Safe mechanical joining processes by digital manufacturing supervision in steel coil productions

H C Schmale¹ and T Geddert²

¹ Welding and Joining Department, Salzgitter Mannesmann Forschung GmbH, Eisenhüttenstraße 99, 38239 Salzgitter, Germany
² Technical Customer Service Department, Salzgitter Flachstahl GmbH, Eisenhüttenstraße 99, 38239 Salzgitter, Germany

h.schmale@sz.szmf.de

Abstract. Mechanical joining processes, in particular joining by forming like self-pierce riveting or clinching, require homogenous material characteristics for reliable joint properties. Joining processes in production are called safe, when the estimated properties for each manufactured joint, e.g. strength, remain in predefined narrow boundaries. Thus, an automated process monitoring is possible. A key reliability factor in automated production are varying joining materials properties. In case of steel, the knowledge of mutually dependent manufacturing steps at the coil build-up are crucial: First, milling conditions, such as dressing grade, predetermine the mechanical strength and fracture strain of the later joint. Second, the structure of corrosion protection layer by electrolytic or hot-dip galvanizing combined with forming and corrosion protection lubricants define the gliding abilities at later joining processes. It was found that a high dependency exists between solidification behaviour as well as surface friction level of the joining material and the stability of the joining process and the load capacity of the joint. To achieve safe mechanical joining results, these mentioned material properties must be guaranteed precisely by production monitoring techniques at the coil manufacturing. These include among others, methods for the non-destructive testing of mechanical properties at different coil areas, as well as systems for monitoring surface conditions and layers. As the material properties are build up over several production steps, production data are digitally collected today, analysed under quality aspects and if necessary corrective measurements are set online in the production.

1. Introduction and motivation

Self-pierce riveting with semi-tubular rivets, as well as clinching, are today’s first choice joining technologies when heat sensitive materials or multi material combinations of different steel- and aluminum grades should be joined in automated mass production [1].

Figure 1 gives an overview how a joining process in general should be organized in an industrial environment [2]. To achieve a maximum lightweight benefit of the used materials in the construction, the safety factor in the mathematical design should be as low as possible. The calculated strength, energy absorption level, failure mode and aging behaviour of each joint are only allowed to vary in predefined narrow boundaries during the later production [3].

Therefore, a highly reliable or so-called safe joining process is basic. Characteristic for a safe joining is a high repeatability and robustness of the selected joining process. Beside the general design of the joint, especially the material influences the joining safety most. As the design is directly linked to this aspect, the material content is only linked indirectly. Due to this fact, especially the material aspects,
like material structure, parameters and surface should be handled with special care, as influences are not often seen at first glance at a joining process.

![Figure 1. General aspects for joinability of products, based and modified on [2].](image)

Figure 2 compares different steps of a self-pierce riveting and clinching process. A safe mechanical joining process is characterized by an unlimited repeatable same joining result. Relevant aspects are a symmetrical high form closure, no local material separation, and mechanical properties under load at similar strength and failure behaviour. To achieve a stable joining process for a certain joint, two major factors must be considered. First, the right corresponding joining tools (e.g. punch diameter, die geometry, -diameter and -depth; rivet geometry, -length and -hardness) must be chosen during a sampling. Second, to ensure stable joining results over production lifetime, the properties of the joining material must follow narrow process tolerance bands and possible coil coatings should not interfere the functionality of punches and dies by layer deposition [4].

![Figure 2. Analysis of the material influence on different joining processes by forming; based and modified on [5].](image)
To understand which specific joining material properties are influencing the joining process most, a deeper look is necessary. On the one hand, the friction conditions (marked in blue) decide how unrestricted the metal forming take place, on the other hand the solid forming conditions (marked in black) define the forming potential and the needed joining forces to establish the joint. Based on figure 2, relevant aspects and criteria to determine and measure a safe mechanical joining process can be derived as follows:

