

# MECHANICAL TENSIONING – AN INNOVATIVE METHOD TO IMPROVE THE DAMAGE TOLERANCE OF LASER WELDED ALUMINIUM SKIN-STRINGER JOINTS IN AIRFRAMES.

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The mechanical tensioning (MT) method is a highly promising approach to improve the damage tolerance behaviour of welded skin-stringer joints by the control of the welding induced residual stresses. This paper reports the first results on the application of mechanical tensioning on dual laser beam welded AA6013 fillet joints. The working principle of the mechanical tensioning approach is described and the results of numerical welding simulations, distortion and residual stress measurements are presented. Fatigue crack propagation experiments on the manufactured specimens are currently running and will be subject of the next communication.

## 1. INTRODUCTION

Laser beam welded (LBW) advanced Al-alloy structures are increasingly used in aircraft airframes. The A318, A340 as well as the A380 aircrafts manufactured by Airbus are currently using LBW panels in the lower fuselage area [1]. The production costs, weight reduction as well as reduced number of parts etc. are well-proved and hence accepted as major benefits of the LBW technology [1]. Currently the crack retarding capacity of welded skin-stringer-panels is inferior compared to the capacity of riveted or bonded differential designs. However, the damage tolerance behaviour of the welded parts (which behave as an integrally stiffened panel) needs to be further improved for wider use of this technology. It is well known, that residual stresses have a great impact on fatigue performance of welded structures [2]. “Mechanical tensioning” is a very promising approach, because it allows modifying the welding induced residual stresses by the superimposition of a static elastic load during the welding process as shown in Fig. 1. By this method, it is possible to reduce the welding induced longitudinal tensile residual stresses significantly [3] or by using high pre-stretching forces even one can introduce compressive residual stresses locally in the welded structure [4].

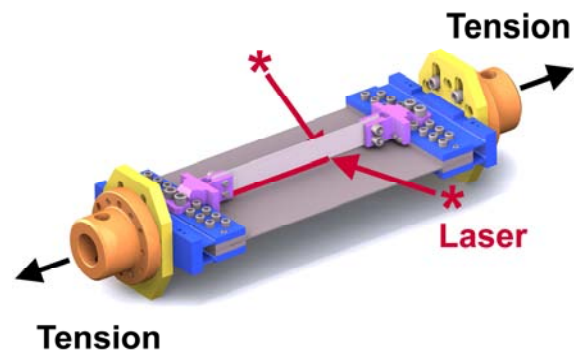


Fig. 1: Principle of mechanical tensioning during laser beam welding of skin-stringer joints to improve damage tolerance properties of such configurations.

## 2. WORKING PRINCIPLE OF MECHANICAL TENSIONING

The basic idea of mechanical tensioning is as easy as effective. During the welding process the parts to be joined are elastically pre-stretched parallel to the weld line. By this procedure a static tension field is generated that suppresses a part of the normally, by thermal expansion, induced plastic yielding in the seam area.

Depending on the pre-stretching force, welding induced harmful tensile residual stresses can significantly be decreased, as shown by simulations and experiments on the example of simplified AA6013 skin-stringer joints in the sections 3 and 4. By increasing the applied force it will be even possible to locally induce compressive residual stresses in the seam area as shown by numerical estimations at the end of section 4. In this way mechanical tensioning can be utilized to tailor the welding induced residual stresses and hereby:

- Avoid large “out-of-plane” distortions in thin walled welded structures and
- Employ a favorable residual stress state with regards to the fatigue performance of the welded structures

Since most of the research work on the so called “tensioning approaches” was so far focused on the first item [4 - 6]. The present, ongoing work addresses to the second item, as mentioned above.

## 3. LASER BEAM WELDING OF THE SPECIMENS UNDER MECHANICAL TENSIONING

A laboratory scale experimental set-up to weld aluminum skin-stringer joints under mechanical tensioning was built up (Fig. 2). The sheets are pre-stressed in a tensile testing machine mounted in a specially designed clamping system. This set-up was used to dual laser beam weld aluminum alloy 6013 fillet joints under different tensioning scenarios and forces. Pre-stretching was applied to the “skin-sheet”, the “stringer-sheet” or both in the same time.

