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# Heat Treatment and Distortion – Challenge for Aircraft Industries

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Heat treatment takes place in a lot of serial processes for manufacturing in aircraft industries. However the occurring contour deviations have to be re-shaped with extensive procedures before assembling. The experiences already show that the distortion behavior of the complex parts can be influenced significantly by new materials, changes in design or process parameters. Due to the fractional knowledge about the interaction of the parameters within the whole process chain, the impact on the final distortion behavior is mostly only roughly assessable. If distortion exceeds given limits concerning contour deviations cannot be re-shaped completely with established procedures. This leads to an increasing assembling effort or even scrapping of the part. To minimize the effort for re-shaping and to predict the distortion behavior especially of welded structural parts a systematic analysis of the whole process chain was done in view of distortion potentials in cooperation with Airbus. Selected parameters of the process steps milling, welding and heat treatment were quantified regarding their significance on distortion by design of experiments (DoE). The results confirm the assumption that not only one process is responsible for the occurrence of contour deviations. In fact the processes interact with each other and distortions can be reduced by a well-directed adjustment of process parameters and design.

***Keywords:*** *Distortion Engineering, Aluminum, Process chain, Process interactions, Heat treatment.*

## 1. Introduction

Thermal joining in combination with heat treatment was successful integrated in serial production of structural parts for aircraft industries [1, 2]. But the contour deviations which were occurred after final heat treatment have to be reshaped with additional extensive processes. Today experiences show already that implementation of new materials, changes in design or even process parameters may take strong influence on the distortion behavior of the complex structure components. Because of today's lack of knowledge of the interactions of the different process setups, only an insufficient prediction of the contour deviations is possible, if the process setup will be changed.

To minimize the effort for re-shaping of today's components and to predict distortions of future designs a research project in cooperation with Airbus was launched within the framework of the Collaborative Research Centre "Distortion Engineering" (SFB 570) which is funded by the Deutsche Forschungsgemeinschaft (DFG). Basic principle of this project is the holistic view of distortion, which requires an analysis of the whole process chain [3, 4]. The analysis of the process chain for manufacturing cylindrical fuselage skin panels in view of so-called distortion potentials [1, 2] shows, that the processes surface machining, laser beam welding and heat treatment mainly influence the final distortion (alteration of size and shape) [5]. Based on these results, running investigations are focused on the influencing parameters of machining, welding and final heat treatment on the distortion.

## 2. Experimental setup

In order to investigate the interaction of machining, welding and heat treatment Al-sheets (6xxx alloy) with a width of 100 mm and a length of 480 mm were machined in a first step. The stringer profiles were joined on the sheets with a $CO_2$-Laser on both sides (Fig. 1a). Finally the heat treatment was realized by aging process typically for the accordant alloy.

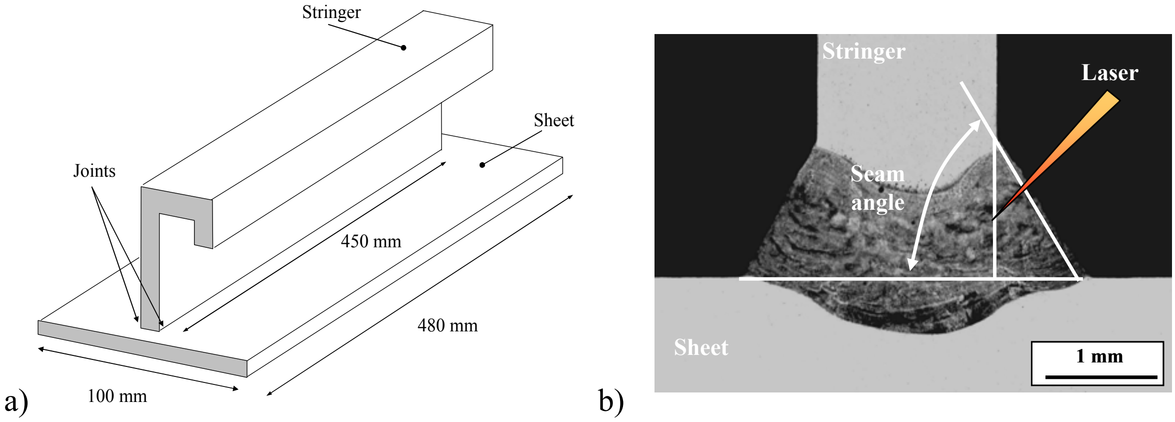



Fig. 1: Welding sample (a) and sketch of seam angle/joining position (b)

