Investigation into the bond strength of the joining zone of compound forged hybrid aluminium-steel bearing bushing

Cite as: AIP Conference Proceedings **2113**, 040028 (2019); https://doi.org/10.1063/1.5112562
Published Online: 02 July 2019

Bernd-Arno Behrens, Valeria Sokolinskaja, Anna Chugreeva, Julian Diefenbach, Susanne Thürer, and Dieter Bohr

Investigation into the Bond Strength of the Joining Zone of Compound Forged Hybrid Aluminium-Steel Bearing Bushing

Bernd-Arno Behrens[1, a)], Valeria Sokolinskaja[1, b)], Anna Chugreeva[1, c)], Julian Diefenbach[1, d)], Susanne Thürer[2, e)] and Dieter Bohr[1, f)]

[1]*Institute of Forming Technology and Machines, An der Universität 2, 30823 Garbsen, Germany*
[2]*Institute of Material Science, An der Universität 2, 30823 Garbsen, Germany*

[a)]behrens@ifum.uni-hannover.de
[b)]vsokolinskaja@ifum.uni-hannover.de
[c)]chugreeva@ifum.uni-hannover.de
[d)]diefenbach@ifum.uni-hannover.de
[e)]thuerer@iw.uni-hannover.de
[f)]Corresponding author: bohr@ifum.uni-hannover.de

Abstract. The proper application of multi-material design is an effective way of saving energy costs and reducing CO_2-emissions. In the production of heavy-duty components, the tailored forming technology offers the possibility of bringing the right material to the right place. In this context, this paper deals with the challenges that arise during compound forging such components using the example of a bi-metal bearing bushing. For this purpose, steel is placed into the highly stressed bearing surface, where high performance characteristics are required, while the rest of the part is made of aluminium to reduce the total weight of the component. Due to the different material properties of steel and aluminium, the process design for bi-metal compound forging is very demanding and requires process-specific heating and forming strategies, which are presented and discussed in this paper. After the implementation, forging experiments were carried out and the bearing bushings obtained were evaluated by metallurgical and mechanical tests. A crucial aspect in assessing the quality of such components is the bond strength, which generally depends on the development of intermetallic phases. Therefore, an analysis of the joint and phase formation in the area of the joining zone of the compound forged parts was performed initially using optical microscopy. The metallurgical studies showed good bonding with form- and force-closed joint and insular intermetallic phases along the joining zone. Afterwards, the bond strength was determined by push-out tests, whose results were finally correlated with the metallurgical findings.

INTRODUCTION

The trend to constantly reduce both energy costs and CO_2 emissions results in increasing demands on technical parts and requires the production of high performance components with improved functionality while simultaneously reducing their weight. However, because of material-specific restrictions, conventional mono-materials cannot meet all these requirements. In this context, multi-material design enables the production of components tailored to specific applications with a high potential for lightweight construction, thus combining the individual advantages of the individual materials in a single component. As a result, the processing of such combinations of dissimilar materials like steel and aluminium is gaining increasing importance for research and development. The industrial production of multi-material components is currently usually carried out by joining two individual components with existing near-net-shape or final geometry. The most frequently used technology for this application is friction welding. An efficient alternative offers compound forging, in which the forming and joining operations are performed in a single process step. Kong et al. conduced basic research on this process by forge welding steel-aluminium-compounds (AISI

Proceedings of the 22nd International ESAFORM Conference on Material Forming
AIP Conf. Proc. 2113, 040028-1–040028-6; https://doi.org/10.1063/1.5112562
Published by AIP Publishing. 978-0-7354-1847-9/$30.00

316L/AA6063) and identified the temperature as having the greatest influence on the forming result regarding the quality of the joint [1]. Politis et al. studied the flow behaviour of bi-metal gears made of steel AISI 1213 and AA6082 by numerical simulation and experimentation [2]. A similar research work was carried out by Wu et al. combining AISI 8620 and AA2014 [3]. Wohletz and Groche investigated the forming behaviour of a steel-aluminium combination (AISI 1015/AA6082 T6) at ambient and elevated temperatures in a combined forward and cup extrusion process. The resulting compounds showed an improved bond quality at rising forming temperatures. At the same time, however, the oxide layer increased, which in turn affected the joining zone properties [4]. An important aspect here is the formation of intermetallic phases, which was investigated by Behrens et al. by compound forging of steel-aluminium combinations [5]. A central focus was also the adjustment of different material-specific temperatures, which is still a challenge due to the different thermophysical properties [6]. In order to obtain an adequate forming result without melting the aluminium part, specific heating strategies are required to generate the appropriate temperature gradients between different areas of the hybrid semi-finished part to adjust their flow stresses [5].

