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RESEARCH ON REDUCING RESIDUAL STRESSES OF SLM PARTS MADE FOR DOWNSTREAM WELDING PROCESS

Fabian EICHLER, Nicolae BALC, Sebastian BREMEN, Markus SCHLESER, Alexander SCHWARZ

Abstract: *In the face of the current trend towards larger and more complex production tasks in the SLM process and the current limitations in terms of maximum build space, the welding of SLM components to each other or to conventionally manufactured parts is becoming increasingly relevant. The fusion welding of SLM components made of 316L has so far been rarely investigated and if so, then for highly specialised laser welding processes. When welding with industrial gas welding processes such as MIG/MAG or TIG welding, distortions occur which are associated with the resulting residual stresses in the components. This paper investigates process-side influencing factors to avoid resulting residual stresses in SLM components made of 316L. The aim is to develop a strategy to build up SLM components as stress-free as possible in order to join them as profitably as possible with a downstream welding process. For this purpose, influencing parameters such as laser power, scan speed, but also scan vector length and different scan patterns are investigated with regard to their influence on residual stresses.*

Key words: *Additive Manufacturing; LPBF; SLM; Welding; Hybrid Manufacturing; Residual Stresses*

1. MOTIVATION

In the development of Selective Laser Melting (SLM) technology (which is also called Laser Powder Bed Fusion LPBF), integration into existing manufacturing process chains is becoming increasingly important. In the ongoing industrialisation of the SLM additive manufacturing process, the ability to combine it with conventional manufacturing processes is also a deciding factor for users. Joining solutions are therefore increasingly gaining in importance. While the SLM process itself has been extensively researched, the possibilities of joining have only been explored by a small number of researchers. Finding the right joining solutions would make SLM technology more accessible, especially to small and medium-sized enterprises.

Among these solutions, welding is the most promising. There are many reasons why welding of additive metal parts is necessary and of great importance for the future. They can be divided into several dimensions:

- Financial benefits, especially for large scale applications
- Manufacturing requirements due to increased part complexity
- Opportunities in customised mass production

With the increasing demand for larger and more complex parts, there is a significant cost advantage to either separating the part into multiple components or printing only the complex regions of the part and welding them to conventionally manufactured regions. This not only reduces costs, but also avoids the constraints of build chamber size, which is currently the biggest limiting factor in large scale applications. These and other advantages make welding of SLM parts a very interesting topic.

2. INTRODUCTION

2.1 State of the art

A number of studies have been carried out to investigate the weldability and resulting part properties of SLM parts made from stainless steel, aluminium, titanium and nickel-based alloys.

Different materials present different technical challenges. When it comes to aluminium alloys, such as the widely used AlSi10Mg, the main welding challenge is porosity in the weld. [1–4] The reason for this has been investigated in several papers and appears to be the result of powder moisture and hydrogen induced pores. [3, 5]

In the case of nickel-based alloys, hot cracking susceptibility is the dominant challenge. [6–11]

For the widely used titanium alloy Ti-6Al-4V, on the other hand, hardening cracking is the main issue. [12–14]

This paper is focused on the welding of SLM parts made of the stainless steel alloy 316L. The first studies on the welding of 316L parts produced by SLM have been carried out in 2013. In general, all the research on the subject has shown that the good weldability of the feedstock material leads to good weldability of the 316L parts produced by SLM. This means that it is generally possible to weld 316L SLM parts using, for example, TIG welding, laser welding or even a hybrid welding process. [15, 16]

However, it can also be noted that there are some issues with the ductility of the welded joint and the tendency to warp or crack due to residual stresses. [17–19]

The as-built properties of the SLM produced 316L parts are different to those of the cold-rolled version. It can be seen that the yield strength is slightly higher than in the fed stock material and the ductility is lower. [19] Both properties are dependent on the direction of loading, as the as-built SLM parts show a strong anisotropic behaviour. Due to the high thermal gradients and higher cooling rates, the finer grain structure and the slightly epitaxial grain growth in the build direction are determining factors for the properties. This has to be considered for a downstream welding process. [20, 21]

The well-documented as-built properties form the basis for the investigation of welding solutions.