- Symmetrical inner & outer joining geometry in xy-direction; deviation \( d_{\text{Join}} \) < 5.0 % of theoretical optimum (symmetry), related to joining element diameter (Self-pierce riveting and Clinching).
- Undercut in xy-direction \( u_{xy} \) > 0.1 mm; undercut in z-height \( u_z \) > 0.5 mm; residual bottom thickness \( t_{\text{bottom, residual}} \) > 0.1 mm (Self-pierce riveting) [6].
- Undercut in xy-direction \( u_{xy} \) > 0.05-0.2 mm*; neck thickness \( t_{\text{neck}} \) > 0.5-0.2 mm*; residual bottom thickness \( t_{\text{bottom, residual}} \) > 0.2-0.5 mm*; *depending on the clinching element outer diameter at 3.4-10.0 mm (Clinching) [7].
- No material separations: no neck crack (Clinching), floor cracks (Self-pierce riveting and Clinching) or rivet base breaks or compressions (Self-pierce riveting).
- No layer deposition on punches or dies by coatings (Self-pierce riveting and Clinching).
- Punch force-stroke deviation in the tolerance-band for automated process controls \( F_{\text{Join}} < 0.5-2.0 \text{ kN} \) at equal stroke position \( s_{\text{punch}} \) (Self-pierce riveting and Clinching) [8, 9].
- Acceptable joint material thickness deviation \( d_{\text{thickness}} \) < 6.0% of nominal thickness \( t_{\text{nominal}} \) (Clinching) and < 10.0% (Self-pierce riveting).

2. Experimental results

2.1. Evaluation of the joining material influence on a self-pierce riveting process

As shown before, especially the friction conditions and the solid forming conditions decide whether a joining process is reliable or not. An example is given by a semi-tubular riveting process analysis, where different material properties were varied for a test scenario.

A comparison is made between two different steel grades, that have an equal thickness, strength, similar yield strength and ultimate strain but totally different surfaces and solidification behaviour. One material is conventionally built up by milling, the other material is made by additive manufacturing in a laser bed process. The mechanical properties are listed in table 1.

| Table 1. Mechanical properties of investigated materials. |
|----------------------------------------------------------|
| **Material** | **Thickness real/nominal (mm)** | **Yield strength YS/ \( R_{p0.2} \) (MPa)** | **Tensile strength TS/ \( R_m \) (MPa)** | **Total elongation TE/ \( A_{80} \) (%)** | **Constriction after uniform elongation UE (-)** |
|-------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|
| CR440Y780T-DP | 1.21/1.20 | 440-510 | 780-900 | \( \geq 14 \) | yes |
| - milled | | | | | |
| - GI 50/50 | | | | | |
| MMn-steel | 1.25/1.20 | 600-625 | 820-840 | \( \geq 13 \) | no |
| - 3D printed | | | | | |
| - uncoated | | | | | |

To show how sensible the joining process reacts, only the upper joining partner (material 2) is changed in the experiment. Figure 3 shows the measured values for punch force and punch stroke during the joining process in the process monitoring.

The surface and especially the solid forming properties have a major influence on the joining process. The "as build" surface of the 3D printed material has a roughness about \( R_z \approx 80 \mu m \) (2a) and about 2 \mu m
after a mechanical polish process (2b). The resulting different friction conditions can be seen in the first section of the joining process until the rivet cuts the punch sided joining material. The curve with 2a material shows a steeper slope as 2b. Although the surface roughness of 2b is equivalent to a milled steel, like material 1, there is still a difference in the curve behaviour. This can be explained on the one hand by a missing zinc coating, that provides good gliding conditions. On the other hand, the solid forming properties are different, especially the material de-stressing of the 3D printed material, which provokes a light impact shock when the rivet finishes its cutting sequence. That behaviour matches with the not existing constriction after reaching uniform elongation in the tensile test.

Figure 3. Self-pierce riveting processes under varied surface- and material-properties at two different 800 MPa steels.

At the end, the rivet geometries of the joints partly made of 2a and 2b material are more asymmetric or the rivet base is compressed, compared to the joint, that is completely made of the milled material 1. These deviations are well known for diminished joint properties, e.g. joint strength [4].

It can be summarized that already small variations in the mechanical properties and surface conditions have a major impact on the joint stability in automated processes and on the ability of process monitoring. So, there is a very high need for exact und repeatable material properties from this point of view.

2.2. Evaluation of the joining material influence on a clinching process

A second example is given for the joining technology clinching. The used materials are described in table 2.

