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Analysis of Machine-Sided Influences during Clinching

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Abstract. Mechanical joining techniques like clinching are standard joining techniques for processing aluminum and steel alloys in the automotive car body manufacturing. When using conventional methods, joints will have a high quality after a final tool check on a specific joining press system. However, if the press system during manufacturing will changed, it can occur that joints get other quality values e.g. smaller interlock. The reason for that has multiple influences, this paper considers especially the press-sided ones. With optical measurements of press deformation and punch speed during real joining processes, new 3D-halfsymmetric simulation models were built up, which consider of press-side behavior such as joining velocity and angular as well as lateral misalignment of the joining tools during clinching process. Sensitivity analyses identifies significant influencing variables. On the base of this, equations of quality changes can be determined. Finally, this allows better prediction of the modification about joint quality after a press change from system A to B or C during manufacturing.

Introduction

Complex and high innovative car body structures exist actually of a lot of different materials e.g. ultra-high, high and mid strengths steel and aluminum alloys partly in one vehicle. Mechanical joining techniques such as clinching and self-pierce riveting with semi-tubular rivet (SPR-ST) are standard joining techniques for realize this modern multi-material design car body structures. For all mechanical joining technologies, there are different machine designs, drive and control types as well as other system-specific properties depending on the application or joining system [1].

The tool kinematics, moving weights and system stiffnesses resulting from the system properties can influence the joining result under constant boundary conditions, which means that the transferability of process parameters from one system to another is only possible to a limited extent. Preliminary investigations have shown that despite comparable process parameters, the average interlocks, for example, which are highly relevant for strength, deviate by about 30 percent. These differences are relevant, for example, when transferring sampling results created in the laboratory to production and can lead to additional expenses during the start of series production. Furthermore, the transferability of joining process parameters is only possible to a limited extent without knowledge of press influences. Against the background of the digitalization of production (Industry 4.0), in which the importance of modeling the equipment and processes used in production is constantly increasing, knowledge and description of the equipment-related influences in mechanical joining is also an essential component.

The aim of the paper is to analyze the influences (tool kinematics, machine stiffness) of conventional joining systems on joint formation and load-bearing capacity in Clinching. The influences of the press systems are to be determined on the one hand by means of experimental process and measurement analyses and on the other hand by means of numerical process simulations. The numerical representation of system influences (e.g. speed profile, angular and lateral misalignment of the joining tools) enables sensitivity analyses in which the determining influences can be investigated and identified systematically. In addition, substitute models are to be derived and validated in the numerical investigations, which represent the system influence on the joining result with less computational effort. The results allow an improved understanding of the clinching process, can be the initial point for future press developments and can also be used for digital production planning tools.

1. Clinching and manufacturing influences

Clinching allows joining sheet metal parts by relying on local plastic deformation of the base material, without additional consumables such as rivets. The basic principle of clinching processes is to create an interlock between the combining thin metal parts with the tools punch, blank holder and die (**Fig. 1**).

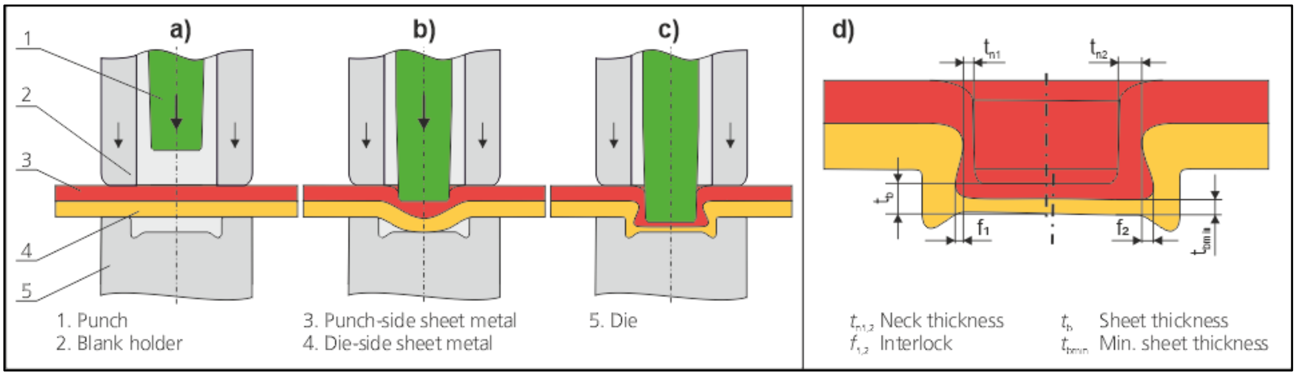

Fig. 1: Clinching: a) – c) Process steps, d) Characteristic [2]

The punch locally pushes metal into the die. The resulting metal flow targets the creation of a mechanical interlock. Depending on the shape of these clinching tools, various geometry quality parameters for interlock f, neck thickness t_n and min. bottom thickness $t_{b.min}$ are reached. Clinching joints evaluates by these certain characteristic values, which directly correlate with the strength of the joints. [2]

Relevant manufacturing influences on the clinching process can be divided according to their location into machine-side, workpiece-side and tool-side manufacturing influences (**Table 1**).

Table 1: Range of different manufacturing influence during clinching

Range of different manufacturing influences during clinching		
Machine-side	**Tool-side**	**Workpiece-side**
• Frame stiffness	• Die geometry and design	• Strength and strength tolerances
• Concentricity of the tool holders	• Coating	• Material thickness and thickness tolerance
• Punch force	• Surface condition	• Surface condition
• Blankholder force	• Alignment and centering	• Forming capacity
• Force/stroke control		• Pre-hardening
• Setting speed		• Lubrication and oiling
		• Additional punching and forming oils

The focus here is on the machine-side influencing variables (green area). These include system stiffness, alignment of the tool holders, punch and blank holder force, positioning accuracy and force/stroke control. [3]

1.1. Influence of component properties, joining tools and elements during clinching

In [4], the coupling of a larger number of FEM simulations with statistical design of experiments and evaluation of results by regression methods in mechanical joining technology was realized for the first time. The investigations were concerned with sensitivity and robustness analyses for the clinching joining process with the objectives of determining relevant process parameters for tool design and evaluating the robustness of the joining process with respect to component variations. In [5], a mechanical clinching process with additional counter pressure by using a rubber ring was developed to join ultra-high strength steel sheets with low ductility. The influence of tool design during clinching with extensible dies on interlock, joint profil and forming force is investigated in [6]. In [7], a parametric study of die geometrie parameter by clinching of aluminum and high strength steel sheets was carried out and mainly effects of joinability are identified. The investigation of [8] present a new method for clinching of high strength steel alloy by using preforming the lower sheet.