A partly factorial experimental design ($2^{7-3}$, resolution IV) [6] was developed to detect the significant influencing parameters on the longitudinal distortion of stringer-sheet joints. Herein the parameters “feed rate” during machining, “finishing” (with/ without) , “sheet thickness”, “orientation” of rolling direction to the welding direction, “seam angle” (see also Fig. 1b), “volume of filler wire” (serial standard / less than 30% of serial standard ) and the “clamping” (vacuum clamping with mechanical clamping on both sides / only one side ) were varied in two steps close to the serial process (Table 1). For the experiments sheets with different initial thickness were used: ~ 7 mm were reduced by milling to 4.0 mm thickness and 3.2 mm sheets which were reduced by milling to 2.4 mm. Thereby the rolling direction is equal to the milling direction. For statistic coverage four samples of each system were welded.

Table 1: Process parameters

| **Parameter** | **Value 1** | **Value 2** |
|---|---|---|
| Feed rate | 10 m/min | 13 m/min |
| Finishing | With | Without |
| Sheet thickness | 2.4 mm | 4.0 mm |
| Orientation | Rolling direction parallel to the welding direction | Rolling direction vertically to the welding direction |
| Seam angle | lower limit | upper limit |
| Volume of filler wire | serial standard | less than 30 % of serial standard |
| Clamping | Vacuum, both sides mechanical clamping | Vacuum, one side mechanical clamping |

After the single process steps the bending in longitudinal direction of the samples were tactilely measured on the backside of the sheet on the joint position in longitudinal direction (Fig. 2).

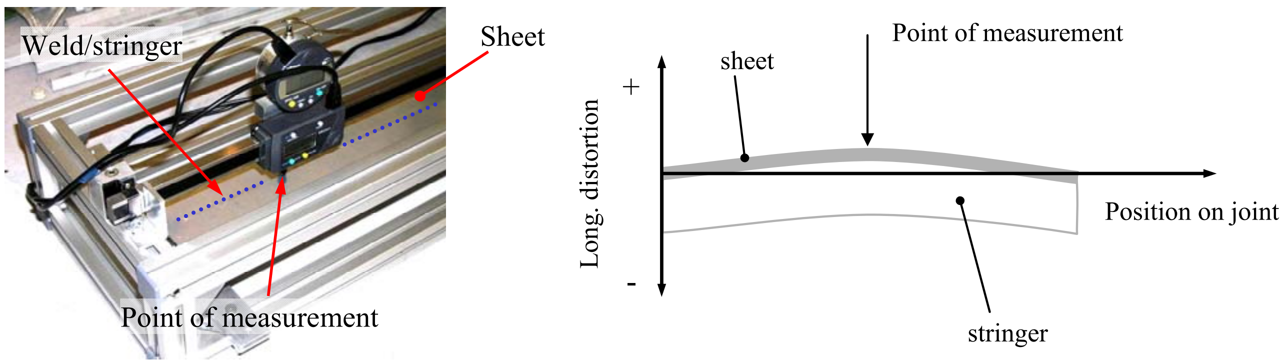



Fig. 2: Measurement of longitudinal distortion

## 3. Results

The analysis of the experiments shows that most of the process parameters have a significant influence on the distortion and confirmed the assumption of interaction of the single processes (Fig. 3). After milling the parameters “feeding rate” (of 13 m/min), “finishing” (with) and “sheet thickness” (of 4.0 mm) decrease significantly the longitudinal distortion, however only the parameter “finishing” (with) and “sheet thickness” (of 4.0 mm) also affect the subsequent processes. Thereby the effect of the “sheet thickness” has the opposite sign after the welding operation. Additionally a low “seam angle” has a nearly constant positive effect on the contour deviation before and after heat treatment. However, the “orientation” of the rolling respectively milling direction in view to the weld does not effect the distortion till the final heat treatment. If the joint is placed vertically to the rolling direction, the contour deviation will be reduced after heat treatment.