Table 2. Mechanical properties of investigated materials according to VDA 239.

| Material          | Thickness real/ nominal (mm) | Yield strength YS/ R\text{p0,2} (MPa) | Tensile strength TS/ R\text{m} (MPa) | Total elongation TE/ A\text{80} (%) | n-value (-) |
|-------------------|-------------------------------|--------------------------------------|-------------------------------------|------------------------------------|-------------|
| CR330Y590T-DP GI 50/50 | 1.48/ 1.50                   | 340-420                             | 600-700                             | ≥ 20                               | ≥ 0,14      |
| CR330Y590T-DH GI 50/50 | 1.46/ 1.50                   | 330-430                             | 590-700                             | ≥ 26                               | ≥ 0,16      |
Here, two similar, but different dual phase steels with comparable strength and yield strength, but slightly different elongation at fracture and different solidification behaviour are discussed. Those minor differences in the joining material behaviour, which are intentionally realized by choosing two fine-tuned different steel grades, have a significant effect in the way the process monitoring reacts, figure 4. The selected sheet thickness including upper and lower threshold is 1.5 mm +/- 5% corresponding to automotive industry quality standards.

Figure 4. Clinching processes under slightly varied material-properties at two different 600 MPa steels.

An average deviation of 5.0 kN in the measured punch force curve all over the joining process results between these two steel grades. Reliable clinching process monitoring systems in automated productions require much smaller tolerance bands of 0.5 – 2.0 kN to safely detect process faults [8, 9]. Typical errors are false installed tools, broken or worn dies or punches, that have a major negative impact on the joining quality. To ensure this auditability, the material properties for the joints must follow very narrow bands for the whole material behaviour and not only for some concrete values on the tension-elongation curve.

Figure 5. Resulting loads of DP- and DH-steel in a clinched joint.
The resulting task for a steel manufacturer is to produce steel coils that have homogenous mechanical behaviour at the whole coil. The different forming behaviour of the joint cannot only be observed during the joining process itself, it is also transferred into later loading properties and failure behaviour of the joint, figure 5. The different elongation at fracture, known from the raw materials, can also be seen at the joint, but here amplified. At the raw material, the difference in elongation at fracture, compared between the DP- and DH-steel is about +28% (referred to the DP). At the joint this effect is doubled up to +60%.

One major reason could be seen in the different failure modes. Due to the needed lower forming forces in the clinching process, the DH-material is less stressed, especially in highly deformed areas like the neck area. That means, that the joint can withstand higher deformations later under load. In combination with the enhanced ultimate strain at the raw material, these two positive effects amplify themselves. Referred to chapter 1, figure 1, this example makes clear why also indirect influences of the material have to be considered regarding the joining safety in all details. So, another important reason to monitor and control very precisely all technological-mechanical properties during a coil build up process are combined effects in later manufacturing steps, here clinching, caused by the raw material, which cannot be directly forecasted from the raw material properties.

3. Measurement of relevant material parameters in steel coil productions

As seen and discussed already in figure 1, a safe joining process is based on fine-tuned material properties. Regarding the mechanical joining process, especially the aspects sheet metal thickness & -distribution, strength, strain hardening behaviour and friction are relevant [10]. This chapter refers to the relevant process steps in steel coil productions to achieve these needed properties for the joint material. To reduce the complexity, only a cold rolled galvanized material is considered. This surface type was also in focus at the joining experiments before.

3.1. General measurement of relevant quality process values

To achieve a constant high-quality steel coil product, a continuous detection of quality process values is indispensable. Therefore, different strategies are used to gain these values, figure 6. First, there are possibilities to measure on- or offline. Online means, that the data will be collected live and process-synchronous inside the production, meanwhile offline implies that the data will be collected or created separately outside the production line.

![Figure 6. Direct and indirect measurement methods [11].](image)

As the offline modus is no more process-synchronous, a clear designation is mandatory to allocate them later correctly to the corresponding coil section. The quality parameters that can be measured online are divided into direct and indirect measurement methods [11].