In [9] and [10], this method was applied and it was demonstrated that a larger scope of FEM simulations for metamodeling can also be realized and that process-relevant influencing variables can be identified. In all these research projects, the geometry of the joining tools or variations in the joining part properties were primarily considered. In [11], a clinching process was investigated on the basis of parametrical numerical study of tool geometric variation. In [12], a two-stage clinching process was investigated in which a conventional clinch joint is produced in the first process step. In the second process step, the clinched joint is pressed together into a thinner shape using additional tools. In [13], a comprehensively overview about the recent advances in the application of finite element methods on clinching process was carried out. That includes influencing factors and parameters like tool geometries and processing parameters.

1.2. Process monitoring and equipment influence in clinching

In [14], experimental investigations on product quality during clinching deal in detail with the influence of deviations from the optimum spatial arrangement of tools and joining parts. The orientation of the tools and parts was varied in a corresponding joining machine and the influence on the joint strengths was analyzed. The machine stiffness or kinematics of the joining tools remained constant. The investigations in [15] concentrate on process monitoring of the clinching process. Among other things, monitoring tests were carried out on different machines. It was found out that different process curves and variations occur during clinching with the two machines investigated, from which it was concluded that the envelope curves must be adapted to the respective joining machine. In the investigations of [16], among other things, the numerical simulation of the clinching process in order to simulate potential faults (e.g. damaged joining tools) in the simulation were used and identified in the force-displacement curve. By means of the applied method, different user or production defects could be detected with relatively high certainty in the load-stroke curve. In [17], a very similar way describes potential sources of error in production as well as process monitoring for the clinching process. In [18], the effect of tool eccentricity on the joint strength in clinching process was experimental investigated by offsetting the center line between die and punch .

1.3. Influence of joining tool kinematics during clinching

The experimental investigations on clinching by [19] shows that even a variation of the punch speed in the range from 3 to 100 mm/s can lead to different joining forces and joint strengths. Unfortunately, the analysis does not address the influence on the geometric joining point formation. By superimposing impact pulses on the clinching process, also known as hit-clinching [20], the joining force can be significantly reduced compared with the conventional process variant, which means that particularly large unloading of the joining system can be realized. The same objective is pursued by the system known as "Dyna-Connect", which also uses oscillating pulsed joining forces and has an additional mass-spring unit. However, joining larger modules results in an increased noise load [21]. Another approach to reduce the necessary joining forces is radial punch clinching. Here, the translational movement of the joining punch is superimposed by a radial movement. The research projects carried out [22] show a joining force reduction up to 55 percent compared to conventional processes with equivalent joining point formation. In [23], a multiobjective takes clinching process parameters such as punch speed, bottom thickness, and blank holder force into consideration besides geometry parameters. The forming speed varies in a low range between 2 mm/s and 8 mm/s and the influence of the joining speed on interlock, neck thickness and tensile force was low. In [24], a new clinching process is develop, where electrical energy stored in a pulse generator is suddenly discharged and initiates a shock wave in a fluid. This shockwave moves through the fluid and forms the sheet into a clinching die.

2. Experimental Process Analysis

2.1. Material combination

For the experimental process analysis, following material combinations are investigated (Table 2).

Table 2: Material combination

No.	Punch-sided material	Thickness [mm]	Die-sided material	Thickness [mm]
V1	EN AW-5182	1.25	EN AW-5182	1.25
V2	HC260LAD	2.00	HC260LAD	2.00
V3	HC420LA	1.25	EN AW-5182	1.25

The selection of the material combinations should take into account different aspects, such as the required joining energy/force being as different as possible (spectrum from thin and middle strengths to thick and hard), steel-steel/aluminum-aluminum/mixed joints.

2.2. Press systems

The press system for conventional clinching process, we used for the investigation, varied about press shape, type of drive unit, type of drive unit control and blank holder system, listed in **Table 3** and shows Fig. **2**.

Table 3: Clinching machines

Press form	Type of drive unit control	Type of drive unit	Blankholder system	Joining press manufacturer and system name
C-shaped press	Stroke	Electro-mechanical	Pneumatic	ECKOLD MFG-005 (1)
	Stroke	Electro-mechanical	Spring	TUCKER ERT80 (4)
C-shaped stationary press	Load	Hydraulic	Spring	ECKOLD DFG 500/150 (2)
Die-Set in a conventional symmetrical press	Stroke	Electro-mechanical	Spring	PROMESS 70 (3a)
	Load	Electro-mechanical	Spring	PROMESS 70 (3b)

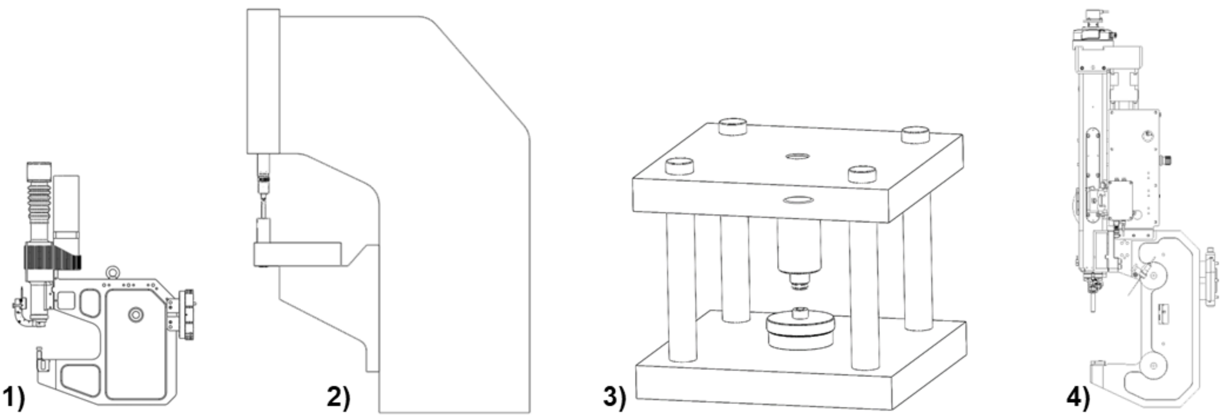

Fig. 2: Conventional clinching machine systems (1,2,4) and reference system 3

When joining the parts on the different machines, comparable process parameters are set, and the same joining tool geometries are used to identify only the system-side influences on the joints. The system manufacturer ECKOLD GmbH & Co. KG carries out the determination of suitable joining tools. In the experimental investigations, the following system parameters or boundary conditions are varied for each material combination:

- Joining system (Table 2) machine stiffness
- Blank holder force-displacement profile
- Control mode
- Joining speed (up to approx. 50 mm/s)

The characteristic values of the joining result are measured based on the micrographs and the joining load-stroke profile is recorded accordingly. That includes five cross sections per parameter set and separation direction 0°/90° (**Fig. 3**) with relation to the C-shaped frame.

