process robustness or monitoring in terms of quality assurance can be derived.

Introduction

Mechanical joining technologies are becoming increasingly important with the trend towards light and multi-material designs in the automotive industry. Providing robust connection techniques will be of particular importance. Thus, rejection rates are reduced and costs are cut in the parts production. This article discusses the example of clinching and its potentials and limits concerning FE-based sensitivity analysis and optimization for the joining by forming technology.

Mass manufacturing processes are subjected to parameter variations, which can cause fluctuations of characteristic result values. Also, in the mechanical joining technology, there are numerous tasks regarding sensitivity analysis, robustness evaluation or optimization. Especially in terms of efficiency and reducing costs, standardization of tool sets for various compounds are great issues. In Kuehne (2007), on the example of the Mercedes S-Class, the potential of such an analysis of different clinching tasks is shown. Such a complex and comprehensive analysis is very expensive, and so, the use of FEM in the process development and process evaluation is significantly increasing. Relating to Held (2009), the ever-growing use of simulation programs at all stages of component manufacturing is caused primarily by the automobile manufacturers to expand the understanding of the process continuously and to exploit cost saving potential.

A sensitivity analysis and robustness evaluation provide, at an early stage of development, the definition of appropriate measures to ensure the process and, thus, the product quality (Will 2005). Therefore, the numerical robustness is of special importance in order to improve properties and to reduce production costs in the virtual development process (Roos 2004). It is essential, particularly in terms of design and quality assurance of mechanical joining, to have proper knowledge of the amount and sensitivity of each influencing parameter variation and tolerance on the joining process. For assessment, sensitivity analysis and robustness evaluation are required. A successful application of a Finite-Element based approach for sensitivity analysis, coupled with an appropriate statistical design of experiments (DOE), have not yet been found in the mechanical joining technology.

Clinching is an important mechanical joining technique, which is standardized according to DIN 8593. Clinching is defined as a mechanical joining process producing a connection between two or more sheets exclusively by a local forming operation. The joining process is divided into three sub-processes (see figure 1). After positioning the sheets in step A, the punch pushes the joining area off the sheet plane. While punching, the sheet material is now pressed down to the die bottom (B). A further punch stroke increases the radial flow of the material between punch and die filling the die shape and realizing the interlock of the sheets (C).

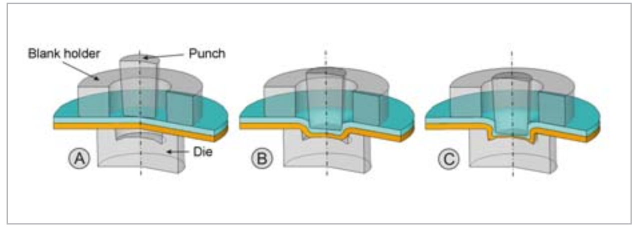


Fig. 1: clinching of round points with rigid dies

To evaluate the affecting parameters, defined result variables are required. For clinching, these are mainly the neck thickness tn and the interlock f (see figure 2) as far as the evaluation of the load capacity of compounds is concerned. The thickness of the bottom tb is seen as a constant parameter in a normal forming process, which is set in advance in the sampling process and can be non-destructively tested using a thickness gauge (Steinhauer 2007).

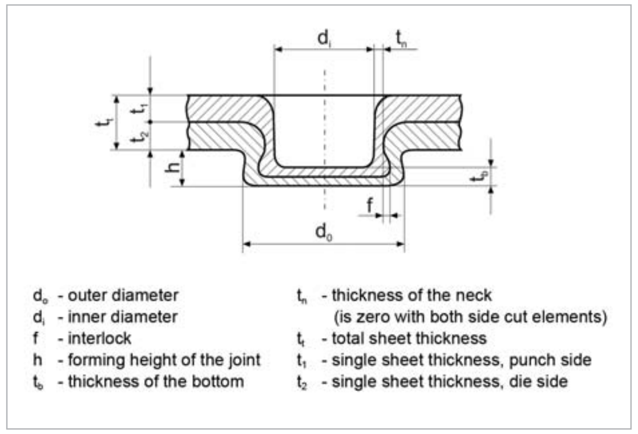


Fig. 2: Relevant geometrical parameter of a clinching joint related to DVS (2009)

The numerical description of clinching is subject of numerous studies and FEM-based projects. In Dietrich (2006), Paula (2007), Lee (2010), Mucha (2011) and other sources, suitable tool geometries to improve the forming of the joint and the joint strength under pull-out tension were numerically, but iteratively identified. Initial findings about the FEM-based optimization of clinching processes based on the Taguchi method and the Response Surface Method were obtained in Oudjene (2008) and Oudjene (2009). However, numerical sensitivity analysis and robustness evaluation with more than two parameters based on statistical design of experiments have not been conducted yet.

In principle, the statistical-numerical analysis of clinching has to be divided into two categories. A key aspect is the provision of appropriate tool and process parameters (design parameters) for an optimal joining. For this purpose, the first type deals with the identification of relevant parameters using sensitivity analysis and a required subsequent process of optimization. The second type of analysis is concerned with the identification and evaluation of process robustness, i.e. result value variations caused by process uncertainties (e.g. friction, material strength variations). Both types of analysis will be considered in the following.