While, for example, the thickness of a semi-finished product can be measured directly over the entire length of the strip, the friction ratio and strength of the semi-finished product can only be measured indirectly over other corresponding process data of the rolling and dressing process. Otherwise, if direct measurements are necessary, they must be checked offline by laboratory tests.
3.2. Relevant manufacturing steps at a hot-dip galvanizing process

Today, nearly the main steel production process is monitored and is digitally supervised over the different manufacturing steps. Figure 7 gives an overview of a modern hot-dip galvanizing process.

Figure 7. Hot-dip galvanizing: A combined process to set up surface and mechanical properties.

The main stages to set up the material properties to get a cold rolled strip with hot-dip galvanized surface are the temperature control at the furnaces including the cooling conditions to adjust the needed material structure. For example, a typical process route is shown to setup a dual-phase microstructure.

In contrast to the electrolytic galvanizing, the important surface-, friction- and mechanical properties are setup in only one production line. Therefore, a quick online process control is necessary. The relevant measurement and control steps in the hot-dip galvanizing are explained next.

3.3. Continues thickness measurement and -control during the whole coil build up process (i)

For constant final product properties, at first an accurate material thickness with narrow process tolerance bands is needed. Therefore, the thickness of the coil is measured multi times during the coil build up process to guarantee accurate thickness values for the final product. As it is a multi-layer product, each layer must be measured, controlled, and adjusted concerning their specific thicknesses, see also figure 10. While the coil thickness is adjusted by milling, the coating thickness is controlled by an air knife procedure after passing the zinc pot that wipes up the zinc coating at a different weight level by air flow [12].

Concrete, the coil core thickness of the steel is measured before the annealing process, then afterward separately the hot-dip galvanised zinc coating thickness on each coil side, and at least the thickness of the end product including the steel core with the zinc coating on both coil sides. A most accurate radiometric method via X-ray emitters in transmission or backscattering technique are used, which measures contactless online with positional accuracy and combined in post-processing, figure 8.

Forming processes in general as well as mechanical joining by forming require predefined material thicknesses including an average value and a suitable tolerance band. Most processes in automotive applications allow a maximum tolerance of 5.0-10.0% of the standard thickness. This matches as well with mechanical joining process requirements, see chapter 1. In the given example the installed tolerance band is adjusted to that quality requirement. At fully controlled processes a much smaller thickness tolerance can be produced, see real process data at figure 8.
3.4. Measurement of different material strengths at the hot-dip galvanizing (ii)

The material tensile strength and yield strength is determined on representatives in offline laboratory tests or online by monitoring specific process data in the process. For example, the resulting rolling force for an IF steel, assuming constancy of the alloy analysis, gives a direct indication of the strength of the material when the annealing temperature in the radial tube furnace (RTF strip 1) changes by a previous setup change of the radial tube furnace (RTF set), figure 9 left. In figure 9 right, the resulting rolling force answer can be measured and analysed at about 900 to 1,000 m coil position.

Suitable models can also be used to react to analytical peculiarities so that, for example, annealing, cooling, or rolling conditions can be influenced to keep the mechanical-technological properties within the agreed tolerance window or to minimize fluctuations.

3.5. Selectable zinc coatings and surface check systems in the hot-dip galvanizing (iii)

One of the last steps in finishing the coil properties is the apply of the hot-dip galvanizing. This process step defines the coating type, the coating thickness, the surface texturing, roughness and afterwards the lubricant material and the lubrication level.

All these production factors are combined responsible for the friction behaviour of the material. As seen in the analysis of joining results in chapter 2, the surface conditions play a major role. At the self-
pierce riveting example, the effect of different friction levels could be seen in the process curve and the corresponding geometrical effects on the rivet. Beside the roughness of the surface, the gliding ability of the surface material plays a major role regarding friction and is stated as a critical process parameter for mechanical joint quality [13].

Two different coatings are available at the selected production route of a cold rolled galvanized material. Table 3 illustrates the abilities of the two zinc coatings concerning the gliding ability and the forming potential. The coating GI 40/40-E is a standard product, mainly based on zinc with 40.0 g/m² coating weight on each coil side. ZM 40/40-E is a new developed coating in the last 5-8 years, based on a zinc matrix with integrated magnesium particles. For a 1:1 ratio comparison the coating layer was also adjusted at 40.0 g/m² on each coil side.