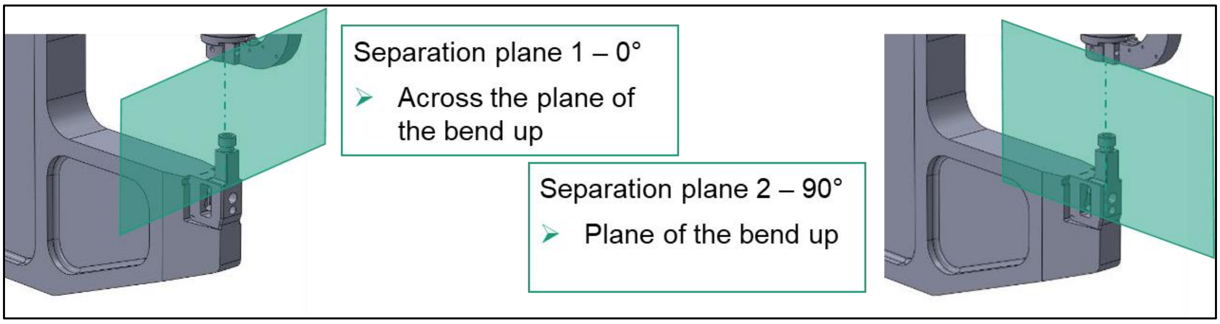

Fig. 3: Separation plane orientation into account to joining frame position

When evaluating the separation plane 2, i.e. in the bend-up plane, the values interlock f_1 and neck thickness t_{n1} on the left side of the cross section are oriented towards the frame, and the values interlock f_2 and neck thickness t_{n2} are oriented away from the frame.

2.3. Results

The results of experimental process analyses for the first combination EN AW-5182 t = 1.25 mm into EN AW-5182 t = 1.25 mm shows **Fig. 4**.

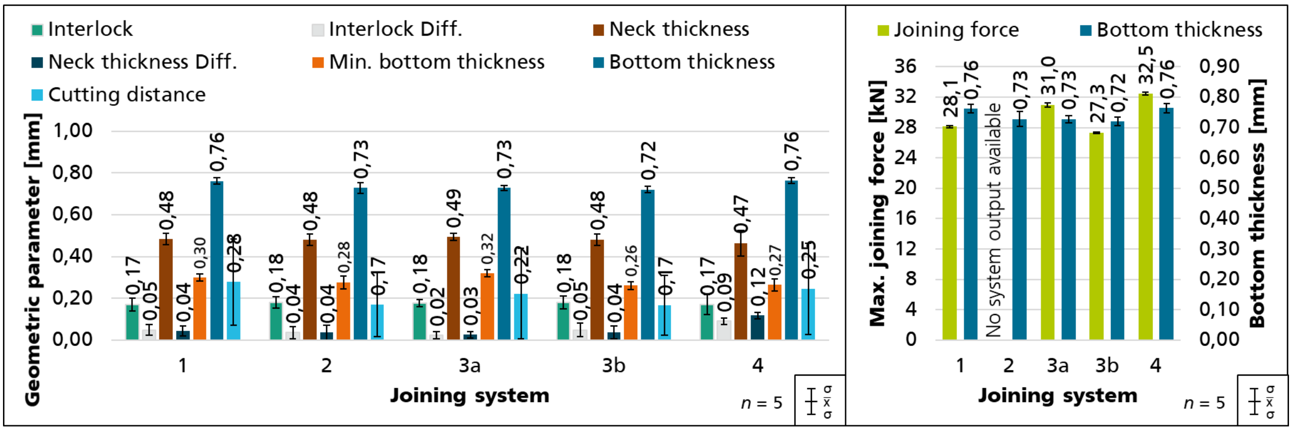

Fig. 4: Experimental results of EN AW-5182 t = 1.25 mm into EN AW-5182 t = 1.25 mm

In the left bar chart of **Fig. 4** quality parameters interlock f, interlock difference f_{diff} between f_1 and f_2 into same cross section picture, neck thickness t_n, neck thickness difference $t_{n.diff}$ between t_{n1} and t_{n2} into same cross section picture, minimum bottom thickness $t_{b.min}$, bottom thickness t_b and the cutting distance t_c are presented for four joining systems. The cutting distance t_c means the distance between cutting plane of cross section and perfect middle cross section cutting plane. A higher cutting distance leads to smaller values. Joining system 3, the reference system D of **Fig. 2**, separates in version "a" and "b". Version "a" includes a stroke control unit for end position of the punch and version "b" a load control unit for the same end position. Additional connection of the press systems to the results is not made due to the independence of the research results.

In the right bar chart of **Fig. 4** the corresponding maximum joining forces are presented. The maximum joining force information is missing for system b, because this system does not have an internal force value output. The evaluation shows approximately the same characteristic values in the statistical average for all of them. The interlock f varies between 0.17 mm to 0.18 mm, the neck thickness t_n varies between 0.47 mm to 0.49 mm and the minimum bottom thickness $t_{b.min}$ varies between 0.26 mm to 0.30 mm. The maximum joining force varies between 27.3 kN to 33.5 kN.

The results of experimental process analyses for joint combination HC260LA $t = 2.0$ mm into HC260LA $t = 2.0$ mm shows **Fig. 5**.