Setup of a stochastic analysis of clinching

For the numerical description of the clinching process, the FEM-software Deform is used, which was developed specifically for solid forming processes. Important for the calculation of forming processes, such as clinching, is the possibility of a re-meshing option. Thus, areas of strong deformation and the resulting geometry variations or distortions can be re-meshed and the new node and element data can be transferred from the previous to the new mesh.

Assuming ideal rotationally symmetrical dies and neglecting any material anisotropy, the problem can be described 2D rotationally symmetrical. The interaction between Deform and optiSLang is assured via appropriate input and output files. Additionally, a script is required, which identifies the result variables of neck thickness and interlock on the basis of geometric features and transfers them to the output file. In advance, the FEM model has to be parameterized.

Subject of the analysis is the material combination EN AW-6016 with a thickness combination of 1.5mm in 1.0mm. Figure 3 shows the Finite-Element Model in the initial state and the comparison of cross section of simulation and experiment. An important basis for the numerical calculation of the forming process is the material flow curve, which indicates the flow stress concerning the state of forming. The friction values are based on experience being currently iteratively adjusted for the correlation of joint forming and load in experiment and simulation. This provides a perspective option to optimize friction values with the objective of creating the best possible correlation in the experimental verification of the simulation.

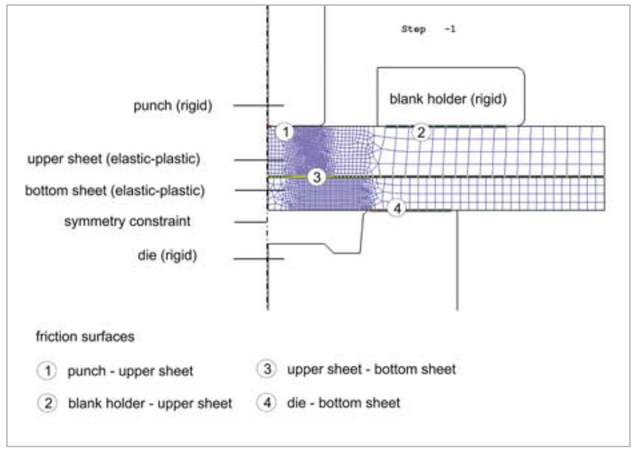


Fig. 3a: FEM-model

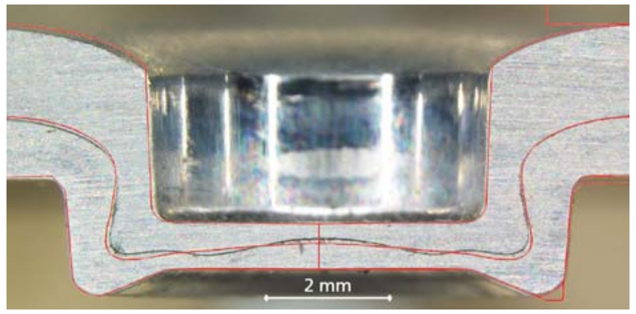


Fig. 3b: Comparison of cross sections experiment and simulation (FEM-result: red line)

Sensitivity analysis according to design parameters

Design parameters and result values

The design of the clinching joint essentially depends on the geometric shape of the tools, punch and die. Another influencing variable is the blank holder fixing the sheet before clinching and stripping it after the forming process. Due to known proper blank holder adjustments and because of the proven small impact of the blank holder shape and load in a technologically meaningful variation, the parameters of this device are not considered in the analysis. The following listed parameters and their variation limits are subjects of the analysis:

	Parameter	Minimum	Maximum
Die	die depth	1.0	1.8
	groove depth	0.3	0.8
	AD	4.0	6.0
	RD	6.0	7.5
	α	0.0	10.0
	chamfer	0.1	0.5
	RR	0.0	0.5
Punch	punch diameter	4.5	6.5
	pin radius	0.1	0.4
	A1	0.0	5.0
	A2	0.0	6.0

Fig. 4a: variation limits

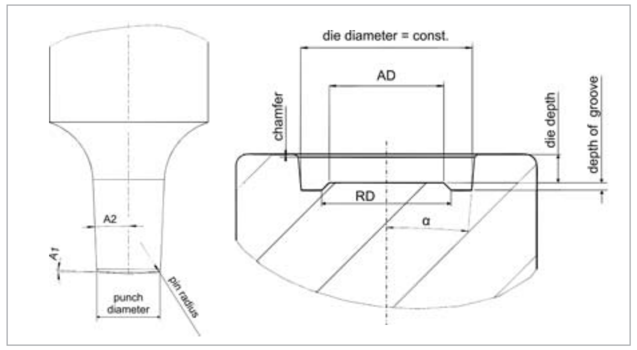


Fig. 4b: Design parameters

The relevant result values for joint strength, neck thickness and interlock have already been explained in the introduction. With regard to the dimensions of the required drive and C-frame, the joining force is another important parameter. For assessing the forming and possible damage of the sheet material due to strong deformation, both the joining force and the damage values at critical clinching points can be identified. However, the investigations are focused on the geometric parameters and the joining force.