Table 3. Influence of the zinc coating concerning friction and (deep) drawing potential.

| Zinc-Coating | Lubricant | Parameter |
|--------------|-----------|-----------|
| GI 40/40-E   | Anticorit 3802 39 S PTFE film | Parameter |
|              | $F_{BH} = 5.0$ kN | $F_{BH} = 30.0$ kN |
|              | Material: CR180BH | Thickness: 0.7 mm |
|              | Lubricant: see diagram | Drawing ratio: 2.0 |
|              | Punch diameter: 50.0 mm | Die diameter: 52.9 mm |
|              | Die radius: 3.0 mm | Cupping speed: 1.2 mm/s |
|              | Cupping stroke: 18.0 mm | $F_{BH}$: Blank Holder Force |
| ZM 40/40-E   | $F_{BH} = 30.0$ kN | $F_{BH} = 30.0$ kN |

To evaluate the friction influence on the forming potential, a cup deep drawing test is performed. One can be seen that the zinc-magnesium coating (ZM 40/40-E) enables a much better forming characteristic compared to a single-phase zinc coating (GI 40/40-E) at a drawing ratio of two.

This positive effect can be used to reduce wear and deposits at different forming tools [14]. To prove that the better gliding effect results only of the coating and not of the lubricant, a reference try with a PTFE-film was performed, that proved the assumption. Transmitting these results of a typical forming test into mechanical joining can help to increase process windows. Concrete advantages are reduced danger by material separation of neck- or floor cracks. A second benefit of zinc-magnesium coatings are a lower friction coefficient over production time, figure 10.

The main benefit of lower friction, that could be seen first in a better forming behaviour has also advantages over production lifetime. The friction conditions in the forming tool by using a zinc-magnesium coating are significantly lower, so that the abrasion level of the coating can also be improved [14]. Regarding clinching and self-pierce riveting the friction improvements on the coating development can support reduced joining force, less wear at punches and dies as well as enhanced process windows for different material combination for a discrete joining tool definition [15]. For critical joining tasks the use of hot-dip galvanized steel offers more degrees of freedom compared to electrolytic galvanized steel, where actual only one coating type is available on the market for mass production. The type of zinc (Z or ZM) is determined by customer requirements. Extensive tests can be carried out to assist the customer regarding to the friction properties. The roughness, but even more the three-dimensional description of the surface texturing can provide helpful information regarding the friction conditions, whereby the roughness is determined discontinuously in the process, textures only in laboratory tests.
Figure 10. Friction behaviour of different coatings over production lifetime.

Beside the zinc coating type also the lubricant type and level, that is applied at least on the coil controls the gliding ability of the joint material. Figure 11 shows an example how the oil/lubrication level is measured online during the coil build up process.

Figure 11. Measuring of the oil/lubricant level in the production.
With this technology not only an information status at a certain location or time on the coil is available, but instead a complete overview on the coil. The oil film measurement (OFM) is a contactless online production technology. It is based on the Lambert Beer Law. It states that the thickness of an oil layer $d$ is directly proportional to the absorption of light $E_{\lambda}$.

$$E_{\lambda} = \log_{10}\left(\frac{I_0}{I}\right) = C \cdot d \quad (1)$$

The thickness of the oil or lubricant layer can be calculated:

$$d = \log_{10}\left(\frac{I_0}{I_{\lambda}}\right) \cdot \frac{1}{C} \quad (2)$$

If the oiled strip surface is illuminated by a light with an intensity $I_0$, part of the light is reflected by the metal surface. On their way, the light rays pass through the oil layer twice. In this process, the intensities of specific wavelengths of the light are attenuated by the oil. The intensity $I_{\lambda}$ of the transmitted light is measured. $E_{\lambda}$ is a spectral extinction and is oil type specific and $C$ is the substance quantity concentration.

In practical applications, special lamps are used as light sources. Only a small number of characteristic wavelengths in the mid-infrared range (MIR) of the electromagnetic spectrum are affected by the oil and evaluated accordingly [16].