This contribution deals with a process for the manufacturing of bi-metal bearing bushings by closed die compound forging process. The aim was to identify an appropriate thermomechanical process route and to characterise the bond quality as a function of the process parameters. For this purpose, steel-aluminium components were used, which were joined by shrink fitting. In order to define the temperature distribution suitable for subsequent compound forging, the induction heating process was investigated both simulatively and experimentally. The determined heating concepts were then applied within the forging trials and the manufactured components were examined with regard to the bond quality. For this purpose, metallographic investigations of the joining zone were carried out using microsections and push-out tests to determine the bond strength.

MATERIALS AND METHODS

The workpieces consisted of a larger hollow aluminium cylinder (AA6082) and a smaller hollow steel cylinder. As a result, the inner rolling surfaces have a high wear resistance, while on the outside, where lower requirements apply, a light and tough material is used. The models of the studied bi-metal workpieces and bearing bushings are shown in Fig. 1 (a, b). AA6082 was used as the aluminium alloy, while three different alloys (4820, 5140, 1020) were used for steel in order to investigate the material-specific influence on formability and the resulting compound bond [7].

In order to avoid forming defects (e.g. cracks) the steel temperature should be in the semi-hot or hot forming temperature range, which is however restricted by the melting temperature of aluminium (approx. 580 °C). Consequently, an inhomogeneous temperature distribution needs to be set within the bi-metal workpieces, for which induction heating is highly suitable due to the variety of adjustable parameters [8]. Figure 1 (c, d) shows the heating concept with a water-cooled inner induction coil modified with magnetic flux controller and the corresponding experimental setup. In this way, eddy currents are mainly induced in the steel part, causing it to heat up and subsequently transfer the thermal energy to the outer aluminium part by means of conductive heat transfer.

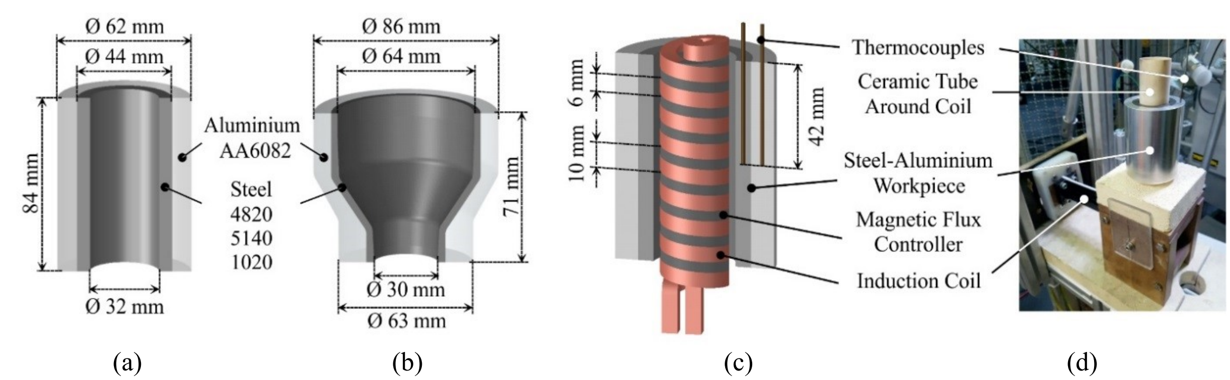


FIGURE 1. Design of steel-aluminium workpiece (a) and bearing bushing (b), induction heating concept for hollow bi-metal cylinders (c) and induction coil with magnetic flux controller (d)

For the experimental heating tests, a medium-frequency generator (Hüttinger TruHeat MF3040) with an adjustable operating frequency in the range between 5 and 30 kHz and a maximum power of 40 kW was used. The induction coil was connected to a capacitor box with a total capacity of 47.1 µF in an oscillating circuit. In order to establish the highest possible temperature gradient between steel and aluminium in a short time, all experiments were performed at 100 % voltage (= 300 V) during which the heating time was varied. The maximum operating frequency was approx. 16.5 kHz. In the tests, time-temperature curves at two positions were recorded using NiCr-Ni thermocouples (Type K) (Fig. 1 c, d).