Specimens were welded for the reference configuration without pre-stretching, with pre-stretching of 50 MPa and 100 MPa for each configuration. Accompanying optical distortion measurements and thermocouple measurements were carried out to visualize the impact of mechanical tensioning on the welding induced “out-of-plane” distortions and to provide further input for structural welding simulations as described in section 4. Due to the rather limited pre-stretching forces of 50 kN provided by this set-up, currently a new loading frame with a nominal capacity of 1000 kN is under construction.



Fig. 2: Specimen *in mechanical tensioning set-up equipped with thermocouples.*

#### 4. MODIFICATION OF THE WELDING INDUCED DISTORTIONS AND RESIDUAL STRESSES

##### Experimental Results

Optical 3d surface measurement systems are today state of the art to monitor welding distortions. Since the induced distortions are directly coupled to the welding induced residual stresses, distortion measurements are normally seen as fastest and easiest way to validate structural welding simulations. Additionally, residual stress measurements of welded structures are normally time intensive and expensive, since for reliable results special techniques as neutron- or synchrotron diffraction are needed [7-9].

In the presented work for all specimens optical distortion measurements have been carried out. Residual stresses on two specimens were measured using the neutron diffraction technique. In Fig. 3 the results of the optical distortions measurements are presented for two cases. Later in this section in Fig. 7 measurement results for all different experimental cases can be found. It could clearly be shown that by mechanical tensioning for two scenarios (skin-sheet only; stringer- and skin-sheet) the welding induced “out-of-plane” distortions were significantly reduced. By applying a load of 100 MPa during the welding, the maximum distortions dropped from approx.  $\pm 2.7$  mm to  $\pm 1.4$  mm. **Hence, for the laser beam welding of aluminum skin-stringer joints, mechanical tensioning provides the possibility to effectively reduce welding induced distortions.**

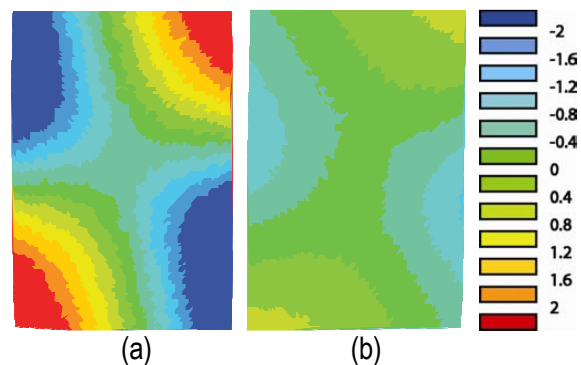


Fig. 3: Measured “out-of-plane” distortion in millimetres for (a) a reference panel without pre-stretching and (b) a panel with 100 MPa pre-stretching each skin and stringer.

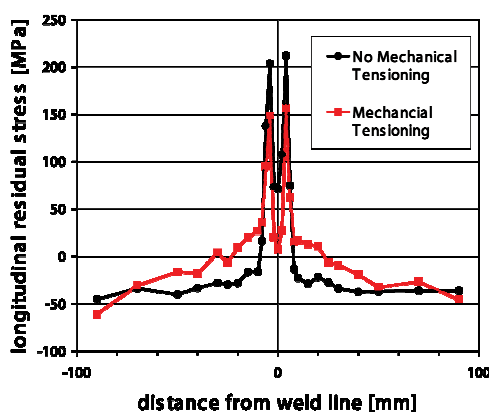


Fig. 4: Longitudinal residual stresses in two welded specimens [3]. Note: For clarity no error bars are shown, the average standard deviation is about 12-15 MPa.

Encouraged by this results, residual stresses were measured in two laser beam welded T-joints (Fig. 4). One specimen was welded without mechanical tensioning; the other was welded while pre-stretching the “skin-sheet” with 100 MPa. The Al (311) reflection was measured at a wave length of 1.64 Å. The nominal size of the gauge volume was 1.5 mm × 1.5 mm × 30 mm. A cubic gauge volume was used for longitudinal strains, but the gauge volume was moved in longitudinal direction during the measurement to cover approximately the same volume as for the other two directions and improve grain statistics. **It could be shown that at a pre-stretching stress of 100 MPa the harmful high tensile stresses in the whole weld seam area could be decreased by approx. 60 MPa.**

### Numerical welding simulations

In order to overcome the experimental limitations with regards to the maximum stretching forces and beam line accessibility the commercial welding simulation software SYSWELD was used to model the effect of mechanical tensioning on the welding induced residual stresses for all experimental tensioning scenarios and one virtual scenario of higher mechanical tensioning stresses.