All the papers that have been published in this field contribute a different approach on the SLM side of the process or the welding process. Different specimens have been built and different tests for mechanical properties and microstructure have been carried out. In conclusion, some results are considered to be generally valid:

- There is no particular issue with porosity in the weld when the SLM parameters are controlled and approach 100 % relative density. [15, 18, 21, 22]
- The mechanical properties, that can be achieved with laser or TIG welding of SLM 316L are often in the range of conventionally manufactured stainless steel parts. Depending on the process parameters in SLM and welding, the Ultimate Tensile Strengh increases with slightly reduced elongation and ductility. [15, 19, 21, 22]
- When welding dissimilar joints the yield strength in the SLM base material is always the highest when compared to the yield strength of wrought or cold rolled 316L. [21]
- In many cases heat treatment such as annealing is recommended for the SLM part as preparation for the downstream welding process. [19, 21, 23]
- The orientation of the build-up direction of the SLM specimens in relation to the welding direction has an effect on the yield strength, elongation and fracture properties of the subsequent welded joint. [21]

Previous investigations at UTCN and FH Aachen - University of Applied Sciences have shown that not only the orientation of the SLM part itself plays an important role, but also the amount of residual stress in the specimens. High residual stresses can lead to distortion and cracking when the SLM part is confronted with a downstream welding process. [18]

The special properties of the SLM-process lead to the introduction of thermal stresses, which then result in residual stresses during cooling. The very high temperatures introduced into the built-up solid by the melting of a new layer lead to a temperature gradient there. The material is initially heated selectively and cannot expand, so that stresses arise. [24] The yield point, which is reduced by the increased temperature, can be exceeded. In this case, plastic deformation may occur. In the second step, the new molten layer and the heated area, of the solid material below, cool down. This means that the upper layers shrink. This shrinkage is hindered by the layers underneath. The resulting stresses can cause the component to deform away from the build platform in the direction of the laser. In the worst case, this can lead to detachment of the component from the build platform, or to cracks in the component. If no such external defects occur, because they have been prevented by supports, for example, a very high residual stress state may still be present in the component. This may only become apparent when the component is detached from the building platform or when heat is applied again. [24–28]

Welding SLM parts with high residual stresses can reduce the yield strength by heating the material. If the yield strength is lower than the residual stresses present in the material, plastic deformation will occur. The authors believe that in order to weld larger 316L SLM parts, it is essential to reduce the residual stresses in the SLM part.

A large number of research studies have already been carried out and published on the subject of residual stresses and distortion in LPBF-manufactured components. The publications deal with various influencing factors and avoiding strategies, a selection of which is briefly presented below.

One strategy for the reduction of residual stresses can be the reduction of the volume energy density (VED) introduced to the material. As a result, the size of the melt pool is reduced and therefore less material is subject to shrinkage during cooling. [29–32]

Only one publication could be found that came to the opposite conclusion, i.e. that higher energy input results in lower stresses. [33]

The volume energy density is a combination of several parameters such as laser power, scan speed, hatch distance layer height. The literature suggests that for the same VED, a slower scan speed with less laser power is preferable.[34–36]

With regard to distortion or residual stresses in the LPBF process, a relatively clear picture emerges when comparing one-dimensional line or strip strategies, i.e. strategies with scan vectors in only one component dimension, and checkerboard strategies.

Compared to the line strategy with vectors along the largest component dimension, the use of a checkerboard strategy appears to be advantageous. The advantages are not so clear when comparing the checkerboard strategy with the layered 90 ° alternating line exposure. [37]

In a later study of the effect of different scan vector rotation angles on line strategies, Robinson et al. hypothesised that a scan vector rotation of 90 ° in successive layers would result in a superposition of tensile and compressive stresses, reducing the resulting maximum stress. [38]

For the size of the checkerboard squares, the results so far are also inconclusive. While a few studies say that the scan vector length and thus the size of the checkerboards has an influence [27, 29, 30, 33, 39], other experiments with different field sizes show that no difference was noticeable. [25]

2.2 Research Question

The aim of this paper is to find the most favourable SLM parameters to avoid or reduce residual stresses and to prepare the parts for a downstream welding process. To this end, it asks the following research questions:

1. Does a lower volume energy density (VED) have a positive effect on the reduction of resulting residual stresses while maintaining a high relative density?
2. Does the checkerboard scan strategy with its generally shorter scan vectors have a better effect on the reduction of the resulting residual stresses compared to line strategy?
3. Does the composition of the VED have an effect on distortion and residual stresses? Is a slower scan speed with lower laser power or a faster scan with higher laser power beneficial in reducing residual stresses?

All the experiments and actions explained below serve to answer these research questions.