The experimental forging tests were carried out fully automatically on a spindle press (Lasco SPR 500) with a maximum energy of 40 kJ using the induction heating strategy previously determined and a handling robot for the transfer. Figure 2 shows a model and the actual tool system mounted in the press. The forming of the bearing bushing was carried out in a single step, in which a closing plate with disc springs ensures near-net-shape geometry. The transportation time after heating was limited to 6 s for all of the forging tests. After forming, the final parts were air-cooled. The forged parts were then separated and metallographically examined in the area of the joining zone with regard to possible defects and intermetallic phases. Moreover, push-out tests were carried out in order to evaluate the bond strength as a function of the process parameters.

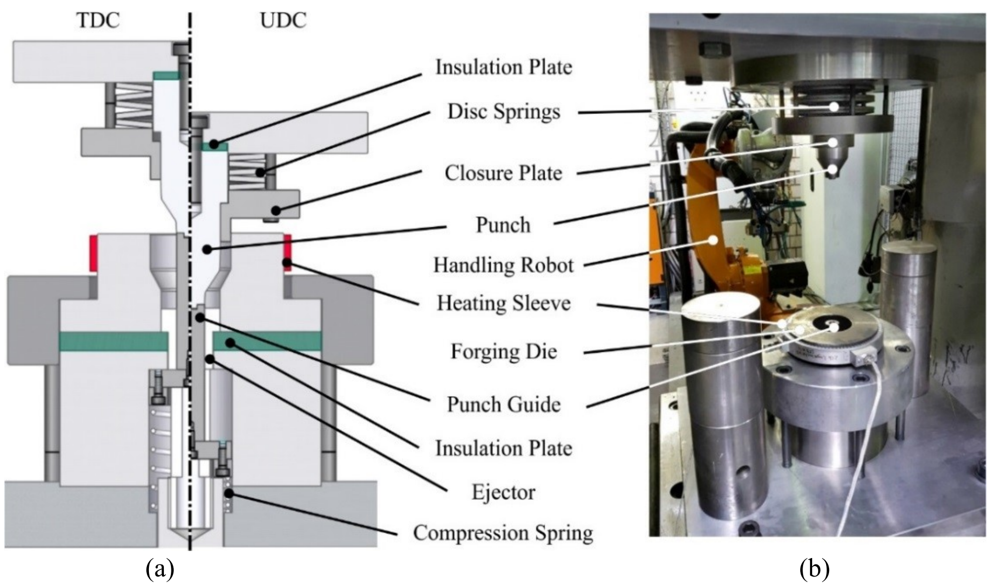


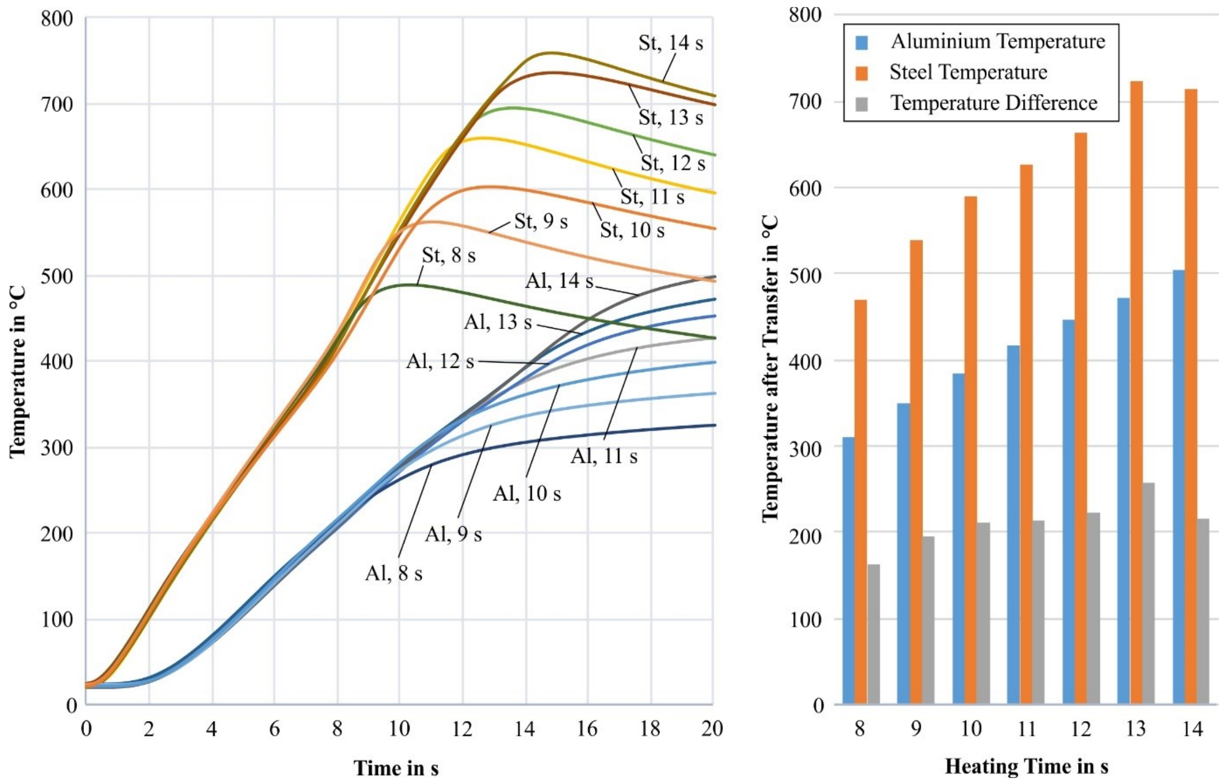
FIGURE 2. CAD model (a) and actual forming tool system for closed-die forging of bearing bushings (b)