The developed numerical model consists of around 180.000 elements. First a transient thermal-metallurgical analysis with two moving 3d conical Gaussian heat sources was performed in order to simulate the dual laser

beam welding process [10]. Dependent on the local thermo cycles the change in material properties is modeled by the metallurgical part of the analysis on the basis of a standard material database for the AlMgSi alloy family. Both transient mechanical property and temperature fields acted as input for the next simulation step, a transient mechanical analysis. On basis of the temperature fields (Fig. 5) local thermal expansion fields were calculated for each time step and fed into the mechanical analysis as pre-defined strain data. Additionally the local mechanical properties were changed for each step on basis of the metallurgical analysis.

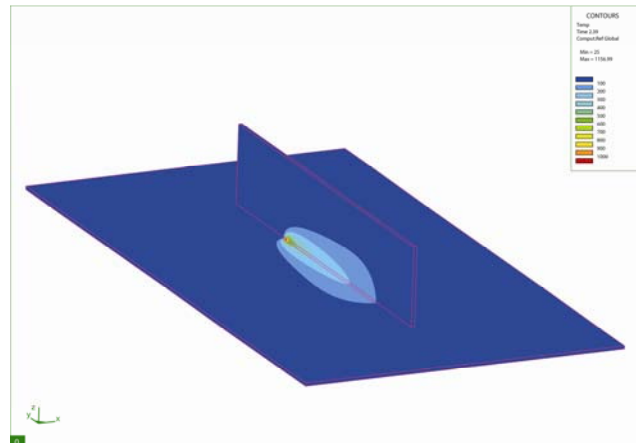


Fig. 5: Calculated surface temperature field for one time step in the transient welding simulation.

### Validation of the numerical model estimations

During the welding temperature field measurements were carried out. Twelve thermocouples were placed in the middle of a specimen, six on each side of the weld line. Fig. 6 shows the comparison between those measurements and the numerically estimated thermo cycles via transient thermal FEM analysis. **The simulated temperature fields show very good agreement with the measurements.** It is important to note that a best possible capturing of the real experimental thermo cycle in the simulation is a key to obtain reasonable distortion and stress estimations.

In Fig. 7 the measured and numerically estimated “out-of-plane” distortions for all experimental configurations are shown. **The simulations estimate the induced “out-of-plane” distortions with a very good accuracy.**