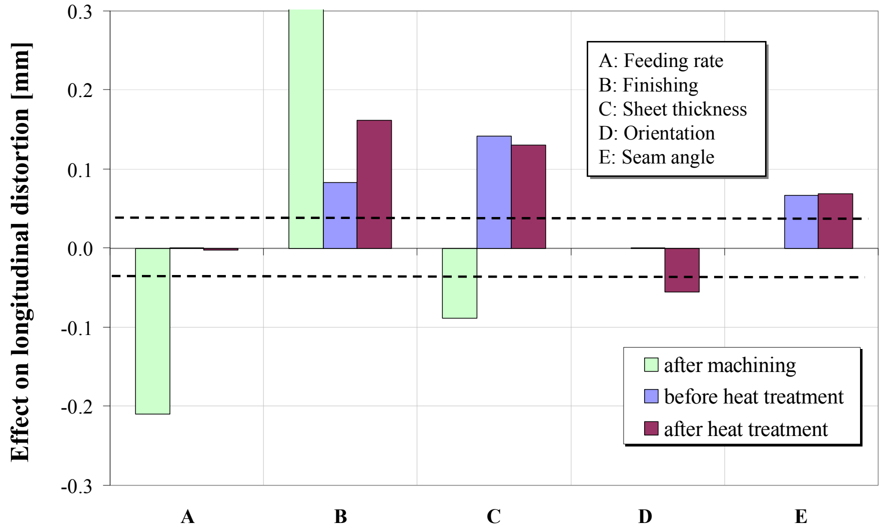



Fig. 3: Analysis of the DoE

Further analysis of the influencing parameters reveals their impact on the longitudinal distortion. The influence of “feeding rate” and “finishing” on distortions were mainly caused by inhomogeneous residual stresses which were already discussed elsewhere [7, 8]. This applies also to the observed impact of the sheet thickness [9] where inhomogeneous temperature distributions lead to tensile residual stresses.

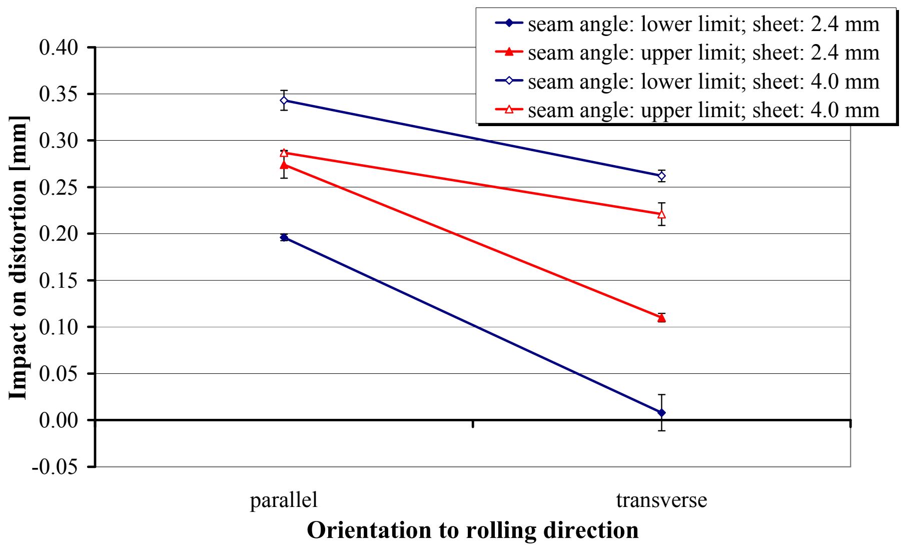
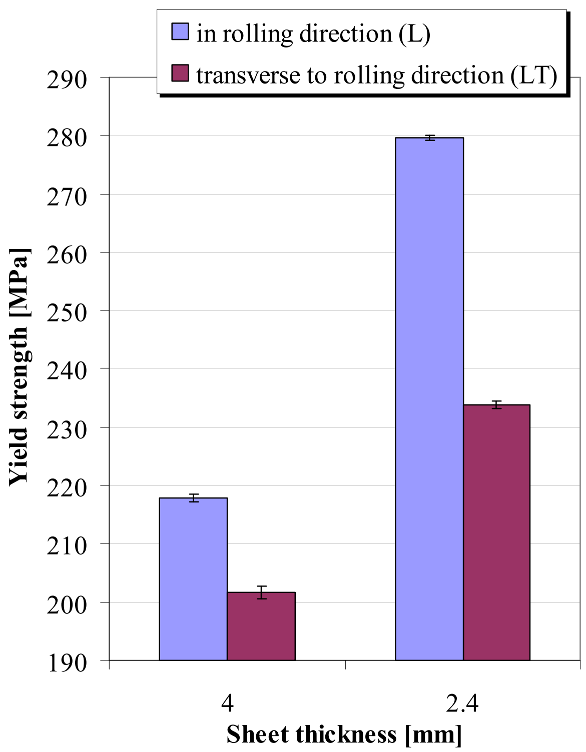