Assessment of sensitivity analysis

For the generation of parameter sets to be calculated, the Latin Hypercube Sampling is used. This allows meaningful result assessment already with a set of 100 samples and sufficiently high values of CoP (Coefficient of Prognosis). Here, the CoP was 94% being the indicative value for the forecast quality of the analysis and with the best related meta-model concerning the neck thickness. With 64% of influencing relevance, the die depth is the most important parameter. The variation of the punch diameter affects 19% of the neck thickness variations. For these two most important parameters, the automatic regression analysis identified a functionally polynomial-based correlation between the parameter values and the outcome variable (see Figure 5, top right). However, the 2D plot of the die depth vs. neck thickness shows that the relationship can be described as nearly linear. Here, the neck thickness decreases significantly with increasing die depth.

A similar clear correlation of a parameter can be seen evaluating the interlock (see Figure 6). Here, the punch diameter is the parameter with the greatest influence. Die depth, alpha and pin-radius, each with about 10% relevance, form the second row of influential parameters. Similar to the evaluation of the neck thickness, a nearly linear correlation between the most important parameters and the objective values can be determined also for the interlock. Here, the critical point regarding the proper size of the interlock is having a low punch diameter and little die depth.

The joining force is the third analyzed influencing parameter. With 71% relevance, it is almost exclusively dependent on the size of the punch diameter. As expected, the joining force increases with rising punch diameter.