RESULTS AND DISCUSSION

Induction Heating

In the heating experiments, the heating time was varied in one-second intervals, with the maximum time being limited to 14 s in order to prevent melting of the aluminium. It is important to note that the temperatures resulting after an additional transfer time of 6 s, during which compensatory processes still take place, are crucial for the subsequent forging operation. In this context, Fig. 3 shows relevant time-temperature curves from 8 s to 14 s heating time and the corresponding temperature values and differences after the transfer time representatively for all three material combinations.

As a result of the induction heating setup presented above, the steel part initially heats up much faster than the aluminium part, which is delayed by about 2 s due to the retarded heat conduction. A temperature equalisation takes place approx. 90 s after heating, which is due to the shrunken joint. Because of that the heat transfer between the two materials is comparatively slow, which is however positive for creating a high temperature gradient. As was already investigated in [9] by means of flow curves, a temperature in the hot or semi-hot forging area (T>700 °C) is required in the steel part. From the bar chart (Figure 3 (b)) it can be seen that at least a heating time of 12 s is necessary to obtain a suitable forming temperature in the steel. With a further increase to 13 s, the temperature gradient between steel and aluminium increases further and reaches a maximum. At 14 s, the gradient decreases again, as only the aluminium temperature increases.



(a) (b)

FIGURE 3. Time-temperature curves obtained by experimental test using 4820 and AA6082 (a) and corresponding temperatures after transfer time (b)

Forging Experiments

The forging experiments were carried out at heating times of 13 s and 14 s based on the results of the heating tests. The heating time of 13 s (incl. transfer time) produces the highest temperature gradient. After 14 s, the temperature gradient decreases again, but the aluminium temperature rises further possibly leading to improved diffusion processes and thus an enhanced bonding. As mentioned above, a further increase in the heating time was not investigated. Although the melting temperature would not have been reached after the transfer time, preliminary tests have revealed that this would be the case due to the additional deformation-induced heating.

Figure 4 shows an illustrative cross-section of a forged bearing bushing (4820-AA6082, 14 s) with four magnifications. As the overview image shows, the aluminium encloses the steel in the upper part of the bearing bushing because of its significantly lower flow stress. However, a complete die filling can be achieved, which is due to the use of the closure plate, further leading to an additional resistance to axial displacement between the two materials. A closer view on the interface between steel and aluminium reveals different characteristic areas. In the upper area of the bearing bushing, a macroscopic form fit with gaps was identified due to the undercut. The joining zone then turns into a form- and force-close joint free of any gaps and enhanced by a wavy topography due to the mechanical processing. On the bottom face of the component, small gaps appears again, varying in size depending on the process parameters. The bond characteristics described could be observed consistently for all parameter combinations, indicating that the cause must be process-related. According to Mori et al., the bond quality in such processes mainly depends on the degree of plastic deformation [10]. In particular, the surface exposure, the relative normal pressure (in relation to the yield strength of the weaker base material) and the mechanical pre-treatment of the surfaces (e.g. by scratch brushing) play a decisive role. Simulative investigations of the forming process, which were partially published in [9], shed light on the observations regarding the different bond qualities across the component cross-section and correlate with the dependencies described by Mori et al. Accordingly, the surface exposure in area 4 (Fig. 4) is lowest and/or tends towards zero. It increases in area 3 and reaches its maximum in the upper region (1 and 2). At the same time, however, the contract stresses and thus the normal pressures in area 1 are lowest due to the axial material arrangement, which finally explains the occurrence of the gaps in both regions.