### 4. Digital manufacturing supervision in steel coil productions

The mechanical joining process require joining material properties concerning well-adjusted thickness, strength, and friction, compared to figure 1. These material parameters are influenced at different steps in the process and are both measured directly by meter and provided outside production. A comprehensive quality system records these parameters for each strip and provides them in a visualisation and evaluation tool. By linking all production processes, even complex correlations can be identified and optimal solutions for the final product can be created at the actual coil in production. Through such findings, relevant data can be linked to the strip and used for direct process modification at the subsequent stage. Examples are internal strip joining parameters based on the steel analysis, varied annealing temperatures or rolling forces due to different process routes or steel analyses. The aim is always to set the best mechanical or technological properties and general qualitative parameters with as little variation as possible. At Salzgitter AG, DEWuQ (Datasystem to Develop Materials and Quality) was developed for that purpose.

Figure 12 illustrates a life cycle of a data mining project [11]. DEWuQ as a typical representative owns most of its functions. The system is a methodical framework based on data mining for predicting the physical quality of intermediate products in interlinked coil manufacturing processes. Technological and temporal restrictions limit physical product quality inspections to the final process step. As internal material defects cannot be monitored by external state-of-the-art sensors, quality deviations must be identified as early as possible in real time by data mining on distributed sensor measurements along the process chain. First, a selection is needed to allocate only data that determine the quality. Therefore, data mining algorithms are used with un- and supervised data. At the data pre-processing, the data were cleaned (e.g. rolling force signal is filtered and rounded), transformed (e.g. first derivation of rolling force signal after time) and an attribute selection takes place (e.g. specific changes in the rolling force over time derivation). To interpretate these data a modelling is needed. One concept are unsupervised learning and clustering models. They are often used as a first step in data mining for getting an impression of patterns and relationships in complex date sets. Clustering algorithms divide a set of observations into groups with similar properties. Featured values are all numeric and can be interpreted as points in a metric space. Given a set $X = \{\bar{x}_1, ..., \bar{x}_n\}$ of $n$ observations represented by data points in a $p$-dimensional Euclidean space, e.g. $\bar{x}_i = \{\bar{x}_{i1}, ..., \bar{x}_{ip}\}$, $\bar{x}_i \in \mathbb{R}^p$ the dissimilarity between to observations $\bar{x}_d$ and $\bar{x}_p$ can, for instance, be measured by the Euclidean distance. A selected algorithm can now display similarities over the Euclidean distance in a cluster.

Supervised methods are used if some observations can already be labelled according to a know target concept and a rule or function for this assignment should be learned from the data. Given distinct class
labels, the Naïve Bayes [17] classifier predicts the class of a given observation $\mathbf{x}_i$ based on the prior probability $p(C)$ of the class and $p(x_{i1}, ..., x_{ip} | C)$, the likelihood of the feature values given the class $C$

$$p(C | x_{i1}, ..., x_{ip}) = \frac{1}{Z} p(C) \prod_{j=1}^{p} p(x_{ij} | C)$$  

(1)

$Z$ is a normalization constant and can be ignored for classification. The probabilities are estimated from the set of labelled observations. Predicted is usually the class with the highest estimated probability.

The following interpretation is based first in data visualisation where the possible correlations of the modelling are displayed, e.g. a correlation between material strength and rolling force. The evaluation decides whether the mathematically ascertained correlation is valid in real production, so afterwards a decision support is possible in the deployment.

---

**Figure 12.** Life cycle of a data mining project; based and modified on [11]: DEWuQ as a typical representative of data mining industrial production systems.

The DEWuQ system helps to analyze complex interactions between different process steps in the coil build up which are invisible or unknown until yet. It is the master digitalization tool for the future to improve quality of actual steels any further and to introduce new, more sensitive materials in production.

5. Summary and Conclusion
Performed clinching and self-pierce riveting experiments with steel grades with similar but clear distinguishable properties have shown the high sensitivity of those mechanical joining technologies regarding the joining material. It could be presented that only small changes at the friction-, yield strength-, ultimate strain- and solidification behaviour have major impact on the joining quality and resulting joint properties. Automated productions who uses clinching and self-pierce riveting techniques require fine-tuned joining material properties for a safe joining process. Safe means a high repeatability and robustness of the joining process. Therefore, the steel manufacturer has to implement a quality control system. At the example of a hot-dip galvanizing process the relevant measuring techniques are presented. As not all coil properties could be directly measured, advanced analytics were used. A data
mining system, like DEWuQ can control a complex manufacturing line and offer customer specified material properties for a safe mechanical joining process.