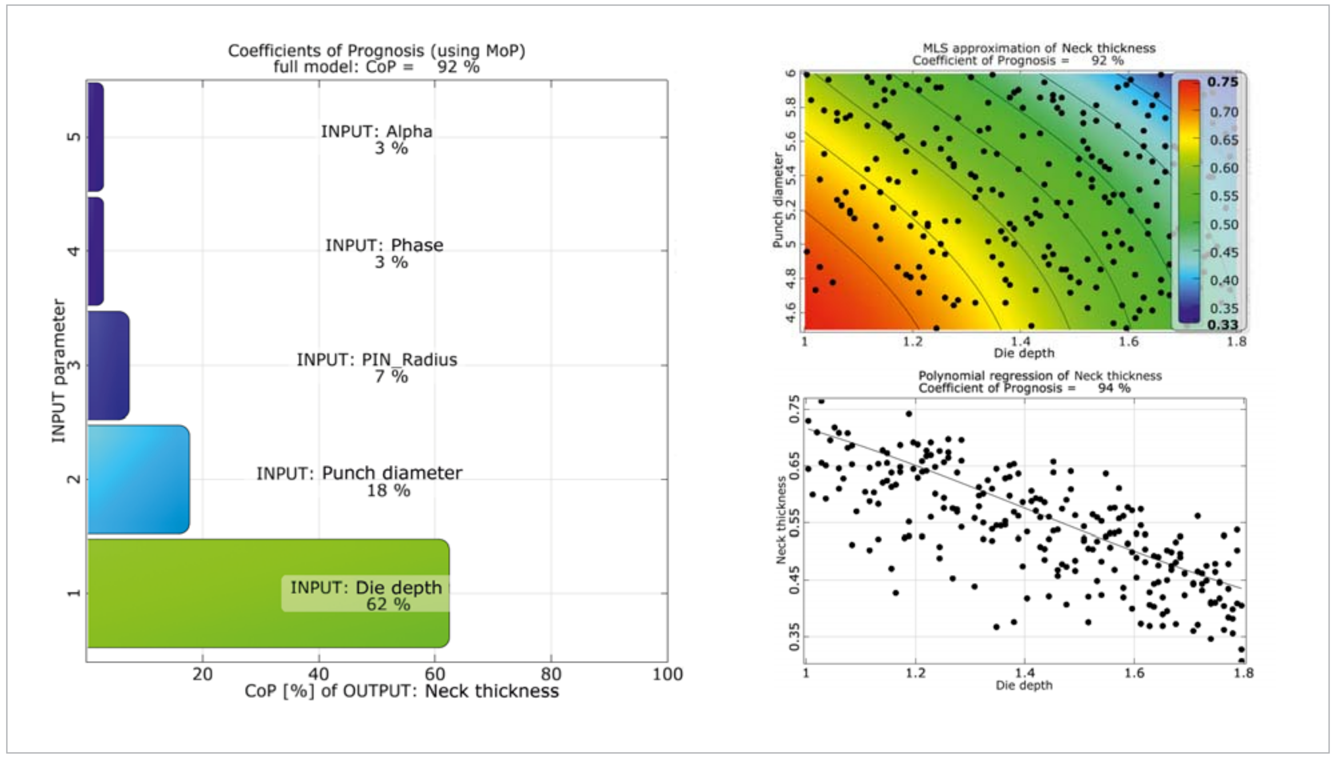


Fig. 5: Relevant influencing variables concerning the neck thickness

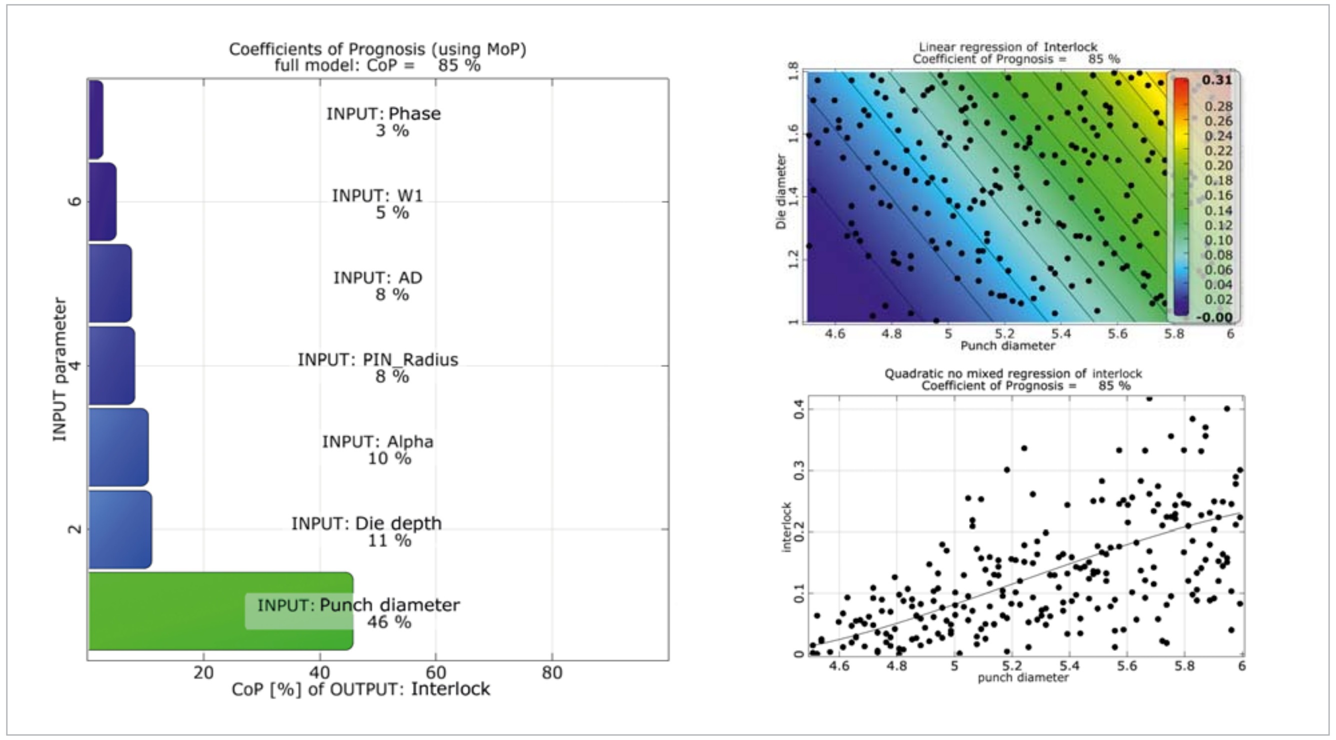


Fig. 6: Relevant influencing variables concerning the interlock

Optimization of the clinching process

Parameter and objective values

Concerning clinching, the objective value to be optimized is the joint strength, which, however, cannot be derived just from the cross section of the calculated joining. Neck thickness and interlock affect the load capacity of the clinching joint. Both values should be high with respect to increased joint strength. However, no clear assessment can be made when a clinching point reaches its maximum load capacity. This is strongly dependent on the load direction as well as on the sheet materials and thicknesses.

Figure 7 shows the possible failure modes after point loading: neck fracture (top), pull-out failure (bottom) and multiple failure (center). To avoid neck fracture, the neck thickness should be maximized. Accordingly, pull-out failure can be avoided in providing the largest possible interlock. In the sensitivity analysis, punch diameter and die depth were determined as major influencing parameters concerning neck thickness and interlock. As shown in figure 5 and 6, the value tendencies as a function of these two influencing design parameters are exactly opposite. For optimizing, the parameter AD, i.e. the die bottom diameter, is also considered. The optimization is conducted by using the Adaptive Response Surface Method (ARSM) with maximizing the neck thickness as the objective function. As constraints, a minimum interlock of 0.5 x neck thickness and a maximum joining force of 30kN were defined.

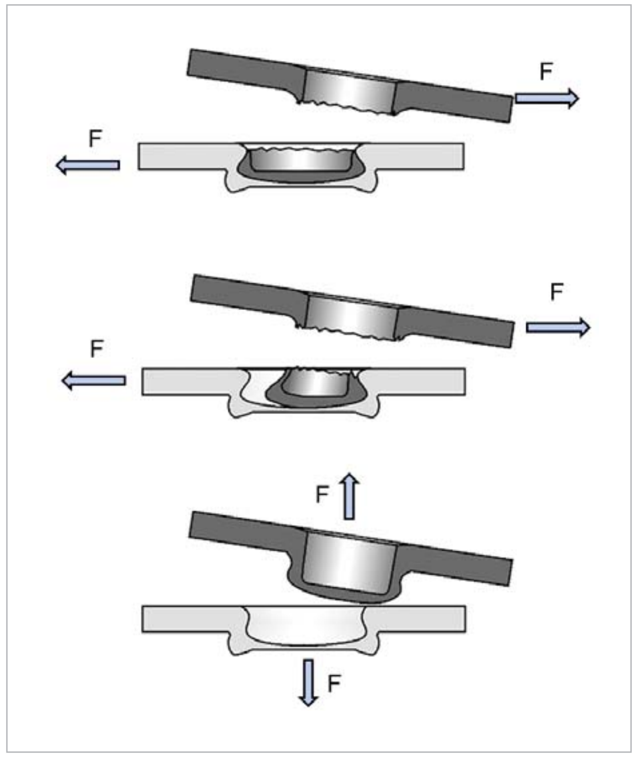


Fig. 7: Failure types after loading the clinching point load according to DVS (2009) neck fracture (top), pull-out failure (bottom) and multiple failure (center)

Results of parameter optimization

Already after 9 iterations, the best design is determined and the varied parameters converge (Figure 8). Especially for the die depth an optimum (1.6mm) was found quickly.