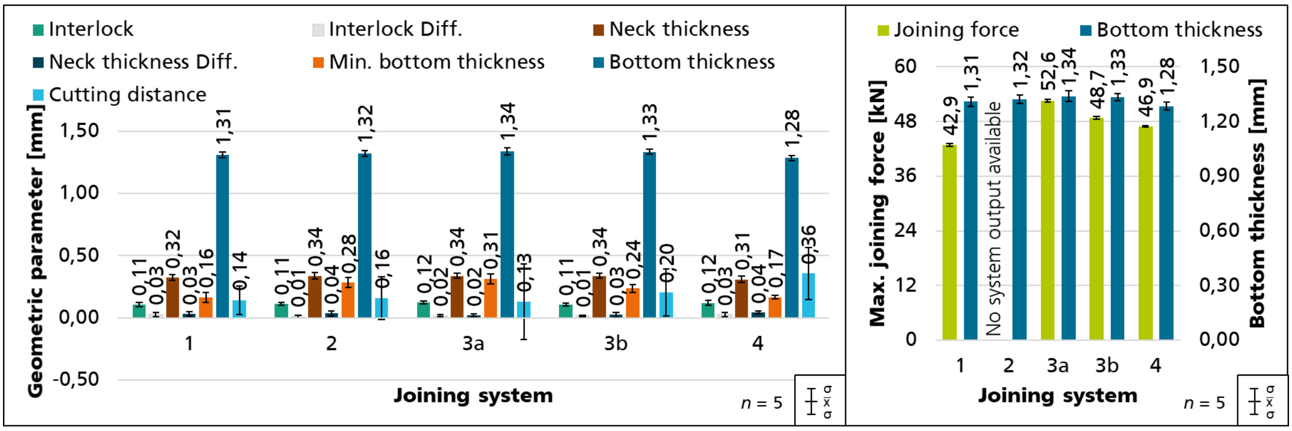

Fig. 5: Experimental results of HC260LA $t = 2.0$ mm into HC260LA $t = 2.0$ mm

Analogous to the results of the first joint, the results here also show statically comparable characteristic values for all geometric parameters. The Interlock f varies between 0.11 mm to 0.12 mm, the neck thickness t_n varies between 0.31 mm to 0.34 mm and the minimum bottom thickness $t_{b.min}$ varies between 0.16 mm to 0.31 mm. The maximum joining force varies in the range from 46.9 kN to 52.6 kN.

The results of experimental process analyses for joint combination HC420LAD $t = 1.25$ mm into EN AW-5182 $t = 1.25$ mm shows **Fig. 6**.

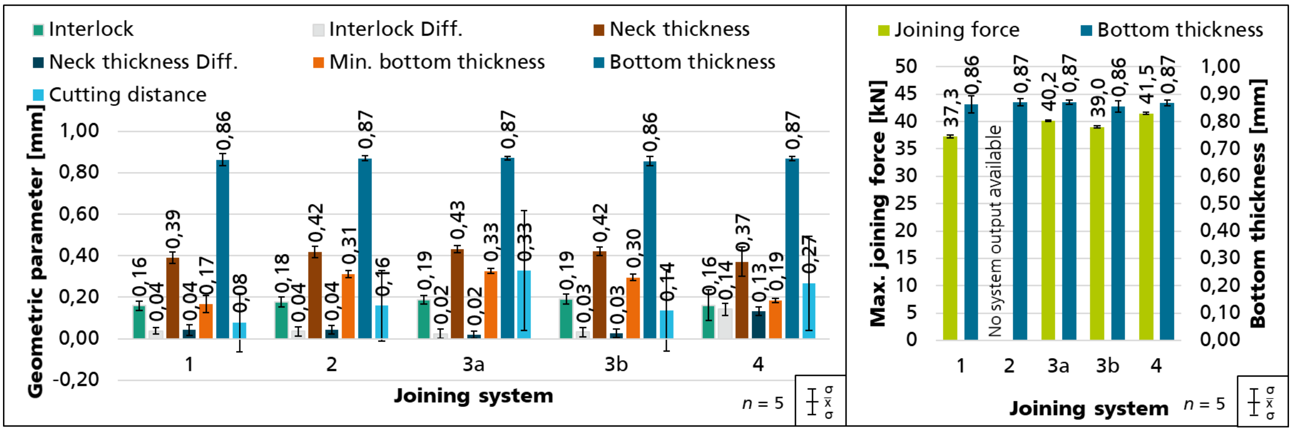

Fig. 6: Experimental results of HC420LA $t = 1.25$ mm into EN AW-5182 $t = 1.25$ mm

In the evaluation of this combination, slightly increased deviations of the geometric characteristic values can be identified. The Interlock f varies in a range from 0.16 mm to 0.19 mm, the neck thickness t_n varies between 0.37 mm to 0.43 mm and the minimum bottom thickness $t_{b.min}$ varies between 0.17 mm to 0.33 mm. The maximum joining force varies in the range from 37.5 kN to 41.5 kN. These variances in the output variables are examined in the following under the more precisely defined aspect of the system characteristics.

Conclusion

The results of the experimental process analysis relatively small changes in the characteristic values in the grind and sometimes larger ranges of the necessary joining forces. Since the joining tools were the same in all systems of the respective joint, the scatter can only come from the system-side and workpiece-side influences. Since the parts to be joined were taken from the same sheet metal blanks, the influence of the workpiece-side influencing variables can also be estimated as low but cannot be completely neglected. Therefore, the significant influencing variables are those on the equipment side. The partially adjustable parameters here were the joining speed and the blankholder force. The control behavior of the joining speed and blankholder force or the elastic deformation during the joining process are system-specific and cannot be changed. Based on experimental process analysis, it is not possible to differentiate which parameters have which influence. For this reason, the system-specific influencing variables joining speed profile and elastic deformation during the joining process will be analyzed in more detail. Metrological system analysis. For a more specific identification and description of the system-side influences on these varying joining results, the press systems are now analyzed metrologically in the form of analysis about elastic deformation and exact velocity profiles.

2.4. Elastic deformation analysis

For the characterization of the joining systems, the systems under consideration (Table 2) are measured with an optical measuring system (*GOM Pontos*) regarding the deformation during joining at discrete points in order to subsequently perform a comparison of the total strains between experiment and numerical simulation. At the same time, rotation about the y-axis is analyzed in addition to pure vertical and lateral displacement in the z- and x-directions. Since the highest joining forces are required for the joint combination HC260LA in HC260LA, this joint was selected for the deformation analysis. The results in form of displacement field at discrete points of this analyses show pictures 1-3 in **Fig. 7**.