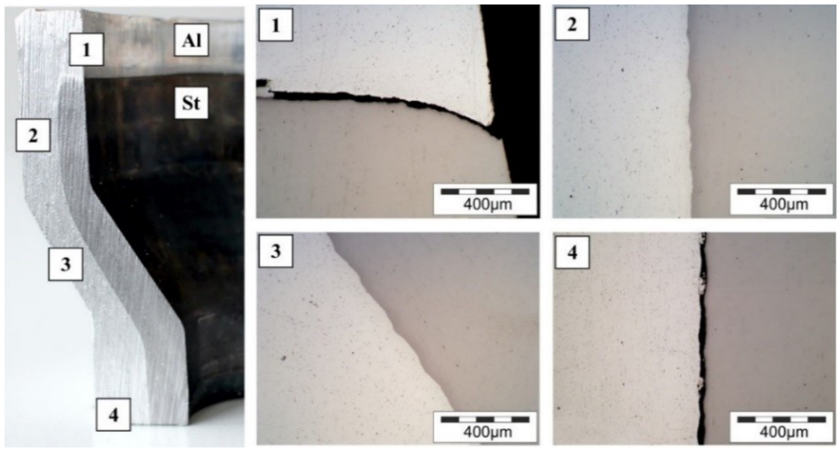


FIGURE 4. Material distribution in forged bearing bushing and micrographs of zones with different bond quality (4820-AA6082, 14 s)

In order to investigate the bond strength quantitatively, push-out tests were carried out, which results are compared in Figure 5. Due to the different material flow and the small lifting bevel at the punch, a slight conical form-fit resulted in the cylindrical push-out specimens. Therefore, the test were conducted from both sides evaluating the results with and without the influence of the form-fit (Figure 5 (b)). As the bar chart shows, higher bond strengths tend to be reached at a heating time of 14 s both with and without form fit. As expected, the highest values can be found when testing with form fit. Differences specific to material can only be observed with 1020, in which at constant parameters lower strengths tend to be achieved. The described observations can be explained on the basis of micrographs.

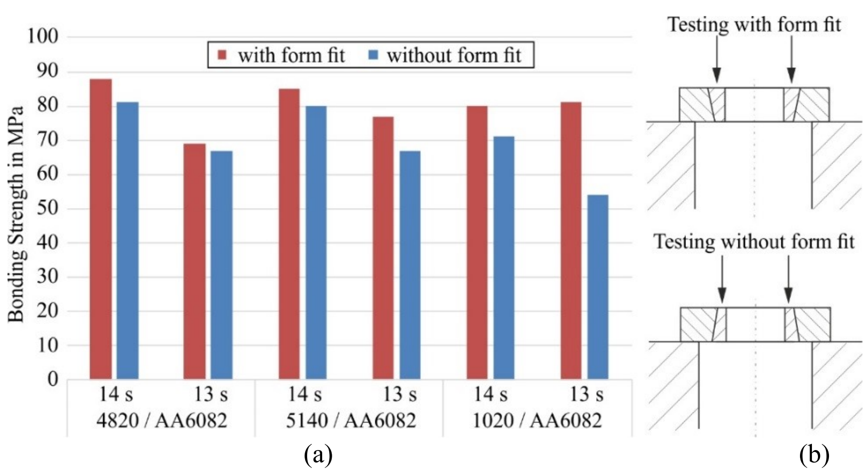


FIGURE 5. Bond strength as a function of material combination, heating time and pushing direction (a) and corresponding push-out experimental setups (b)

In this context, Figure 6 shows microsections in the area of the joining zone for different combinations in the axial middle of the specimen before testing. As can be seen from the example of 4820, a heating time of 13 s led to a weaker bond with more gaps compared to a heating time of 14 s. The higher temperature promotes diffusion processes. In addition, the further reduced flow stress makes it easier for the aluminium to adapt to the contour of the steel, which finally results in a defect-free joining zone explaining the higher strengths. Regarding the quantitative values there are no great differences between 4820 and 5140. However, the micrographs show that more defects occur on the aluminium side in the case of 5140. At the same time, characteristic dark shading along the joining zone can be seen, which suggests the formation of a thin intermetallic phase (IMP). As a result, it is possible that the strength reducing effect of the defects is compensated so that similar values to 4820 can be achieved. For 1020, the low strength values can also be explained by the micrographs, which show a joining zone continuously covered by defects.