As already mentioned, a definition of an optimal correlation between neck thickness and interlock is not possible without further analysis. Therefore, in the following optimization, the constraints defining the relation between the interlock and the neck thickness will be adjusted. Figure 9 (right) shows the differences in the cross sections for a quotient of neck thickness/interlock of 0.25 and 0.5. Based on these individual optima, a Pareto optimization can be conducted and, as a result, a range of optimal joining for any neck thickness and interlock is generated.

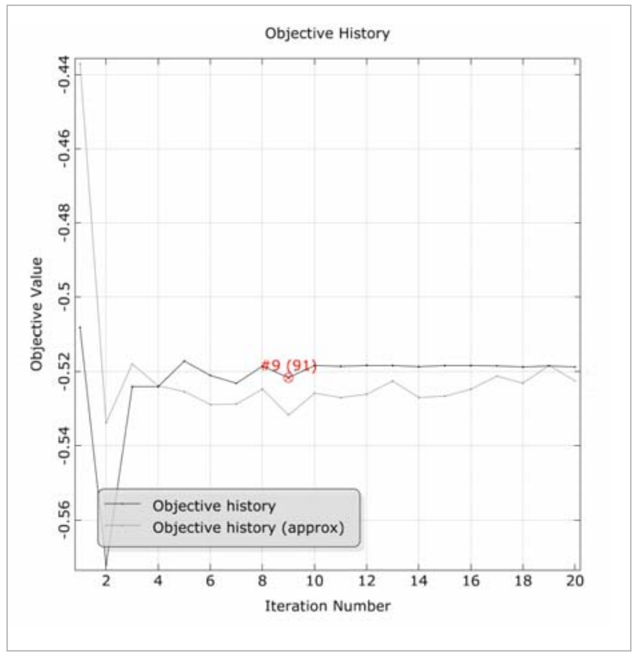


Fig. 8a: convergence of objective value (neck thickness)

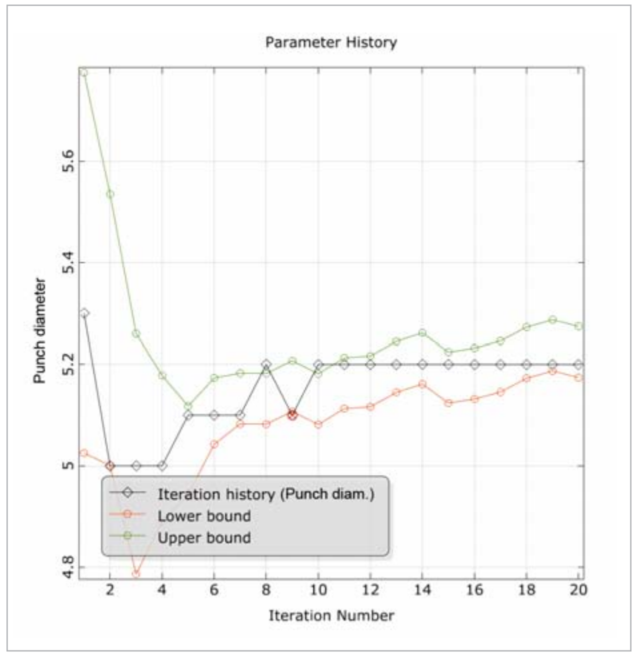


Fig. 8b: parameter punch diameter

In addition to the die optimization for individual joints, in practice, alternative joining solutions are increasingly sought for different sheet materials and thicknesses. The aim is to provide a punch and die set for proper clinching of three or more different material combinations and/or thickness combinations. This problem can be also solved by using ARSM. Here, the maximum of all single-neck thicknesses is defined as the objective function (to be maximized). As constraints,

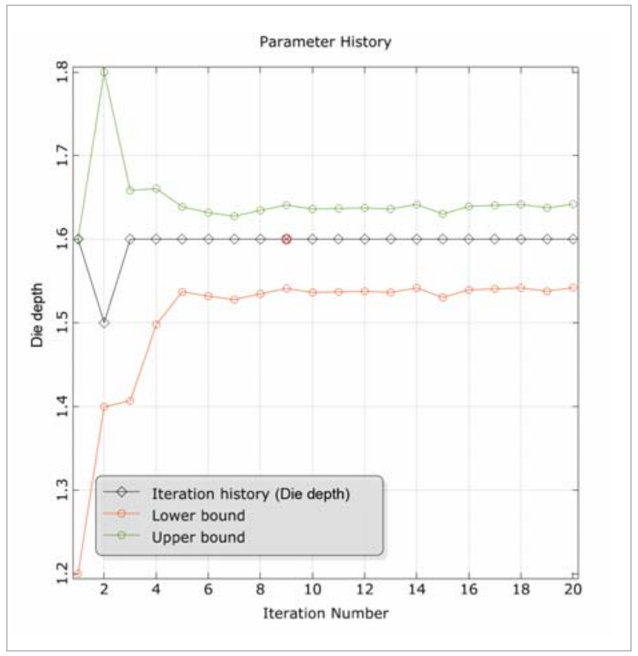
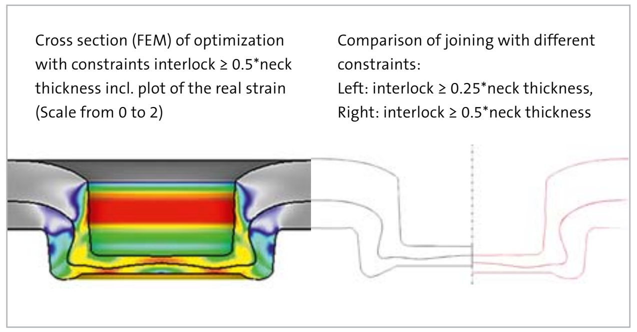


