INVESTIGATING THE POTENTIAL OF HYBRID HOT FORGING PROCESSES WITH REGARD TO THE FORMING AND JOINING OF SHEETS AND MASSIVE ELEMENTS

[1]SARA MOHAMMADIFARD, [2]MALTE STONIS, [3]JAN LANGNER, [4]BERND-ARNO BEHRENS

Prof. Dr. Dr. Institut für Integrierte Produktion Hannover gemeinnützige GmbH (IPH) Hollerithallee 6, 30419 Hannover, Germany
E-mail: mohammadifard@iph-hannover.del

Abstract- Every year about two billion components are manufactured by forging. Because of the high temperatures and high forming forces required, many components are produced in a segmental manner and later joined together, e.g. by welding. In order to save manufacturing steps – and thus costs and time – a production process is to be developed in which elements of different steels are simultaneously deformed and joined in a single forging. These elements could have very different geometries and thus strongly influence the manufacturability of complex parts. This combination of deformation and joining is called a hybrid process. In this paper, an investigation on the simultaneous forging and joining of massive bulk and sheet elements is described. The aim is to characterize a first influence of the different forming temperatures on the resulting joint zone of the hybrid process. For this purpose, a series of tests are carried out using a screw press. To find out if there is a correlation between the temperature and the quality of hybrid forgings, the samples are analyzed by means of tensile tests and metallographic analysis. These analyses show the influence of the forming temperature on the joint zone. Based on the knowledge gained, the joint zone can be characterized and evaluated. The main finding is that at higher forming temperatures, the areas of material bonding are significantly stronger than at low temperatures. The findings obtained contribute to the development of joining by hybrid forging. The results can be used to further investigate the relevant manufacturing processes and component properties of hybrid parts.

Keywords- Forging, forming, hybrid process, massive element, sheet element, tensile test, metallography

I. INTRODUCTION

In times of rising energy prices and stricter environmental regulations, lightweight construction plays a special role in general mechanical engineering and especially in the automotive industry. According to studies carried out by the European Environment Agency, passenger cars account for 14 % of Europe-wide CO2 emissions [1]. One way to reduce CO2 emissions in the automotive sector is to reduce vehicle weight. For medium-sized cars, a reduction in weight of 100 kg results in a reduction in fuel consumption of 0.3-0.8 l/100 km and a reduction in CO2 emissions of 8-11 g/km [1,2]. Consequently, lightweight construction is necessary for further efficiency improvements in all divisions of automotive engineering and at the same time represents the key to the realization of new technologies, such as electrical and hybrid drive technology [3]. For forging companies, innovative products and production processes are a future-proof way of countering the rising competition products from low-wage countries [4].

The aim of this investigation is to explore the fundamentals of a new forming process in which massive and sheet metal components are formed and joined together in one process step. The new forming process is intended to expand the design possibilities for components in such a way that parts of a forged part which are subjected to low loads are substituted by sheet metal structures, or sheet metal parts can be partially reinforced by massive parts. In the hybrid forming of sheet metal and massive elements, they are shaped and joined at the same time. This eliminates the need for an additional joining operation and the production costs are thus reduced

II. STATE OF THE ART

The forged bond between two or more components can be based on different mechanisms. It is generally divided into mechanical interlocking, friction grip and material bonding. In this paper, the investigations focus on material bonding. Therefore, this type of bond is first introduced in the following paragraphs and then some previous studies in this area are described.

Material bonds are not easily disassembled because they are formed at the molecular or atomic level. Material bonding is produced by adhesion and/or by diffusion processes (formation of intermetallic compounds) [5]. Adhesion is not yet fully understood. The best-known theory is that the bonding of two surfaces is effected by intermolecular and interatomic forces (van der Waals forces, hydrogen bonds, electrostatic forces and ion) between the molecules and atoms of the two materials [5]. By chemically activating the exposed surface or creating physically or chemically reactive sites, the amount of adhesion forces can be increased [5]. Intermetallic compounds are formed by means of diffusion processes when melting and fusing the edge zones [6]. For strong connections, heat or high pressure is often required to melt the components at the interface and to cause the diffusion of atoms. This leads to atoms of one material entering the crystal lattice of the other. With complete

solubility of two elements in the solid state, mixed crystals arise [6]. In the case of complete insolubility in the solid state, diffusion processes can form superstructures or intermetallic phases [6].