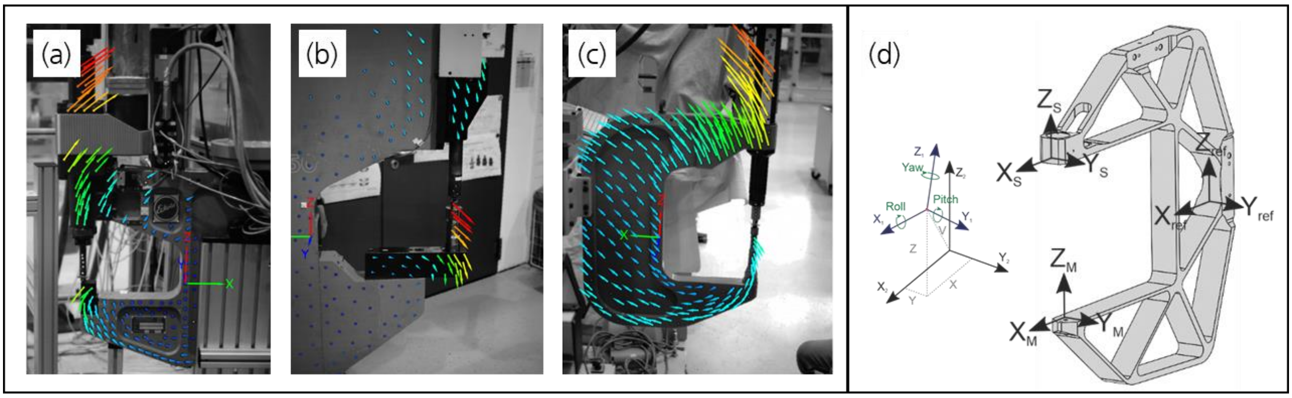

Fig. 7: Results of max. elastic deformation during clinching process (a-c) and definition of coordinate systems for 6-DoF analyses (d)

The displacement field contains displacement vectors for each discrete point and visualize value and direction. The scaling of the vectors is adapted here to the maximum displacement of the respective system. Nevertheless, the die and the punch holder spring open. For the determination of the vertical, lateral, and angular misalignment, a six degrees of freedom (DoF) analysis is executed. For this purpose, coordinate systems are defined in the punch holder and die, seen in **Fig. 7** (d), and the displacement of all six DoF is measured. The difference of both coordinate systems relative to each other leads to the resulting final misalignment, presented in **Table 4**.

Table 4: Results of 6-DoF-analyses

Misalignment X [mm]	Misalignment Z [mm]	Angular misalignment [°]
0.104 to 0.287	0.348 to 1.055	0.08 to 0.346

2.5. Joining velocity analyses

In addition to the knowledge about the elastic deformation behavior, the information about the real speed profile of the punch is important. This is because both the drive type itself and the control unit of the drive influence the speed profile. To determine the speed profile of the joining die, two high-speed cameras (*Photon Fastcam SA1.1*) with a measuring rate of 500 to 2000 images per second are positioned as shown in **Fig. 8**, which record the movement sequence in the joining process.

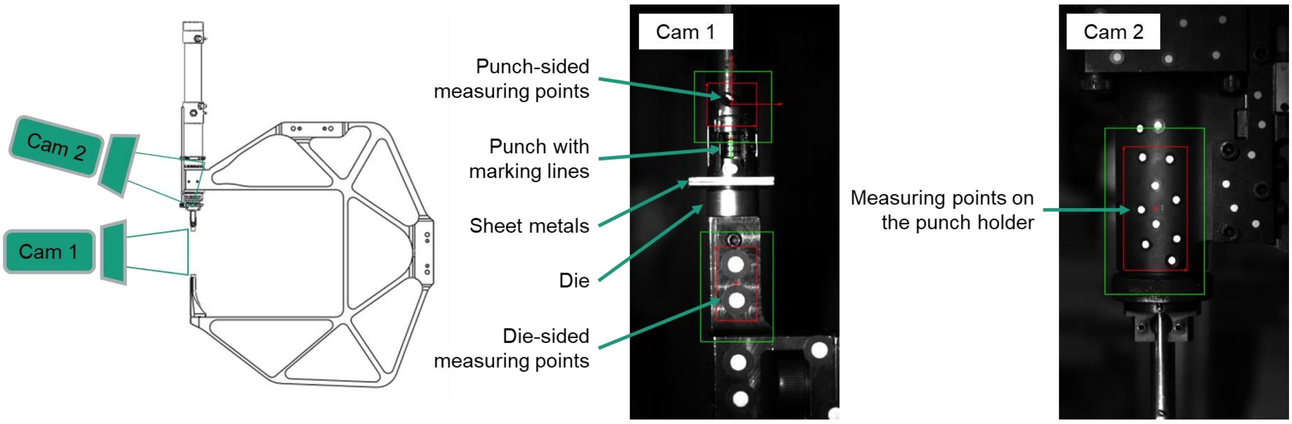

Fig. 8: Measurement setup and image preview of the determination of the punch velocity profile

The evaluation of the high-speed recordings is carried out with the *NI Vision Builder for Automation* software. The speed profile can then be derived from the displacement of the measuring points on the joining tools over time, seen in **Fig. 9**.

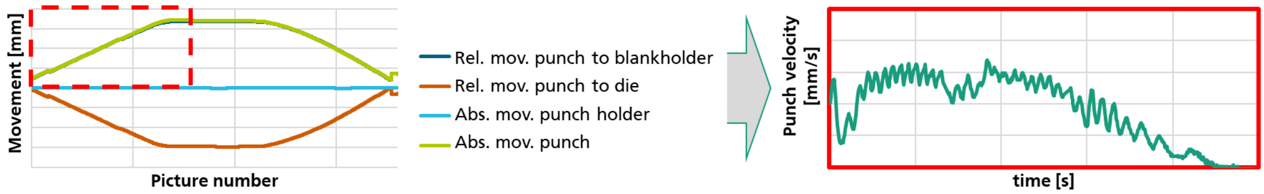

Fig. 9: Evaluation of real velocity profile of clinching punch

Based on the point displacements over the time of the entire joining process (punching process plus backstroke), the velocity profile during the joining process can now be derived (red box of **Fig. 9Fig. 9:** Evaluation of real velocity profile of clinching punch). This was carried out and evaluated in the same way for all joining systems. Because the velocity profiles have different characteristics, only a simpler averaged mean velocity was determined for the subsequent numerical investigations. The results of these mean punch speed are shown in **Table 5**.

Table 5: Average punch speeds

Joining system	1	2	3a	3b	4
Average punch speeds [mm/s]	47	4	6	17	54

3. Numerical Simulation

Numerical simulations are a good way to study specific parameters without correlations that are unavoidable in real experiments. For this reason, a numerical simulation model is built up in the following, which allows the influencing parameters system stiffness and joining speed to be investigated in a differentiated manner. For numerical simulation of clinching process with elastic deformation behavior of press system a half-symmetric 3D simulation model were build up in *Deform V12.1*, shown in **Fig. 10**.