Fig. 8c: parameter die depth


Cross section (FEM) of optimization with constraints interlock ≥ 0.5*neck thickness incl. plot of the real strain (Scale from 0 to 2)

Comparison of joining with different constraints:
Left: interlock ≥ 0.25*neck thickness,
Right: interlock ≥ 0.5*neck thickness

Fig. 9: cross sections of optimal joints with different constraints

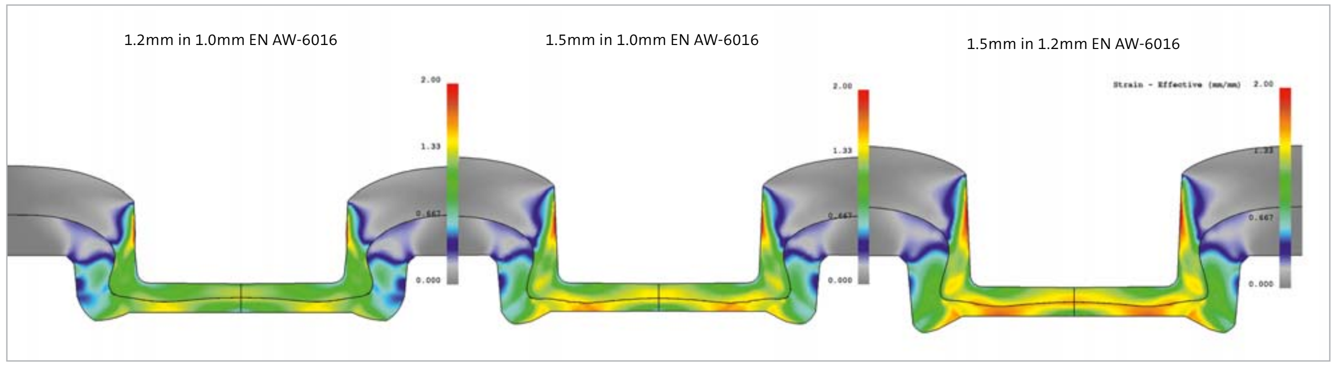


Fig. 10: cross sections of optimized joints; different combinations of sheet thicknesses, constant material and dies

the compliance of an interlock minimum of 0.15mm and a maximum counter-piping of the blanks from the die of 0.2mm were chosen. The cross sections of the FEM at the three sheet thickness combinations in Figure 10 show, impressively, the potential of this approach for tool optimization.

An issue can be seen, however, in the fact that for optimization a precise match of experiment and simulation is necessary. Therefore, a careful determination of parameters (flow curves) is essential. Additionally, realistic coefficients of friction for the four friction pairs have to be determined. In contrast to the sensitivity analysis, a deviation of the prediction accuracy of the FEM always leads to inaccuracies of the optimization results. Furthermore, the implementation of the material damage as a limit or objective function has not yet been possible. For this purpose, adequate damage criteria for clinching and corresponding limits for the sheet materials still have to be investigated.

Sensitivity toward process uncertainties

Parameter and result responses

The clinching process is affected by a variety of process uncertainties. Material properties such as yield strength, tensile strength, braking elongation or the sheet thickness of semi-finished products are typical to be subject of tolerances (Will 2006). Due to changes in the state of lubrication and surface shapes, during the process of clinching, the friction values also vary over a lifetime period of a die set (about 200,000 to 400,000 points). Furthermore, effects of abrasion or adhesion may occur. Here, an assessment of quantity regarding realistic limits and distribution functions is, however, very difficult to determine. A locally varying intensity of deformation or associated pre-hardening of the sheets by previous forming processes (e.g. bending or deep drawing) is also possible.

Figure 11 shows the parameters for clinching disregarding the tool and machine stiffness in the present considerations. Looking closely at these parameter blocks, it appears they are resulting in a large number of individual values. For example, there are four frictional combinations: blank holder/sheet, punch/sheet, sheet/sheet and die/sheet. The used parameters and their related scatter ranges evaluated from the analysis are shown in figure 12. As result values, neck thickness, interlock and the joining force are evaluated compared to the design parameters in the same way as in the foregone sensitivity analysis.