In industry and research, different basic approaches to producing hybrid parts with material bonding have already been implemented. LANDERL has shown the possibility of composite casting of magnesium combined with aluminum for mass production of car engines [7]. VICARIO has analyzed the production of such hybrid parts using die casting [8]. In sheet metal forming, tailored blanks are well known to research and industry. In bulk forming, the research of tailored parts is quite new. Basic research has been conducted using friction-welded parts at Marquette University in Milwaukee and Ohio University in Athens, USA [9]. There, joined slugs made of steel, aluminum and copper were formed by upsetting and side pressing. JOHN investigated aluminum magnesium slugs produced by lateral extrusion [10]. Hybrid forging has been introduced by PANG who forged a hot aluminum part around a cold steel part [11]. Hybrid forging processes with different materials were also investigated by BEHRENS. Inter alia, the buckling behavior of cylindrical hollow and hybrid specimens was analyzed [12]. Furthermore, basic studies on a new hybrid forging process chain were being performed. The aim of these investigations was to develop a process for steel-aluminum parts. The results show the feasibility of deposition welding with subsequent hot bulk forming process to produce hybrid-forged parts [13]. KACHE investigated the practicability of hybrid forging using sheet metal and massive elements. Successfully produced sample parts demonstrated the feasibility of hybrid parts joined by material bonding or form fitting. A combination of both joining mechanisms in one demonstration part was not part of the study [14].

III. EXPERIMENTAL INVESTIGATION

3.1. Development of the hybrid forging process

Hybrid forging makes it possible to produce load-optimized structural components in a single-step process. The components are formed and welded together in a single forging operation. Thus, the hybrid forging process is clearly faster than a conventional process producing similar parts, in which the joining operation needs to be performed in an additional step after the forming operation [15].

In order to evaluate the interdependencies between the main process parameters of the hybrid forging process and the quality parameters, first a demonstration part had to be designed. The demonstration part is a simplified control arm for automotive application and consists of a massive element which can be used as connecting points. The massive element is connected to a sheet element. As shown in Fig. 1, on the left side of the control arm the massive element is designed to be joined by material bonding [14].

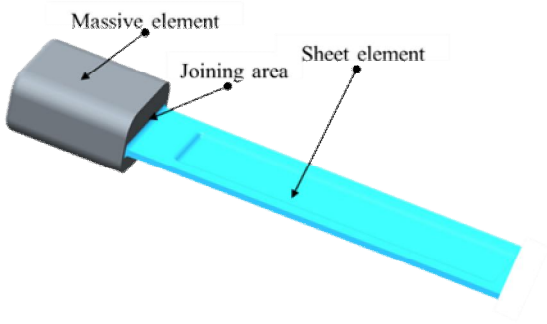


Fig. 1: CAD-model of demonstration part for hybrid forging

3.2. Equipment, preparation and testing

The massive element consists of the steel C45 (1.0503) and has the dimensions 60 x 20 x 38 mm with a recess measuring of 25 x 3 mm. The sheet element is made of the steel DC01 (1.0330) with the dimensions 140 x 25x 2 mm (Fig. 2).