Sheet metals	
Punch-sided sheet metal	Die-sided sheet metal
HC260LAD (*t* = 2,0 mm)	HC260LAD (*t* = 2,0 mm)
3D-Simulation parameters	
Elements, punch-sided sheet metal	Elements, die-sided sheet metal
70.000 (round blank radius = 20 mm)	40.000 (round blank radius = 20 mm)
Flow curve model	Damage criteria
Johnson-Cook material model	Normalized Cockroft & Latham
Flow curve model parameter	Friction model
A=350, B=448, C=0,031, n=0,44, m=2	Combined friction model (µ,m)
Mech. to Heat	Friction model parameter
90% (constant)	St-St 0,1/0,1
Solver (Deformation)	Heat transfer coefficient
MUMPS	11 N/sec/mm/C
Solver (Temperature)	Iteration method
Conjugate gradient	Newton-Raphson

Simulation model

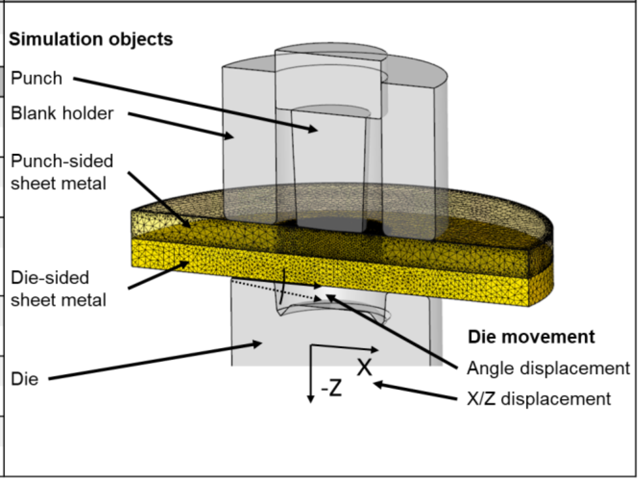

Fig. 10: Simulation model of clinching process with press system elastic deformation in Deform V12

The model includes the plastic deformation of sheet metal forming, an ability of spring mounted die movement in X- and Z-direction for simulation of lateral and vertical misalignment. The angular misalignment, that occurs in C-shaped press forms during conventional clinching, is modeling in two variants. Variant 1 uses a constant angular misalignment from start to end of the simulation. Variant 2 is modeled with a rotation to the point at the upper left corner and constant angle velocity during clinching process, shown in **Fig. 11**.

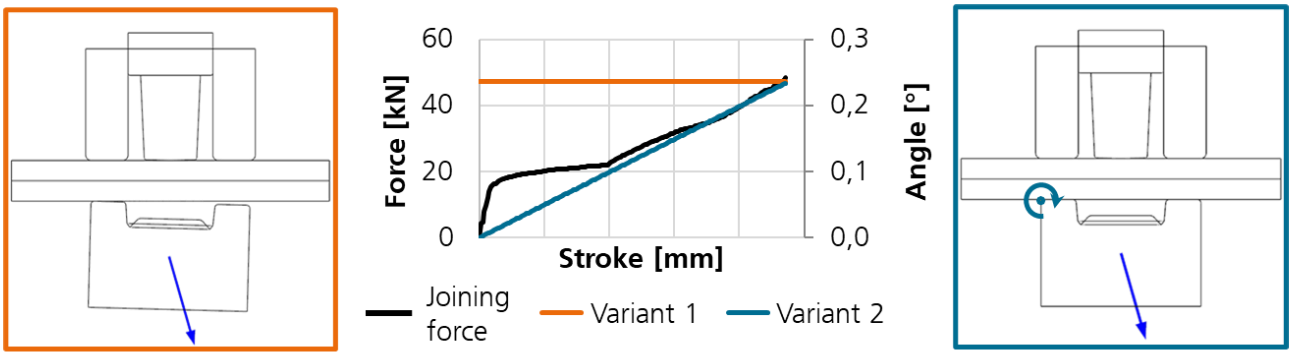

Fig. 11: Angular misalignment modeling variants

The chosen parameters of the combined friction model were validated by numerical sensitivity analyses by fitting the calculated with the experimental joint contour and force-displacement curve for clinching processes. The metal sheets to be joined are modelled with plastic deformation behavior. All other objects are considered as rigid to reduce the calculation effort. For the following numerical analysis, the flow curves of the sheets were determined by tensile tests and fitted with a JOHNSON-COOK material model (1)

$$k_f(\bar{\varphi},\dot{\bar{\varphi}},\vartheta) = [A + B \cdot \bar{\varphi}^n] \cdot [1 + C \cdot ln(\frac{\dot{\bar{\varphi}}}{\dot{\bar{\varphi}}_0})] \cdot \left[1 - \left(\frac{\vartheta - \vartheta_0}{\vartheta_m - \vartheta_0}\right)^m\right] \quad (1)$$

Furthermore, it is assumed that 90 % of the forming energy is converted into heat and thus the joining components heat up during the joining process. The generated heat can then be transferred to the joining tools with a constant heat transfer coefficient. The validation of the numerical simulation and the experiment shows **Fig. 12**.

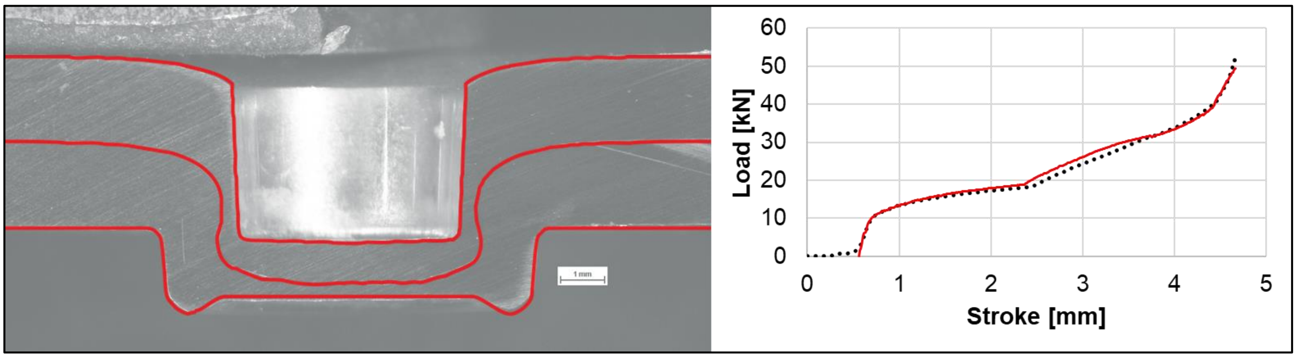

Fig. 12: Validation of simulation model

On the left side in **Fig. 12**, a comparison between cross section joint contours demonstrates a good match. On the right side in **Fig. 12**, the comparison of the load-stroke curves also shows good agreement between experiment and simulation. On the base of this validation, the numerical simulation model can be used to the following system-sided influence analysis.