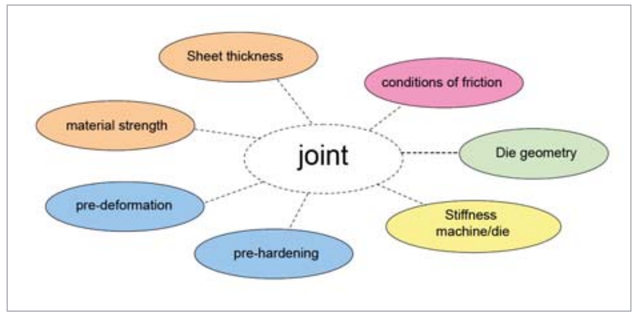


Fig. 11: Selection of relevant process parameters of mechanical joining subjected to tolerances

		Uncertainty	Min	Max
sheet material	upper	thickness in mm	1.36	1.64
		tensile strength in N/mm^2	170	240
	bottom	thickness in mm^2	0.9	1.10
		tensile strength in N/mm^2	170	260
friction factors		punch - upper sheet	0.15	0.45
		blank holder - upper sheet	0.15	0.45
		upper sheet - bottom sheet	0.15	0.45
		die - bottom sheet	0.15	0.45

Fig. 12a: Uncertainties and their variation: limits

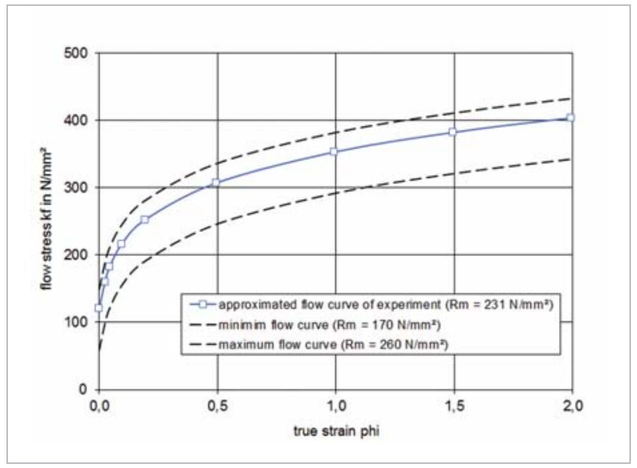


Fig. 12b: Uncertainties and their variation limits: scheme of the flow curve shift

Results of the robustness evaluation

The influence of the neck thickness by parameter variations can be considered as moderate. Values in the range from 0.47 mm to 0.63 mm are expectable.(see Figure 13, right). With a CoP of 97%, the predictive capability of the meta model is adequate. The greatest influence on the objective is affected by the variation of the sheet thicknesses, wherein the variation of the bottom thickness within the accepted scatter range causes more effects on the neck thickness than the variation of the upper thickness. The friction between the two sheets causes a rather small effect. However, a variation of the material strength has virtually no significant effect on the specification of this geometric size.

The critical point in terms of a very small neck thickness (and the associated low joint resistance or an increased risk of cracking during forming) consists in the use of minus-tolerated sheets on the punch-side and plus-tolerated sheets on the die-side. Appropriate strategies to avoid reaching this extreme range may be a limited tolerance width of the sheets or, at least, a check of the sheet thickness.
Even a CoP-value of 89% allows a sufficient prognosis for the evaluation of parameters influences on the interlock. It is also mostly affected by the thickness of the bottom sheet. In contrast, the sheet thickness variation of the upper sheet is of negligible relevance. On the other hand, the formation of the interlock is strongly affected by two friction pairings: the