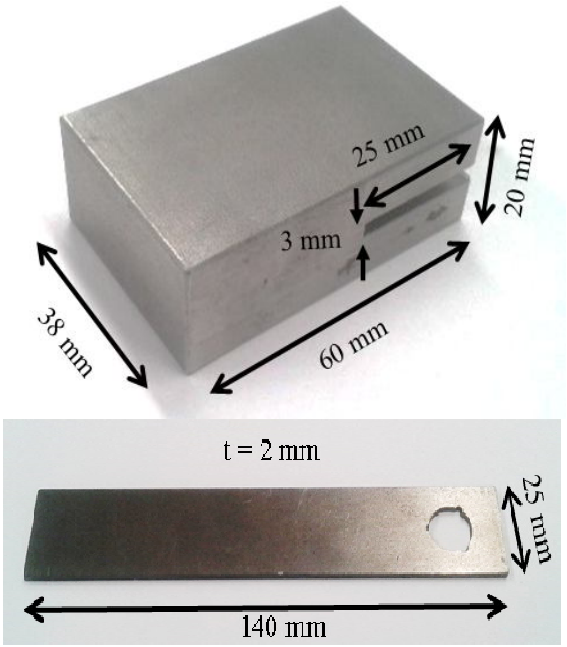


Fig. 2: Above: massive element, below: sheet element

The test preparation involves the cold forming of the interlocking elements. At first, the slot in the massive element is pressed on the sheet element so that its position does not change during heating and transport of the parts. This is necessary, as in the hot state (1,250 °C) the strength of the sheet decreases to such an extent that it cannot be correctly inserted in a short time with sufficiently high precision. In addition, at high temperatures, the elements expand to different degrees and acquire substantial oxide layers so that it is difficult to insert the metal sheet into the massive element manually. In order to ensure comparability of the tests, this procedure is carried out with all samples, even with those treated at lower temperatures, where it is not required to the same extent. The upper and lower dies are shown in Fig. 3.

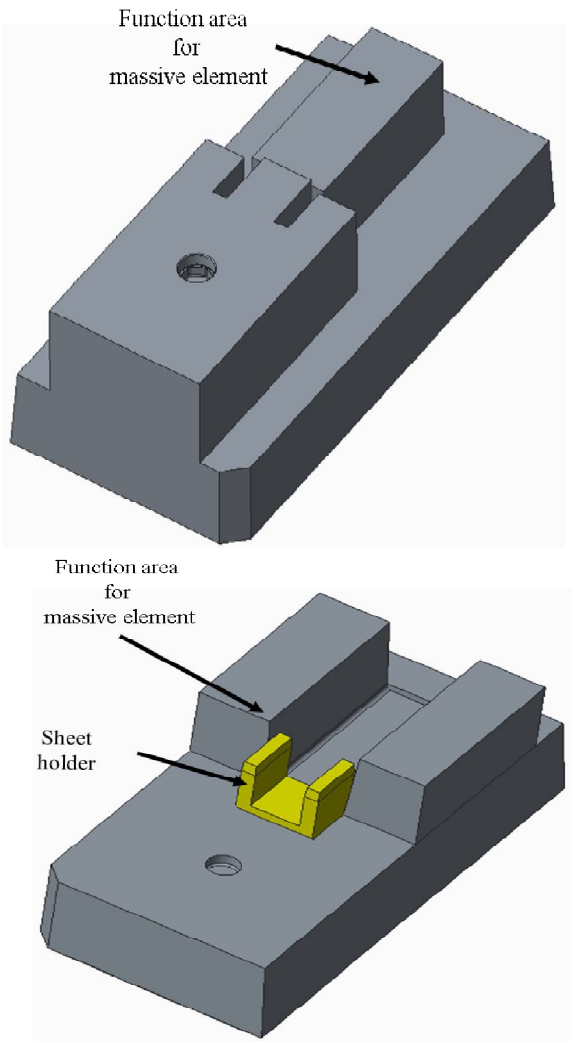


Fig. 3: Above: upper die, below: lower die

The components are then heated to temperatures between 800 °C and 1,250 °C in a furnace for 20 minutes and are formed in an upsetting operation with blockers along the sides of the bulk part with a screw press type "Weingarten PSH 4.265f". The upper and lower dies are manually coated with a water-graphite mixture before each forging operation in order to reduce friction and extend the service life of the tools. The impact energy of the forging operation can be varied between 10 kJ and 30 kJ. Higher energies are not possible since a maximum forming force of 11,000 kN must not be exceeded. After positioning the parts into the lower die, the screw press performs the forging operation and then the parts are removed. For cooling, the parts are stored at approximately 30 °C in still air. The investigation parameters are shown in Table 1.

Table 1: Parameters of experimental investigations

Parameter	Massive element	Sheet element
Material	C45 (1.0503)	DC01 (1.0330)
Temperatures	800 / 1,000 1,150 / 1,250 °C	800 / 1,000 1,150 / 1,250 °C
Dimensions	38 x 60 x 20 mm	140 x 25 x 2 mm

IV. RESULTS AND DISCUSSION

In this section, the joint zones of the forged samples are analyzed. To evaluate the joint quality, the samples are subjected to material tests. Five samples at each temperature are tested for ultimate tensile stress in the tensile test and two other samples are metallographically investigated. Conclusions about the nature of the created joint zone are drawn here. The investigation of a single sample using both test methods is not possible, since both are destructive tests.

4.1. Tensile test results

To analyze the causes of fracture during the tensile test, the various failure forms are classified. The results are shown in **Error! Reference source not found.**.