3. METHODOLOGY

In order to evaluate the resulting residual stresses, twincantilever specimens were fabricated with the different process parameters. The parameters are varied as described in Chapter 4. The initial parameter which was varied was a parameter with good density that is used by standard. It is described in Table1:

Table 1

Initial parameter starting point with density of 99,9%

Laser Power P_L	Scan speed v_s	Hatch distance h_s	Layer height l_Z	Spot size d_S	VED E_V
180 W	800 mm/s	80 µm	45 µm	50 µm	62,5 J/mm^3

$$E_V = \frac{P_L}{(v_S * h_S * l_Z)} \qquad (1)$$

The Volumetric Energy Density (VED) which is described in equation 1 is a measurement of the amount of energy introduced into the process and is used to ensure the reproducibility and transferability of the process parameters between different systems.

These cantilever specimens are based on the temperature gradient mechanism and are a widely used method to qualitatively compare internal residual stresses. [40]

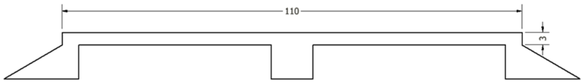

Fig. 1. Twincantilever geometry without Support

The design of the test specimens is shown in Figure 1. They are 10 mm wide, 110 mm long and have a bar height of 3 mm. The stamp in the middle has a base area of 10*10 mm. The test specimens have angled massive supports on the string side to avoid distortions in the process. Before starting the process, the overhang areas to the left and right of the center must be provided with support structures.

The specimens were built on a ConceptLaser M1 SLM machine. The machine with its 250*250*250 mm build chamber has a 200 W laser and a spot size of 50 µm. As shielding gas Nitrogen was used and the build plate has no preheatment function. Also no post-process heat treatment was performed. The material used was 316L powder with a PSD of -45/+15 µm. Maximum 5 % of the particles are larger than 45 µm and maximum 5 % of the particles are smaller than 15 µm.

After construction, the sample supports were removed by wire erosion. Thus no mechanical influence was exerted on the specimens and the deformations can develop due to inherent stresses.

Throughout the experiments the relative density was measured optically in parallel with the deformation measurements for each parameter. The reason for this is that a lower density is associated with a lower mechanical strength and could therefore have an effect on the deformation of the cantilever.

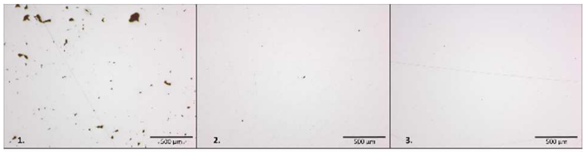

Fig. 2. Example of optical density measurements with 96,7 %(1.) 99,8 %(2.) and 99,9 %(3.) density

As shown in Figure 2, the density measurements in this work ranged from 96.76 % (No.1) to 99.99 % (No.3) density. In order to obtain valid results, only those cantilevers were included in the analysis that reached the minimum density of 99.8 % (No.2). In some graphs, measured values that are disqualified due to insufficient density are still displayed for the purpose of completeness, but they are then faded out in color.

The deformation measurements used to derive the residual stresses were analysed by 3D scanning the resulting deformation against the CAD data. The Steinbichler Comet 6 was used for this purpose. Its measuring principle is a structured light projector coupled with a high-resolution camera. The light diffraction generates a point cloud that can be reverse-engineered into a STL-file that can be compared with any CAD format.

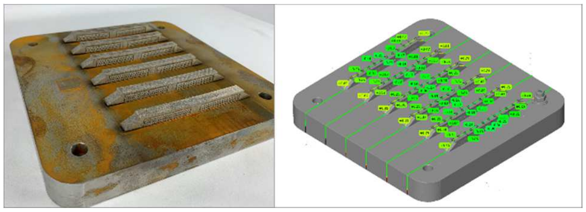

Fig. 3. Twincantilever geometry after wire erosion (left) and after scanning and measuring.

The Figure 3 shows how the twincantilever are cut of in order to be scanned. After the scan, the data is analysed with GOM Inspect. The Z-height of twelve measurement points is compared along a measurement line to eliminate as many interferences as possible. In addition to showing the true distortion in Z-height using the original distortion curves (Fig. 4), the maximum deviations in Z-direction are compared with each other and shown in bar graphs.

The example in Fig. 4 shows the different distortions over the complete measurement track in absolute numbers.