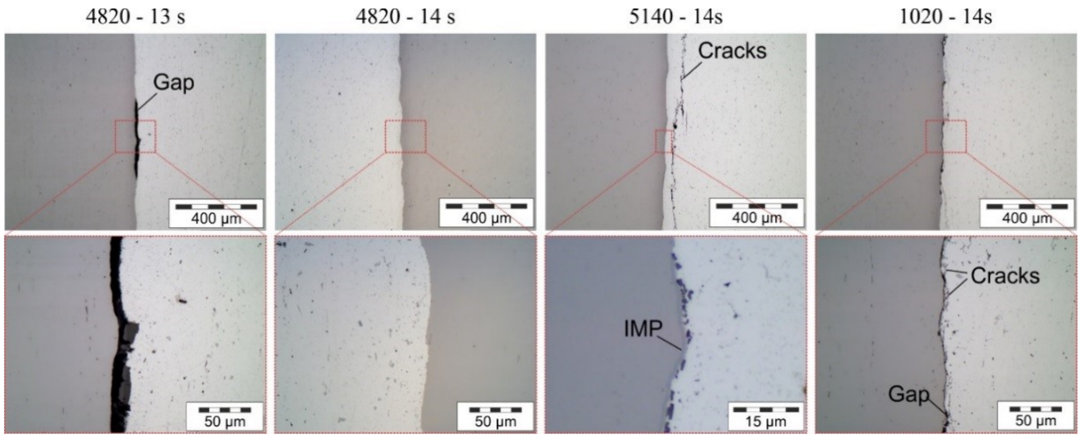


FIGURE 6. Micrographs of joining zone for different parameter combinations before push-out testing

SUMMARY AND OUTLOOK

The presented contribution dealt with the challenges of compound forging of dissimilar materials exemplified by a steel-aluminium bearing bushing. The results of inductive heating experiments have been demonstrated, in which different temperature gradients between the two materials could be adjusted by varying the heating time. Within the experimental forging tests, the highest heating time (14 s) was found to be effective, as although the temperature gradient was lowered again, the aluminium temperature was increased, resulting in an improved bond. The results were confirmed by push-out tests in combination with metallographic micrographs. However, it was not possible to produce a full-surface bond over the entire component, since gaps occurred mostly in the reduced face area. Consequently, further investigations are planned in which extruded semi-finished products are to be used instead of workpieces produced by shrinking in order to improve the material bond. The design of the heating strategy will be particularly challenging here, as the improved bond in the semi-finished product is accompanied by increased heat transfer, which increases the risk of undesired melting.

ACKNOWLEDGMENTS

The results presented in this paper were obtained within the Collaborative Research Centre (CRC) 1153 “Process chain to produce hybrid high-performance components by Tailored Forming” in subproject B2 funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Fundationen) – Projectnumber 252662854. The push-out investigations presented in this paper were obtained in cooperation with subproject A1 of the CRC 1153. The authors would like to thank the DFG for the financial and support of this project.

REFERENCES

1. T. F. Kong, L. C. Chan and T. C. Lee, Strain **45** (4), 373–379 (2009).
2. D. J. Politis, J. Lin, T.A. Dean, D.S. Balint, J. of Materials Processing Technology **214** (11), 2248-2260 (2014).
3. P. Wu, B. Wang, J. Lin, B. Zuo, Z. Li, J. Zhou, Int. J. of Advanced Manufacturing Technology **88** (9-12), 2835-2847 (2017).
4. S. Wohletz and P. Groche, Proc. Eng. **81**, 2000–2005 (2014).
5. B.-A. Behrens and K.-G. Kosch, Materials Science and Engineering Technology **42**(11), 973–978 (2011).
6. B.-A. Behrens and F. Holz, Mat.-wiss. und Werkstofftech. **39** (9), 599-603 (2008).
7. K. A. Nazari and S. G. Shabestari, Journal of Alloys and Compounds **478**, 523–530 (2009).
8. A. A., Abrikosov, “Fundamentals of the Theory of Metals”, Vol.1, North-Holland (Amsterdam, 1988).
9. B.-A. Behrens, A. Chugreev and T. Matthias, wt-online **10**, 691–697 (2018).
10. K.-i. Mori, N. Bay, L. Fratini, F. Micari and A. E. Tekkaya, CIRP Annals **62**(2), 673–694 (2013).