- Failure form A: the sheet element tears at a point which is some distance from the joint. The joint can withstand greater forces than the sheet element; therefore, the requirement for the strength of the connection is thereby met
- In the case of the second failure form B, the sheet element tears at the change in cross-section. At this point, the sheet element is exposed to compression in forging and thus becomes thinner than the initial cross-section. However, the bonding at the edge of the massive element is not complete. Such a defect could possibly be avoided by a change in the geometry of the massive element. The strength of the joint cannot be completely characterized using the tensile test. On the basis of the location of the failure, it can be seen that the desired connection is present in the interior of the massive element.
- The failure form C is characterized by the sheet element breaking within the massive element. In these cases, a bonded connection could be created, but the bonded areas are limited. The sheet ruptures in the massive element, where it has a reduced thickness due to the deformation.
- The least amount of bonding area is observed in the failure form D. The sheet was completely separated from the massive element during the tensile test. Scoring and abrasions on the sheet indicate that the bonding of the elements existed at certain points.

Failure form	Test results	Forming temperature [°C]	Number of samples
A		T = 1,150	2
		T = 1,250	5
B		T = 800	1
		T = 1,000	5
		T = 1,150	3
C		T = 800	2
D		T = 800	2

Fig. 4: Failure forms (A, B, C and D) at different forging temperatures

From the results in Fig. 4., it can be seen that at the forming temperature 800 °C over half of the samples fail due to partial (C) or complete extraction (D) but these failure forms occur less frequently with increasing forming temperatures. At the forming temperature 1,000 °C, only the failure form B is occurred. At the forming temperature 1,150 °C, the failure forms A and B are the most common failure forms and at the forming temperature 1,250 °C, the failure form A is seen exclusively. In Fig. 5 the tensile force-extension diagram for some samples is illustrated. The x-axis represents the extension in mm und the y-axis is the tensile force in kN. It should be mentioned that in the case of the failure form B the maximum force is significantly higher than with the other failure forms. For example, a comparison between case B (maximum force 18 kN) and case C (maximum force 10 kN) at 800 °C shows that the maximum force is 1.8 times greater. For the failure form A, as the sheet element fails, the maximum force is not higher than with the failure form B. The failure forms C and D show a similar behavior. In these cases, the plots have a similar shape, but case D is approximately 3 kN higher than case C.

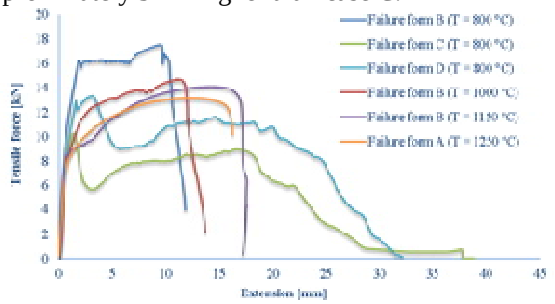
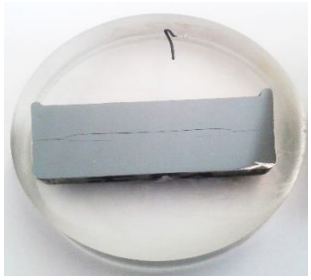


Fig. 5: Tension-extension diagram at different forging temperatures

4.2. Metallography results

To obtain the information about the metallographic changes caused in the samples by the forging , micrographs of the samples are examined. Two samples for each forging temperature are sectioned with a cut-off saw, as shown in Fig. 6. The resulting section is embedded in a synthetic resin, then the surfaces are ground and polished to take photographs under a stereomicroscope and an incident light microscope. During cutting, some samples forged at 800 or 1,000 °C show such a low adhesion that the sheet and massive element are separated without applying any forces (Fig. 6, below). In some cases, this occurs on one face of the sheet element only (Fig. 6, middle).



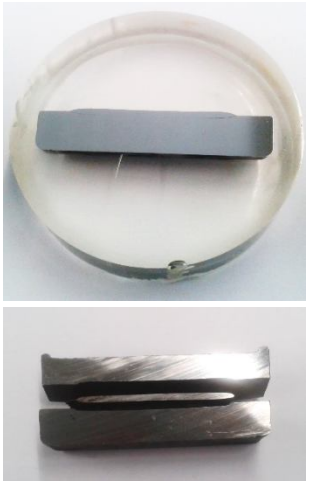


Fig. 6: Above intact sample, middle: one-sided separation, below: no connection

In the following, only samples that remained bonded on both faces are considered.