4. RESULTS AND DISCUSSION

Two upstream measurement series define the desired properties of the test specimens. One of these showed that the distortions displayed depend significantly on the bar height. If it is too small, there is a risk of cracks forming which, as plastic deformation, are equivalent to an uncontrolled reduction of residual stresses. If it is too high, the distortions that appear become smaller and the measurement becomes less distinct. In the case of this article, a bar height of 3 mm was found to be useful in the preliminary investigations.

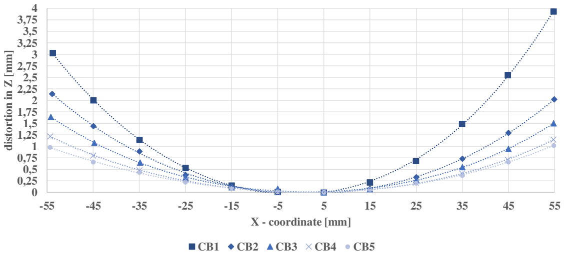

Fig. 4 Curve of real distortion depending on bar height (varied from 1 to 5 mm)

The second preparatory series of measurements was for the scan vector length in the Checkerboard pattern. For this purpose, cantilevers with different checkerboard sizes were produced and evaluated with regard to distortion. As mentioned above, the literature is not conclusive as to whether the scan vector length has a detailed influence, so a checkerboard size is specified in this preliminary experiment. The checkerboard lengths of 2.5, 3, 5, 7, and 10 mm are tested and the result can be seen in Fig. 5.

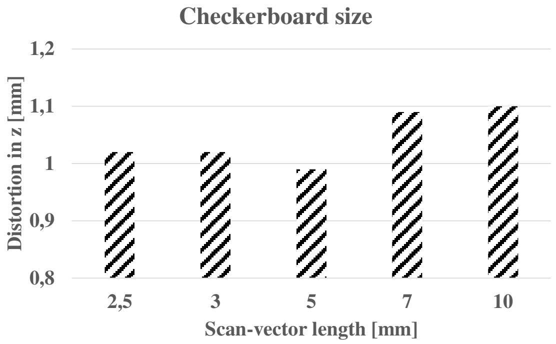

Fig. 5 Distortion based on scan-vector length

For the following experiments only bar heights of 3 mm and if needed only checkerboards with 5 mm scan-vector length were used in order to have good quality and repeatability.

Based on the preliminary studies, a series of measurements will now be carried out to answer the research questions posed.

To this end, twincantilevers with different Volume Energy Densities have been built to investigate the influence of the energy input. The VED was firstly varied by alternating the scan speed at a laser power of 180 W and resulted in VED from 37.5 to 82.5 J/mm³. Those tests were carried out for many parameters and also for two different types of support structure underneath the cantilever parts. The main results are presented in Fig. 6.

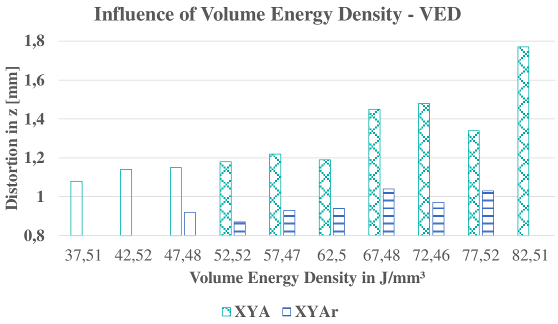

Fig. 6 Main results Cantilever distortion in dependence of VED varied by scan speed

The series XYA is in line strategy which is performed alternating in X and Y direction after each layer but with preliminary support structures that were more prone to cracking (cracked parts were never analysed for distortion). The Series XYAr and all following test series used reinforced support structures.

The results show that reducing the VED by increasing the scan speed is a suitable strategy for reducing distortion and thus residual stresses. This trend can be seen from 82.5 J/mm^3 down to 37.5 J/mm^3. When the VED is lowered below 52.5 J/mm^3, the specimens fall out of the process window due to reduced density. Therefore the theoretical results are shown with blank bars. The significance of these blank bars cannot be evaluated due to the increasing porosity, but they follow the trend of the other samples.

At the VED of 52.5 J/mm^3 the best results can be seen for the line-strategy.

To sum up the results it can be said:

- For the line strategy, the energy input varied in the scan speed has a measurable effect. (XYA) There is less distortion in the specimen with less energy density.
- This is also true when stiffer support structures were used (XYAr) to reduce part failure.