Fig. 4: Impact and interaction of orientation and seam angle

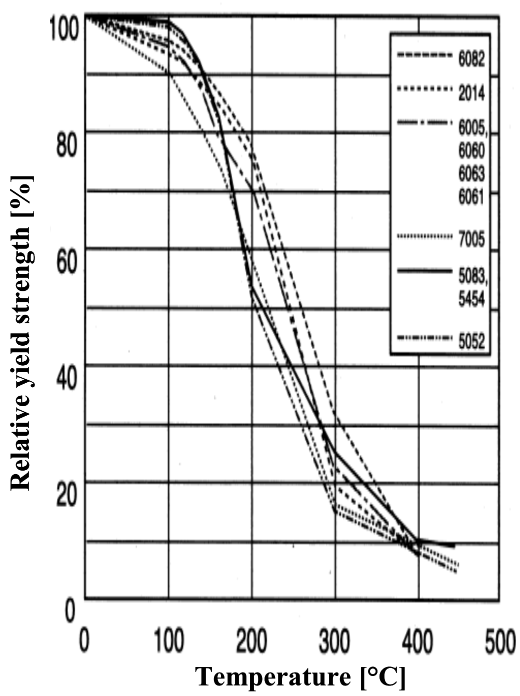
The interaction of the parameters "orientation" and "seam angle" is displayed more detailed in Fig. 4. An increase of shape deviations can be observed for all samples after welding in rolling direction but the influence on the distortion is lower for thicker sheets, although the contour deviations rise with increasing sheet thickness. The diagram shows additionally a decrease of longitudinal distortion with diminishing seam angle. Consequently the minimum longitudinal distortions can be reached by welding thin sheets transverse to the rolling direction with a low seam angle.

## 4. Discussion

The results of the experiments show a significant influence of the "orientation" of the rolling direction in view of the weld (Fig. 3 and Fig. 4). In view of the precise compliance of the experimental parameters it can be assumed that the residual stresses, which accumulate during the whole machining, have nearly the same level, apart from differences in the orientation of the main stress directions during milling in view of their position to the welding direction. Due to the fact, that the rolling direction is equal to the feed direction during milling, the influence of the rolling direction will therefore be superposed by the main stress direction. Consequently slightly higher residual stresses can be expected, if the rolling direction is transverse to the welding direction. The fact, that this distortion potential is not activated till the final heat treatment suggests the presence of a rolling texture within the used sheet material. Tensile tests, which were conducted after milling for the two sheet thicknesses confirm this suggestion (Fig. 5a). The results of the tensile tests display a decrease of the yield strength transverse to rolling direction on the one hand side and but also a correlation of rolling direction and sheet thickness on the other hand side. In this context the dependence of the rolling direction is more distinct for thinner sheets.




a) Yield strength vs. rolling direction




b) Yield strength vs. temperature [10]

Fig. 5: Yield strength vs. rolling direction (a) and influence of heat treatment on yield strength (b)

Based on the fact, that residual stresses above the yield strength will be relieved by distortion, the observed influence of rolling direction on the yield strength of the sheets leads to an increased distortion potential transverse to the rolling direction. During the final heat treatment at aging temperatures of about 200 °C the yield strength is reduced by approximately 20 % to 25 % in the beginning of the aging process (Fig. 5b). Therefore the residual stresses, which accumulate during machining of the samples, will be relieved in different levels during the final heat treatment. Because of the higher yield strength of the thinner sheets less residual stresses will be relieved in comparison to the thicker sheets. The same correlation applies to the different orientation of the weld in view to the rolling direction.

## 5. Summary and conclusions

Experimental investigations were performed in order to ascertain the distortion mechanism and process interaction for machined, welded and heat treated Aluminium samples. The analysis of the design of experiments indentified “finishing” (with/ without), “sheet thickness” and “seam angle” as significant process parameters after welding. After heat treatment the “orientation” of the rolling direction to the welding direction causes also a significant effect on the longitudinal distortion. The residual stresses, which accumulate during the whole machining and finally relieve during the final heat treatment, were identified as most important mechanism for the distortion. Thereby further investigations are necessary to confirm the assumption, that the residual stresses after machining are higher in transverse direction of the feeding.

Apart from this fact the experiments already show, that the longitudinal distortion can be reduced by a finishing during milling in combination with a low seam angle during welding. Relating to the design of weld, the distortion can be reduced with thin sheets and a transverse orientation of the joint in view of the rolling and milling direction. Although the sheet thickness is mostly given by the weight optimized design for the structural parts in aircraft industries. Furthermore the orientation of the rolling direction to the welding direction depends from the size of the structural parts. Parts with more than 2.5 m in length allow in most of the cases only a parallel orientation of the rolling direction and welding direction. In that case, reduced yield strength in rolling direction and a less dependency from the rolling direction will be reducing the longitudinal distortion.

## 6. Acknowledgement

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