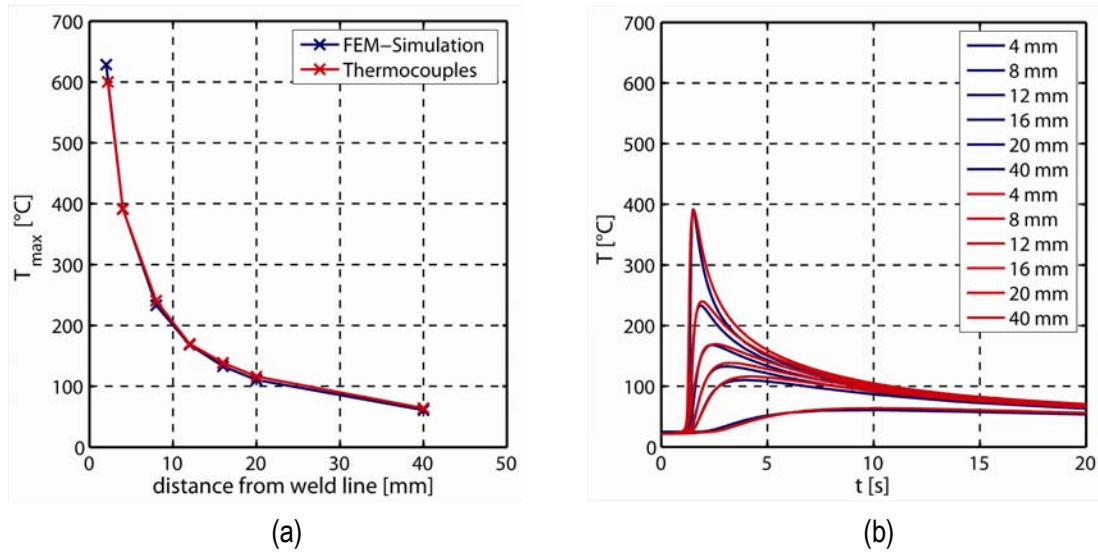


Fig. 6: Validation of calculated thermo cycles by comparison with thermocouple measurements (a) reached peak temperatures as function of the distance from the weld line (b) complete transient thermo cycles. Simulation and measurement show a very good agreement.

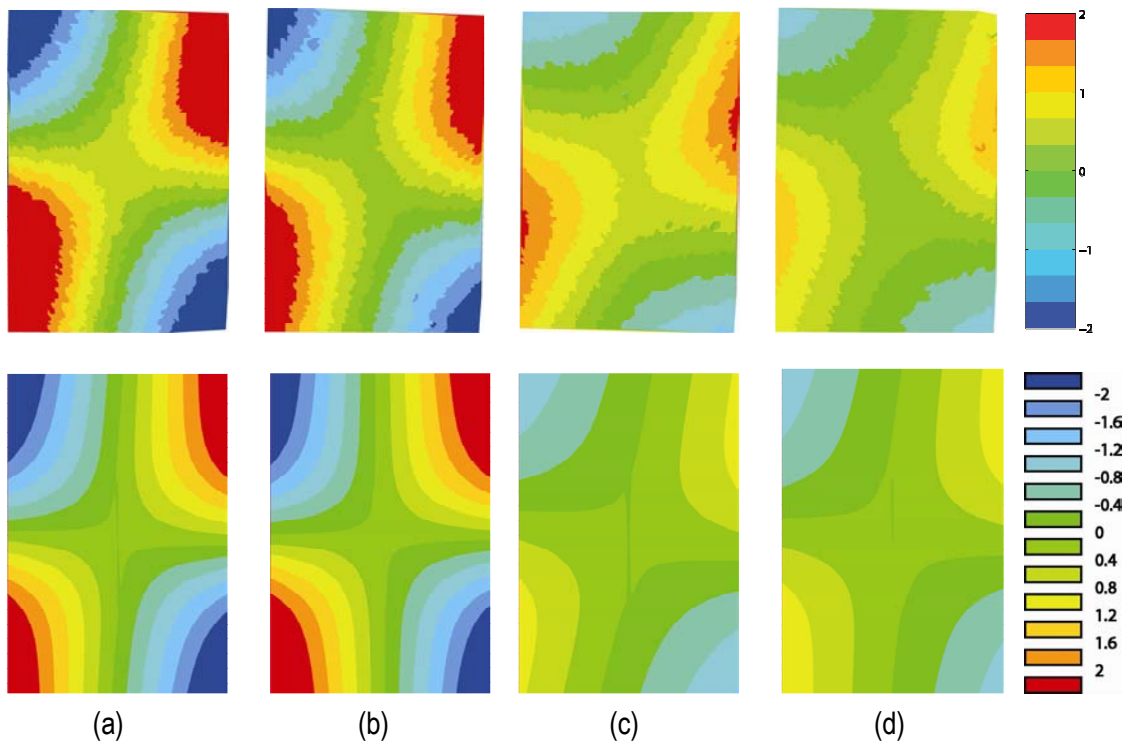


Fig. 7: 'Out of plane' distortion in millimetres, top row measured and bottom row simulated data (a) untensioned reference panel and (b) tensioned stringer 100 MPa (c) tensioned skin 100 MPa (d) tensioned skin and stringer each 100 MPa. Measurement and simulation results use the same colour code and are in very good agreement.