4. Metamodeling and Development of Transfer Functions

Metamodels are a helpful tool for the evaluation of complex multilevel parameter studies and variation calculations. Statistical regression methods for sensitivity analysis are used for the evaluation. The metamodels are multidimensional according to their input and output parameter numbers and include all correlations between all input and output parameters. At the same time, the significance of the influencing parameters on the respective output variables can be identified. Therefore, the correlations of the most important influencing parameters can be visualized in the 3D-space of the illustrated metamodel. Furthermore, the regression models can be extracted for a transfer function and thus enable the calculation of any points in the multidimensional space.

First, numerical sensitivity analyses are carried out for the selected material combination HC260LA t = 2.0 mm into HC260LA t = 2.0 mm based on the validated simulation model for the clinching process with machine system influence modeling. Based on a statistical test plan according to the latin hypercube sampling method. The input variables are systematically varied into defined range (Table 6 and 7) in the simulation models for die rotation variants 1 and 2 and the associated joining result variables interlock f_1, f_2, neck thickness t_{n1}, t_{n2}, min. sheet thickness $t_{b.min}$ and maximum joining force f are calculated.

Table 6: Input parameter range for angular misalignment model variant 1

Input parameter range	Speed [mm/s]	Angular misalignment [°]	Lateral misalignment [mm]	Vertical misalignment [mm]
Min	5.0	0.0	0.00	0.00
Max	50.0	1.5	0.35	1.01

Table 7: Input parameter range for angular misalignment model variant 2

Input parameter range	Speed [mm/s]	Angular misalignment [°]	Lateral misalignment [mm]	Vertical misalignment [mm]
Min	5.0	0.0	0.00	0.00
Max	50.0	1.7	0.35	1.01

Based on input and output values, regression analyses are carried out with *OptiSLang*. The results are generated MOPs (metamodel of optimal prognosis), which describes the influence and the correlations of input and result values. For example, the 3D plot and CoP table (coefficient of prognosis) of the neck thickness for die rotation variant 2, seen in **Fig. 13**.

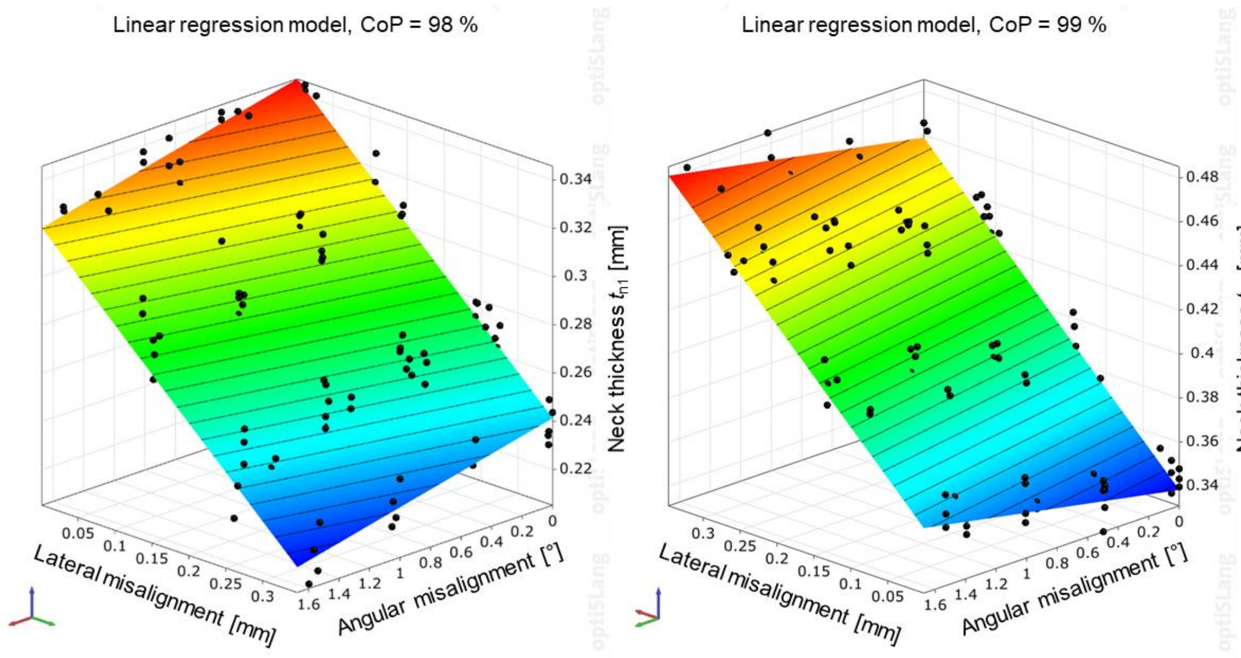

Fig. 13: Metamodel of neck thickness for angular misalignment model variant 2

The CoP value is a quality value of model. A higher CoP value means that the relationship between input and output can be better described with the respective regression model. The CoP table indicates the influence of individual input values on the respective output variable. Using the metamodel, it can now be identified that the neck thickness t_{n1} gets smaller with increasing lateral misalignment and higher angular misalignment. On the other side, the neck thickness t_{n2} gets higher with increasing lateral misalignment and higher angular misalignment. In summary, the interlock difference f_{diff} increases with decreasing vertical misalignment and higher angular misalignment. And we can observe from the CoP table that the lateral misalignment is the significant influencing parameter on the output neck thickness. Analogously, the other MoPs of the output parameters with respective angular misalignment variants can be analyzed and evaluated in this way.