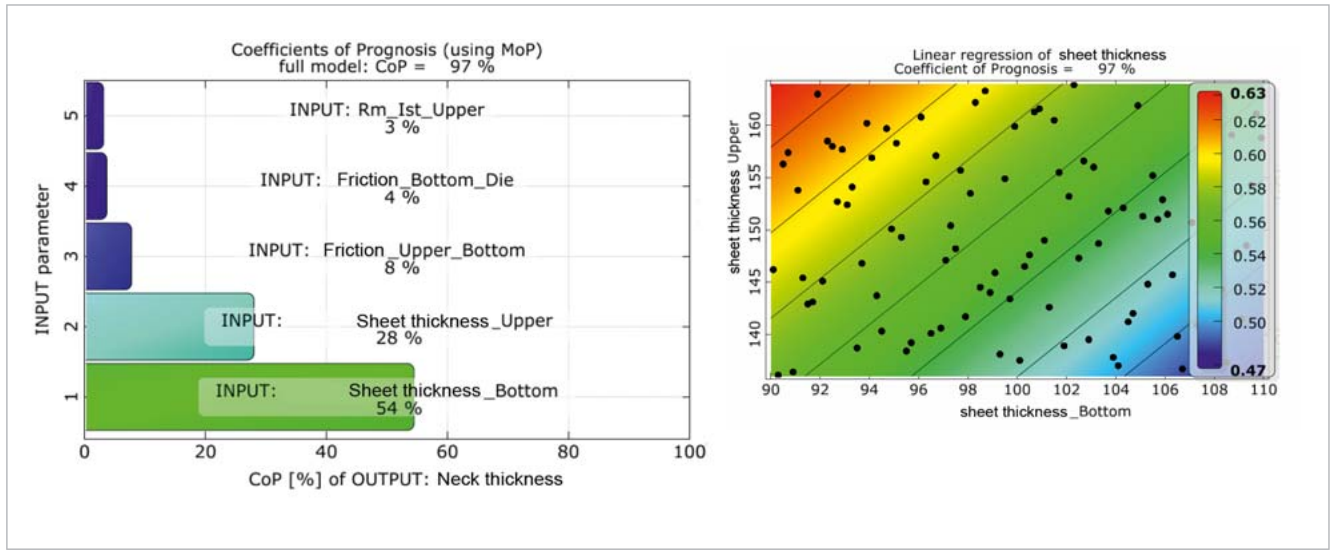


Fig. 13: Relevant influencing variables on the neck thickness

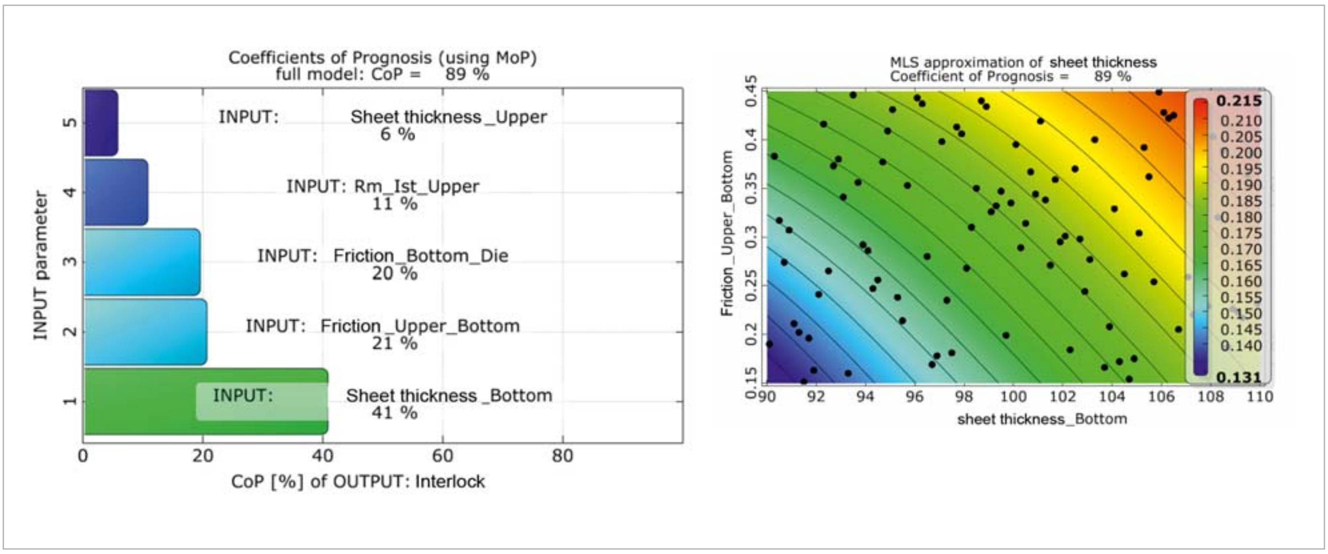


Fig. 14: Relevant influencing variables on the interlock

friction between the sheets and the friction between bottom sheet and die. The tendency of a rising interlock is associated with increasing sheet thickness (bottom) and higher friction between the sheets as well as between sheet and die.

In comparison to the neck thickness, the percentage changes of the interlock due to parameter variations are higher: values of 0.131mm to 0.215mm are to be expected (see Figure 13, right). Here, avoiding a negative tolerance of the bottom sheet, lubrication or lubricant residues on the friction pairings sheet/sheet and die/sheet will lead to less scatter of the interlock. Thus, a robust process can be ensured.

As the sensitivity analysis already indicates, both objectives are affected contrarily by the relevant parameters. Thus, for example, an avoidance of critical values concerning the interlock by ordering exclusively plus-tolerated die-side sheets increases compounds with a low neck thickness. Such changes in the production process are very costly and should be evaluated critically. The analysis of the process robustness allows, however, to gain knowledge about critical parameters and parameter combinations that can be utilized as a basis, for example, to implement a selective control of the relevant parameters as a quality assessment in the development process.

Summary and Outlook

A process chain, being increasingly numerical, especially in the automotive production, requires a profound understanding of the joining processes to improve quality standards and to explore cost saving potential. So far, the various capabilities and applications of FE simulation for sensitivity analysis, robustness evaluation and optimization have not been considered much in the mechanical joining technique. The performed sensitivity and robustness analysis for clinching indicates the potential of the numerically based analysis of clinching processes. From a variety of parameters that affect the joining process, in such studies, the relevant impact parameters are filtered and being provided either for process optimization or an evaluation of the process robustness. The so obtained process knowledge exceeds the previously, often experimentally-generated, understanding and correlation studies. The possibility to assess parameters to such a complex extent and number, never been reached in experiments before, allows to obtain new insights and to find global and general correlations.

Based on these initial studies for clinching, further analysis will be conducted on other frequently used mechanical joining methods. The main focus of further research in the automotive industry is on the increasingly used self-pierce riveting technique. The challenges will be the numerical description of the material separation, the expansion of computing stability and accuracy. As demonstrated in the sensitivity analysis for clinching, mechanical and technological characteristics of the materials, as well as the frictional conditions, are the basic data of the simulation representing the fundamental basis for a realistic numerical analysis. When this data is available, the CAE-based sensitivity analysis and robustness evaluation of joining processes will be a key source of information for method comparison and selection of appropriate joining technologies.

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