In Fig. 8 the comparison between the residual stress measurements and the simulated stress fields is shown. The simulation is able to capture the effect of mechanical tensioning on the welding induced residual stresses. Both measurement and simulation exhibit the typical double peak structure for the longitudinal residual stresses. The largest discrepancy is seen in the depth of the valley between the two stress maxima. Here the simulation is slightly overestimating the measurements. The amount of overestimation is approx. the same for both measurements. Physically this valley is linked to the local softening of the material during the thermo cycle. This could indicate that the used standard material database is not capturing that behaviour for AA6013 correctly and some further improvement of the used material models is needed. **Altogether the experimentally measured and simulated residual stresses are in excellent agreement.**

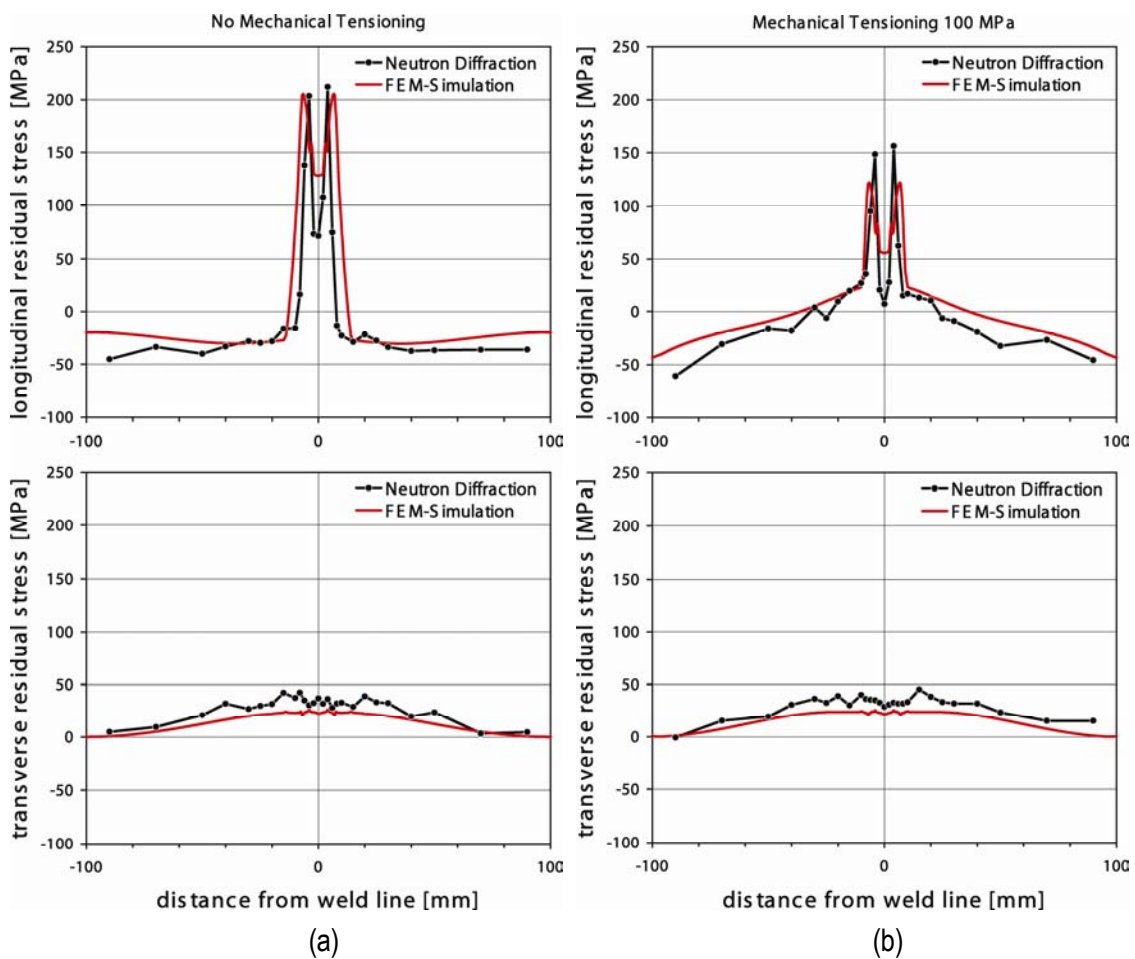


Fig. 8: Longitudinal and transverse residual stresses across the weld line in the skin-sheet for (a) an untensioned reference specimen and (b) mechanical tensioning of skin-sheet with 100 MPa. Shown are the FEM-estimations (red) and the neutron diffraction measurements (black), both are in very good agreement.