The first series of tests of this work also indicated that the checkerboard strategy, which was supposed to be very effective in avoiding residual stresses, does not seem to have the great effect that was promised. This is at least the case for the 316L specimens tested here. In order to verify this, further comparisons were made between the checkerboard and line strategies.

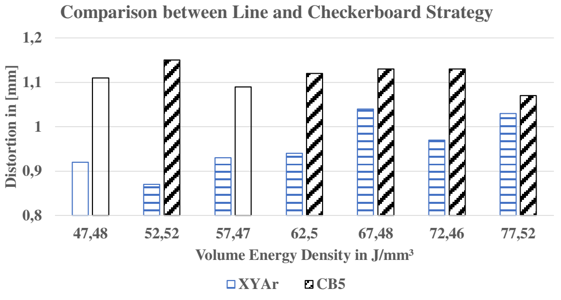

Fig. 7 XYAr versus CB5 series at different VED parameters

The name CB5 series stands for checkerboard in 5*5 mm. It also uses the reinforced support structures. This means that the maximum scan vector length in these samples was 5 mm. This is only half as long as the minimum length found in the XYAr series. According to the literature review above, this should be beneficial for residual stresses as it homogenises the cooling gradients.

The results of Fig. 7 give a different impression. All the samples printed in the course of this work performed worse than their line strategy counterparts. These deteriorated results are almost not affected by the different VED varied via scan speeds.

In the first series of tests, the laser power was fixed at 180 W and the scan speed was increased. This gave a controlled influence on the total energy input and therefore potentially on the size of the melt pool. As mentioned above, the literature on the effect of different scan speeds is not very consistent. However, it may be an effective strategy to either scan fast at high laser power or slower at lower laser power. To this aim the speeds and Laser Power parameter were varied as presented in Table 2.

Table 2

Parameters for varied VED test

Laser Power	160 W	170 W	180 W	190 W	200 W
Scan-Speed	846 mm/s	899 mm/s	952 mm/s	1005 mm/s	1058 mm/s

To get a first impression of the effect of these strategies, another series of tests was started. The results are shown in Fig. 8.

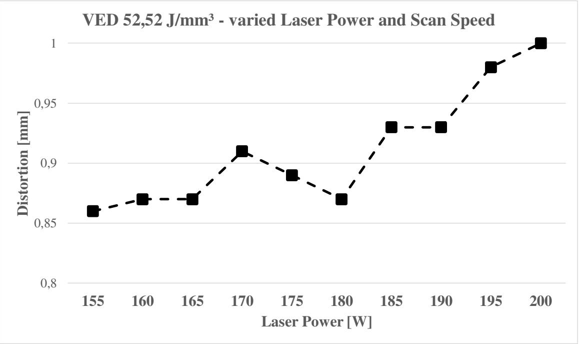

Fig. 8 XYAr at same VED of 52,52 J/mm^3 but with varied Laser Power and Scan Speed

All presented parameters were those, which produced parts with a higher density than 99.8 %. With 99.84 % Density the 160 W parameter was the only one beneath 99.95 % density.

From this first measurements, a trend towards slower scan velocities and lower Laser Power parameters can already be deduced. Here the 160 W parameter with a speed of 846 mm/s seems to be the best parameter in order to reduce the residual stresses and therefor the distortion.

The results presented have all been accompanied by extensive quality checks for density and are intended to test possible strategies for avoiding the increase in residual stresses and distortion. The aim was to prepare the SLM samples in the best possible way for a subsequent welding process. This provided the first important insights into the SLM process which will be discussed in the next chapter.

5. CONCLUSIONS

Preparing the SLM process on 316L parts for a downstream welding process means first and foremost reducing the residual stresses in the part. The present article has approached this issue with a comprehensive review of the state of the art. All possible influencing factors were considered and the researchers decided to focus on three research questions. The questions addressed the VED input, its composition and the influence of the scan pattern or the length of the scan vectors.

When trying to reduce residual stresses, it is always necessary to screen the relative densities. On the one hand, a strict density threshold could reduce the possible field of variables during optimisation, but on the other hand, it is extremely important for the subsequent welding process. Another general finding is the high influence of the number of samples on the build plate. In this work, all build plates were filled identically with 10 twin cantilevers and 10 density cubes, as deviating from this pattern resulted in incomparable results. The authors therefore strongly recommend that the number of samples on a plate should be kept constant to ensure comparability.