Based on the numerically determined result data and MoPs for the system influence during clinching, a transfer function can now be derived for each characteristic value. Afterwards, a comparison and an evaluation with the experimental results can be made by entering the specific system parameters, seen in **Fig. 14**

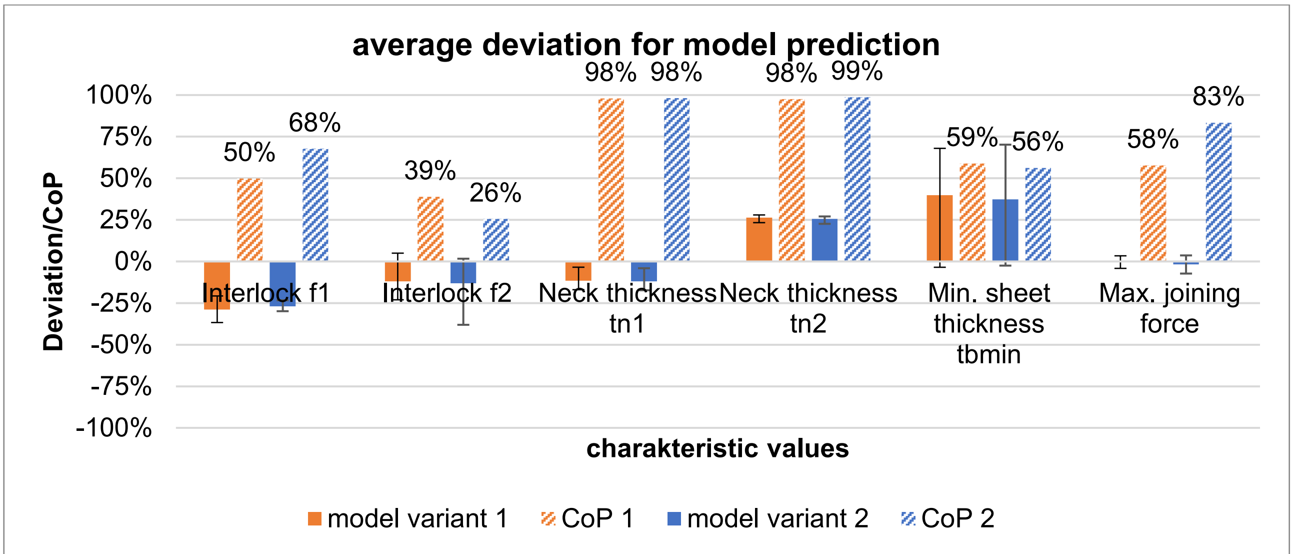

Fig. 14: Average failures for model prediction of characteristic values by clinching

In this figure, the average deviations of the calculated characteristic values based on the regression models from the MoP for each characteristic value to the characteristic values of the experimental process analysis as well as the respective related CoP values are plotted. The relative deviation is shown with a bold bar and the corresponding CoP value is shown with a striped bar. The scatter bars show the maximum and minimum deviations over the 3 examined system types. We can now detect that the average deviation across all characteristic values is 40 %. The characteristic value of the minimum sheet thickness t_{bmin} displays this largest positive deviation. This means that the minimum sheet thickness is predicted to be thicker than it is. In absolute numbers, for an average minimum sheet thickness of t_{bmin} = 0.20 mm, this is a positive deviation of about + 0.08 mm. The corresponding CoP values of the metamodels are also only moderate at approx. 60 %. In addition, the scatter bars are very large, so that the deviation can be even higher. The highest CoP values and the lowest deviation are to be identified when calculating the neck thickness t_n. The prediction of the interlock f is moderate to poor in terms of deviation with an average of 25% and CoP values between 26% and 68%. The prediction of the maximum joining force F is moderate to good in terms of deviation with an average of 2% and CoP values between 26% and 68%. If we look at the evaluation differentiated according to the variant of the angular misalignment modeling, we can detect better values overall for variant 2 with constant die rotation speed. Only the CoP value and the scatter at the interlock f_2 are slightly lower compared to variant 1. All other values are predicted better and with smaller scatter. If we look again at the layered load/angle-stroke diagram in **Fig. 11**, variant 2 is also closer to the real angle change over the joining process.

Conclusion and outlook:

The results of the metamodels and the average deviations of the model predictions represent a useful first possibility to determine the variation of the characteristic values in the grinding of the clinch joint by means of data transfer functions. These are based on numerical variation calculations, which allow a more differentiated evaluation of the system influencing variables. On detailed examination of the results the models for the individual characteristic values show, in part, strongly differing qualities.

For an even better quality of the metamodels, further approaches should be considered in future research work:

- Workpiece-sided influencing variables were not considered here on purpose. These are always present in real experiments and should therefore be considered in future work in combined system-side and workpiece-side influence investigations.
- The low CoP values show that there is a low correlation between input and output parameters. The addition of further influencing factors could lead to an improvement in the model and prediction quality.
- In these investigations, simple linear regression models were applied. More complex regression methods could improve the CoP values and metamodel quality.
- The joining speed in the simulation was simplified and set to a constant value. However, the evaluation of the high-speed recordings showed that the clinching process is a highly dynamic process. Therefore, these dynamic speeds should be investigated more closely in future studies.
- The friction conditions were described here with a hybrid friction model (Coulomb & shear model). New investigations with velocity-dependent friction models should be investigated in more detail in the future.
- The stiffness-dependent rotation of the die under load influence, i.e. the angular misalignment, should be investigated in more detail in future studies.

Summary

In this paper, a possibility of transferring characteristic values from machine system A to B was presented. For this purpose, an experimental process analysis was first carried out for three different joining combinations (Al-Al, St-Al, St-St) on four different plant systems and, among other things, the characteristic values of interlock $f_{1.2}$, neck thickness $t_{n1.2}$, minimum sheet thickness t_{bmin} and maximum joining force F were evaluated. Subsequently, the metrological system analysis was carried out in the form of an analysis of the elastic deformation behavior in the joining process using *GOM*

Pontos and an analysis of the real joining speed profile using *Photon Fastcam SA1.1* high-speed cameras for each machine system. A 3D semi-symmetric simulation model was then built in *Deform V12* to represent the system deformation. While the vertical and lateral displacement could be modeled stiffness-dependent by a spring, the angular displacement was modeled with two other stiffness-free variants. Variant 1 included a constant angular offset over the entire joining process and variant 2 a constant angular velocity. The deformation behavior of the sheet materials was described using a Johnson-Cook material model. Strain rates and temperature-superimposed tensile tests were used to validate the material model. The validation was performed by comparison with the cross section and the force-displacement curve from the experiment. Consequently, a numerical data set was built up with the simulation model and both angular misalignment variants and evaluated with *optiSlang*. As input, the joining speed as well as the vertical, lateral and angular misalignment were varied. As a result, metamodels were generated and significant influence parameters on the output parameters interlock $f_{1,2}$, neck thickness $t_{n1,2}$, minimum sheet thickness t_{bmin} and maximum joining force F were identified. Finally, functions for calculating the prognosis for machine system changes were derived and compared with the results of the experimental process analysis.

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