In Fig. 7 and Fig. 8, the results of an intact sample for two temperatures (800 and 1,250 °C) with three different magnifications are shown.

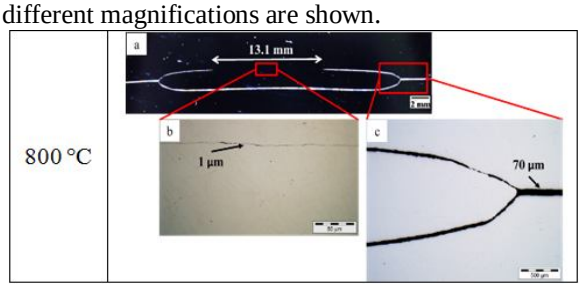


Fig. 7: Results of reflected light microscopy at 800 °C

The results of reflected light microscopy at 800 °C (Fig. 7a), an intermediate layer between the elements can be seen at the lower interface over the entire width of the sheet, but a section of bonding with a length of approximately 13 mm can be seen at the upper interface. At a higher magnification (50 µm scale bar, Fig. 7b), it is clear that a direct transition from sheet to massive element is not achieved in this area, and a layer of about 1 µm thick separates the base materials. This consists of impurities such as oxides from the surfaces of the individual elements. This layer thickness is less than the roughness of the elements to be joined, so that a reasonable strength can be achieved. The lower interface between the elements has a thickness of approximately 50 µm and thus a substantially lower strength, since here the strength of the scale layer is critical. At the outer edges of the sample, using a magnification of 500 µm, (Fig. 7c), where the sheet element ends, an approximately 70 µm thick layer of impurities is formed, and the layer also has a greater thickness at the edge of the sheet element than in the center thereof. The increase of the layer thickness at the edge of the sample with the absence of the sheet element at this point can be explained by the reduced pressure in this region; as a result, the sum of the volumes of the elements to be connected in this section is lower. This in turn, results in lower pressure

the massive element can be deformed. The pressure gradient between the center and the edge of sample leads to a flow of the impurities in the direction of the edge of the samples.

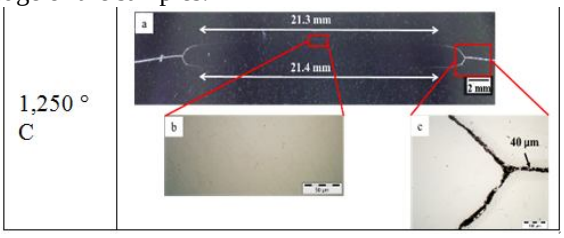


Fig. 8: The results of reflected light microscopy at 1,250 °C

At 1,250 °C, there is no pronounced intermediate layer along the majority of the contact line between the massive element and sheet element. The length of material bonding at the upper and lower interface is almost equal with a length of about 21.3 mm (Fig. 8a). Furthermore, no large-scale (50 µm) deposits can be seen at this area (Fig. 8b). At the outer edges of the sample, using a magnification of 500 µm, (Fig. 8c), an approximately 40 µm thick layer of impurities is formed.

Summarizing, the metallographic evaluation of the samples again reveals large differences between the individual forming temperatures and thus confirms the results of the tensile test. It can be seen that a material-bonding connection of the elements is also possible at the forming temperatures of 800 °C. However, this is much less frequently achieved than in the samples with higher forming temperatures.

Surface structure, material selection and duration of heating are in this case, potentially important variables with regard to the formation of a material-bonding compound. When the temperature increases, the contaminate layer loses thickness in the middle of the sample and is more pronounced at the edge of the sheet element. Additionally small impurities are formed in the edge of the massive element.

With a FEM simulation, the flow of impurities due to pressure differences and therefore, the accumulations of these at the edge of the sheet might be possibly identified.

CONCLUSIONS AND OUTLOOK

This paper describes the investigation of a hot hybrid forging consisting of a massive element and sheet element. The temperature of both elements is simultaneously varied between 800 and 1,250 °C.

The preliminary analyses of the cut samples produced show that a material bond between the massive and sheet element at all temperatures can be produced.