The final general finding relates to the support structure. Alternating support structures were not shown to manipulate the results of cantilever specimens, but did reduce the resolution of distortion. A good trade-off should be made between high process safety (stiff structures) and good distortion manifestation (weaker support).

In regard to the research questions, the results can be summarised as follows:

1. For the line strategy, the energy input varied in the scan speed has a measurable effect. (XYA) There is less distortion in the specimen with less energy density. This is also true when stiffer support structures were used (XYAr) to reduce part failure. The reason for this behaviour, based on the literature, could be explained by the fact that the smaller melt pool reduces the amount of cooling material. (*s. Chapter. 2.1*)
2. In no specimen or comparison point did the checkerboard strategy give a better result in terms of distortion than the XY alternating line strategy. This indicates that the shorter scan vectors, which were expected to have a good effect by homogenising the cooling gradients, were not as successful as the longer scan vectors of the line strategy. In addition, these checkerboard patterns were not sensitive to any variation in VED. This could imply that the length of the scan vectors is not as influential as the reorientation of the stress directions.
3. As far as the composition of the VED is concerned, there appears to be an advantage in reducing the laser power and scanning speed compared to other parameters of the same VED. This should be discussed in terms of reduced productivity, but it could be an advantageous strategy to take the "slower" side of the possible process window whenever a welding process is planned on the printed parts.

The results of this article are an important contribution to the state of the art in the welding of 316L additive manufactured SLM parts. The work lays the foundation for further work on reducing residual stresses in 316L parts produced by SLM in preparation for a downstream welding process.

The next possible research steps could be the following:

- As VED appears to have an influence, also layer height and focal diameter could be changed , in order to vary the size of the melt pool

- Preheating and heat treatment should be tested as they have a major impact on residual stresses but on the other side could also interfere with the mechanical properties

The researchers believe that there is still great potential to adapt the SLM process of 316L in a way that is most advantageous for a downstream welding process, thereby exploiting the great potential of hybrid manufacturing technologies.

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CERCETĂRI PRIVIND REDUCEREA TENSIUNILOR REZIDUALE ALE PIESELOR SLM REALIZATE PENTRU PROCESUL DE SUDARE ÎN AVAL

Rezumat: Având în vedere tendința actuală către sarcini de producție mai mari și mai complexe în procesul SLM și limitările actuale în ceea ce privește spațiul maxim de construcție, sudarea componentelor SLM între ele sau cu piese fabricate în mod convențional devine din ce în ce mai relevantă. Până în prezent, sudarea prin fuziune a componentelor SLM fabricate din 316L a fost investigată foarte rar și, dacă a fost cazul, atunci pentru procese de sudare cu laser foarte specializate. La sudarea cu procese industriale de sudare cu gaz, cum ar fi MIG/MAG sau TIG, apar distorsiuni asociate cu tensiunile reziduale rezultate în componente. Această lucrare investighează factorii de influență din partea procesului pentru a evita tensiunile reziduale rezultate în componentele SLM realizate din 316L. Scopul este de a dezvolta o strategie pentru a construi componente SLM cât mai lipsite de tensiuni pentru a le îmbina cât mai profitabil cu un proces de sudare din aval. În acest scop, parametrii de influență, cum ar fi puterea laserului, viteza de scanare, dar și lungimea vectorului de scanare și diferite modele de scanare sunt analizate în ceea ce privește influența lor asupra tensiunilor reziduale.

Fabian EICHLER, M.Sc., Research Engineer, FH Aachen - University of Applied Sciences, Mechanical Engineering, eichler@fh-aachen.de, 0241 6009 52432

Nicolae BALC, Prof. Dr.-Eng., Professor, Technical University of Cluj-Napoca, Department of Manufacturing Engineering/ Faculty of Machines Building, nicolae.balc@tcm.utcluj.ro, 0264 401794

Sebastian BREMEN, Prof. Dr.-Eng., Professor, FH Aachen - University of Applied Sciences, Mechanical Engineering, bremen@fh-aachen.de, 0241 6009 52473

Markus SCHLESER, Prof. Dr.-Eng., Professor, FH Aachen - University of Applied Sciences, Mechanical Engineering, schleser@fh-aachen.de, 02416009 52385

Alexander SCHWARZ, Dr.-Eng. (TUT, ZA), Research Engineer, FH Aachen - University of Applied Sciences, Mechanical Engineering, a.schwarz@fh-aachen.de, 0212 38242958