### Virtual numerical experiment with higher tensioning forces

In Fig. 9 the numerical estimated stress field for the virtual case of mechanical tensioning the skin and stringer sheet each with 190 MPa is shown. In combination with the used material data, higher tensioning stresses would not be appropriate. It can be seen that **with increasing tensioning stresses, the longitudinal residual tensile stresses will be further decreased** and that it should be possible to introduce compressive residual stresses in the weld area. Additionally, the induced “out-of-plane” distortions can nearly be fully mitigated.

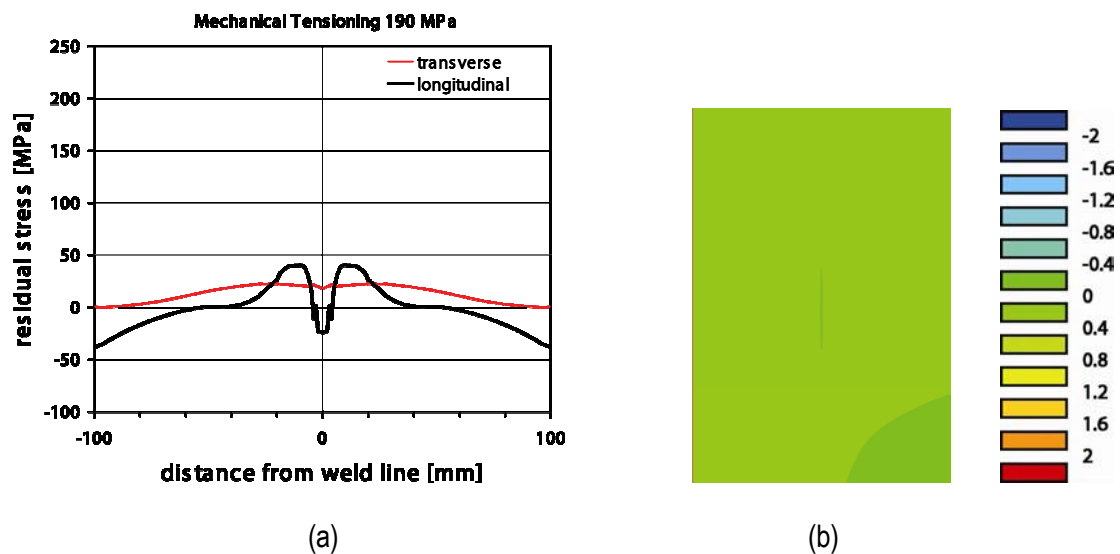


Fig. 9: (a) Simulated longitudinal and transverse stresses for the case of tensioning skin and stringer sheet each with 190 MPa (b) simulate “out-of-plane” distortion for this case.

## 5. CONCLUSIONS

This work showed the possibilities to use mechanical tensioning as a tool to effectively modify welding induced residual stresses and distortions on thin sections. Additionally, it was shown that numerical simulation can provide a good way to estimate the modified residual stresses using the mechanical tensioning technique.

In summary,

- Mechanical tensioning provides an effective way of mitigate welding induced distortions in dual laser beam welded skin-stringer joints.
- As proven by neutron diffraction experiments, by using mechanical tensioning, the welding induced tensile residual stresses can significantly be reduced.
- The numerical estimations for the welding induced stresses and strains showed a very good agreement with the experimental data. The simulations could capture the effect of mechanical tensioning.

- The tool of structural welding simulation also showed its capability to virtually overcome experimental limitations and give valuable information on how to design further experiments. The results showed that with increasing pre-stretching stress it should be even possible to induce locally compressive residual stresses in the weld area. This is believed to create a very favourable situation regarding fatigue crack initiation and growth in the seam area.

Since, there are complex interactions and redistribution effects connected with residual stresses and especially fatigue crack propagation, the impact on the fatigue performance needs to be clarified by experiments and numerical estimations. Fatigue experiments on the fabricated specimens are running currently and the results will be presented in a next communication.

## 6. REFERENCES

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