6. Outlook

Today, the life cycle of data mining projects is restricted to a certain production line or company. If compliance and corporate policy aspects are solved how to handle those specific data, a further exchange to customers is possible. They can use those data to

References

[1] Groche P, Wohletz S, Brenneis M, Pabst C and Resch F 2014 Joining by Forming—a Review on Joint Mechanisms, Applications and Future Trends Journal of Materials Processing Technology vol 214 (Amsterdam: Elsevier) pp 1972–1994
[2] Füssel U and Wittke K 2013 Kombinierte Fügeverbindungen vol 3 (Heidelberg: Springer)
[3] Mucha J and Witkowski W 2014 The Clinching Joints Strength Analysis in the Aspects of Changes in the Forming Technology and Load Conditions Thin-Walled Structures vol 82 (Amsterdam: Elsevier) pp 55–66
[4] Mori K and Abe Y 2018 A Review on Mechanical Joining of Aluminium and High Strength Steel Sheets by Plastic Deformation Int. Journal of Lightweight Materials and Manufacture vol 1 (Amsterdam: Elsevier) pp. 1–11
[5] Dietrich J 2018 Praxis der Umformtechnik vol 12 (Heidelberg: Springer) pp 299–317
[6] Busse S 2012 Self-Pierce Riveting Mercedes-Benz Norm 10361-I (Sindelfingen: Daimler AG)
[7] Busse S 2012 Clinching Mercedes Benz Norm 10453-I (Sindelfingen: Daimler AG)
[8] Varis J 2006 Ensuring the integrity in clinching process Journal of Materials Processing Technology vol 174 (Amsterdam: Elsevier) pp 277–285
[9] Khrebtov P 2011 Neuartiges Verfahren zur Online-Prozessüberwachung und Fehlerklassifizierung beim Durchsetzfügeverbinden von Blechen (Clausthal-Zellerfeld: Papierflieger)
[10] He X., Zhao L and Ball A 2014 Investigations of Strength and Energy Absorption of Clinched Joints Computational Materials Science vol 94 (Amsterdam: Elsevier) pp 58–65
[11] Lieber D, Stolpe M, Konrad B, Deuse J and Morik K 2013 Quality Prediction in Interlinked Manufacturing Processes Based on Supervised and Unsupervised Machine Learning Proc. CIRP of the 46th CIRP Conf. on Manufacturing Systems (Setubal) vol. 7 (Amsterdam: Elsevier) pp 193–198
[12] Elsaadawy E A, Hanumanth G S and Balthazaar J R 2007 Coating Weight Model for the Continuous Hot-Dip Galvanizing Process Metallurgical and Material Transactions B vol 38 (Berlin Heideberg: Springer) pp 413–424
[13] Abe Y, Kishimoto M, Kato T and Mori K 2009 Joining of Hot-Dip Coated Steel Sheets by Mechanical Clinching Int. Journal of Material Forming vol 2 ed E Chinesta (Heidelberg: Springer) pp 291–294
[14] Raab A E, Berger, E and Freudenthaler, J 2012 ZnAlMg Hot-Dip Galvanised Steel Sheets – Tribology and Tool Wear BHM Berg- und Hüttenmännische Monatshefte vol 157 ed G Mayer (Berlin Heidelberg: Springer) pp 126–131
[15] Abe Y, Ishihata S, Maeda T and Mori K (2018) Mechanical Clinching Process Using Preforming of Lower Sheet for Improvement of Joinability Proc. Manufacturing vol 15 (Amsterdam: Elsevier) pp 1360–1367
[16] Bilstein W, Enderle W, Moreas G, Oppermann D, Routsock T and Van De Velde T 2006 Two Systems for On-Line OilFilm and Surface Roughness Measurement for Strip Steel Production Steel Rolling Conference (Paris) Revue de Métallurgie vol 104 (Les Ulis: EDP Sciences) pp 348–353
[17] John G H and Langley P 1995 Estimating continuous distributions in Bayesian classifiers Proc. of the 11th Conf. of Uncertainty in Artificial Intelligence (San Francisco) pp 338–345