The tensile tests reveal that there are four failure forms. The samples with lower forming temperatures exhibit widely scattered strengths and thus the sheet element fails in the cross-section or in the massive element. With increasing forming temperature, the sheet element has a low strength in the tensile test due to the high forming temperatures causing annealing and thus fails before the bonded joint.

In metallography, the samples with higher forming temperatures show better bonding and less impurities between massive and sheet metal elements. However, even at the lowest forming temperatures, some of samples show material bonding.

In future studies, it is necessary to show how the input variables can be further adjusted and have a positive effect on the strength of the material bonding, since the lower forming temperatures offer the greatest advantages in industrial production.

In future research, fundamental investigations should be carried out in greater depth by increasing component complexity and using different materials. Furthermore, the effect of the oxide layer on material bonding must be reduced. To this end, the techniques for removing oxide layers before heating, or on the hot metal surface before forging, should be investigated further. This could involve investigating the effects of a vacuum and a dense coating, e.g. flux.

Moreover, a variation of the sheet element thickness or forming speed could potentially lead to improvement of the joint zone and help to find the best process parameters.

Due to the lack of knowledge in this field, the design of the entire process should be investigated with the aid of numerical methods and new design and procedural guidelines could be drawn up after successful tests on real components. In this case, a backward simulation can be conducted. This means that a suitable forming and heating process based on the required component properties must be defined, and on this basis, the raw material geometry could be optimized.

ACKNOWLEDGMENTS

The authors thank the German Research Foundation (Deutsche Forschungsgemeinschaft) for the funding of the research project “Hybridschmieden: Mono-prozessuales Umformen und Fügen von Blech- und Massiv-Elementen” (DFG STO1011/6-2). The authors declare that they have no conflict of interest.

REFERENCES

[1] Hirsch, J.: Recent development in aluminum for automotive applications, Transactions of Nonferrous Metals Society of China, 2014.

[2] Elalem, A.; Bourawi, M.: Reduction of automobile carbon dioxide emissions, International Journal of Material Forming, 2010.

[3] Pervaiz, M.; Panthapulakkal, Sh.: Emerging trends in automotive light weighting through novel composite materials, Materials Sciences and Applications, 2016.

[4] Holweg, M.: The evolution of competition in the automotive industry, University of Cambridge, 2008.

[5] Arif Butt, M.; Chughtai, A., Ahmad, J.: Theory of adhesion and its practical implications, Journal of Faculty of Engineering and Technology, 2008.

[6] Geipel, T.; Möller, M.; Kraft, A.; Eitner, U.: Comprehensive study of intermetallic compounds in solar cell interconnections including lead-free, low melting point

solders, European Photovoltaic Solar Energy Conference and Exhibition, 2016.
[7] Fischersworring-Bunk, A.; Landerl, Ch.; Fent, A.; Wolf, J.: The new BMW inline six-cylinder composite Mg/Al crankcase, Annual World Magnesium Conference, 2005.
[8] Vicario, I.; Crespo, I.; Maria Plaza, L.; Caballero, P.: Aluminum foam and magnesium compound casting produced by high-pressure die casting, Journal of Metal, 2016.
[9] Domblesky, J.: "Welded preforms for forging", in Journal of Materials Processing Technology 171, 2006.
[10] John, C.; Neugebauer, R.; Popp, M.: Manufacturing Al/Mg composite materials, Journal of Production Engineering, 2010.
[11] Pang, H.; Ngaile, G.: Development of a manufacturing process for high-power-density hollow shafts, Advanced Metal Forming and Tribology Laboratory (AMTL), 2017.
[12] Behrens, B.-A.; Kosch, K.-G.; Characterizing the buckling behavior of cylindrical hollow and hybrid specimens by experimental upsetting tests, in Production Engineering 7.2-3, 2013.
[13] Ravi, R ; Sarma, V.; Prasad, Y.: A hybrid intelligent systems approach for hot forging process design, Journal of the CSI, 2007.
[14] Kache, H.; Stonis, M.; Behrens, B.-A.: Hybridschmieden – Monoprozessuales Umformen und Fügen metallischer Blech- und Massivelemente , in wt Werkstattstechnik online, 2013.
[15] Ross, J.; Knust, J.; Jagodzinski, A.; Stonis, M., Behrens, B.-A.: Simulation Study On The Influence Of Process Parameters On The Hybrid Forging Quality Of A Control Arm, IEEM, 2016.

★★★