Investigations into the influence of joining surface parameters on the strength of sinter joined connections

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Abstract

When MIM parts are sinter joined, the green MIM compacts are first sub-assembled and then joined into complex component assemblies that are ready for use during sintering. This is how high complexities can be achieved using only relatively simple tools and subsequent assembly steps can be made redundant.

Systematic investigations into this innovative joining method are carried out at the Institute of Production Science (wbk) at Karlsruhe Institute of Technology (KIT). Tensile test samples have been developed for sinter joining in order to identify the influence which the quality of the green joining surfaces has on the quality of the joint.

A parameter study was conducted during which the deviations in the surface quality of tensile samples made from carbonyl iron were varied. After sinter joining, the joint quality was determined based on the tensile strength. This paper provides a description and detailed discussion of the correlations between the characteristics of the joining surfaces and the joint strength created by MIM sinter joining.

Introduction

Sinter joining represents an innovative joining method during which complex MIM assembly groups with a high functional density can be produced with less effort by separating them into single parts that are easier to mould and by subsequent joining using the sintering process. For this, the single components are mounted as green compacts and form a defined connection with an adequate process control of the assembly and sintering process. Especially beneficial for increasing the functional density is the fact that, when MIM sinter joining, the connection is done without additional joining elements or process utilities that take up additional space. It is a purely material bonding or form-locking connection created by thermally induced processes.

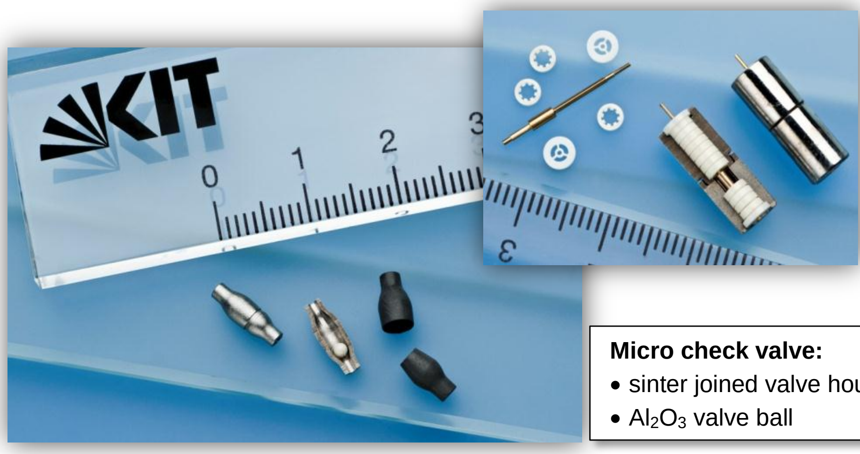

Figure 1: complex µ-assemblies created with the help of MIM sinter joining: on the left µ-check valve, on the right: demonstrator of the SFB 499 "micro casting": casted micro turbine

The advantages of this method include the possibility to visualize free formed surfaces, cavities and undercuts, mobile or fix joints and the possibility to combine different materials with functional characteristics in one assembly group. Because of this, it is possible among other things to reduce space, weight and costs since cost-intensive materials or materials with high density can be used only locally where the function of the assembly group really requires it [1].

The combination possibilities of the usable materials and their ideal debinding and sintering parameters have been already extensively studied in the field of 2K-PIM [2, 3, 4, 5]. But the geometrical requirements related to the accuracy in shape and dimension of the joining surfaces have not yet been extensively analyzed.

First approaches to examine geometries of the joining surfaces in the case of MIM sinter joining were tried at the wbk in 2005. After having examined the necessary fits for reaching a defined shaft-hub connection in the micro dimension consisting of a tungsten carbide shaft and a MIM gear of carbonyl iron [6], analyzes of the MIM sinter joining of complex hollow assembly groups with conical joining surfaces had been carried out on the basis of it [7]. Examples of assemblies that resulted from it are shown in figure 1.

In the course of the studies, it could be shown that it is basically possible to create a seamless connection. But in order to guarantee reproducible results, it has to be continued to systematically examine the necessary accuracies of the green joining surfaces [7].

Motivated by this, an automated test chain for sinter joining of MIM tensile specimen has been built up at the Institute of Production Science (wbk) which have already been presented in [8]. As object under examination serves a hollow, split tensile specimen with conical joining surfaces, on which the characteristics of the joining surfaces can be systematically varied. For a parameter variation with minimal effort, the injection mould has been designed in a way that, the mould cores representing the negative of the joining surfaces, can be replaced separately [8]. Thanks to the automation, the production process takes place under repeatable process conditions and therefore, allows a reproducible test execution.

The quantitative assessment of the sintered connection to determine relationships between dimensional accuracy and shape accuracy of the green joining surfaces and the resulting connection quality happens on the basis of the tensile strength of the sinter-joined MIM samples. The determined relations should be generalized in the future to design guidelines for complex sinter-joined assemblies that help to find a process compatible design.

Figure 2 illustrates the principle of sinter joining using the example of the developed tensile specimen.

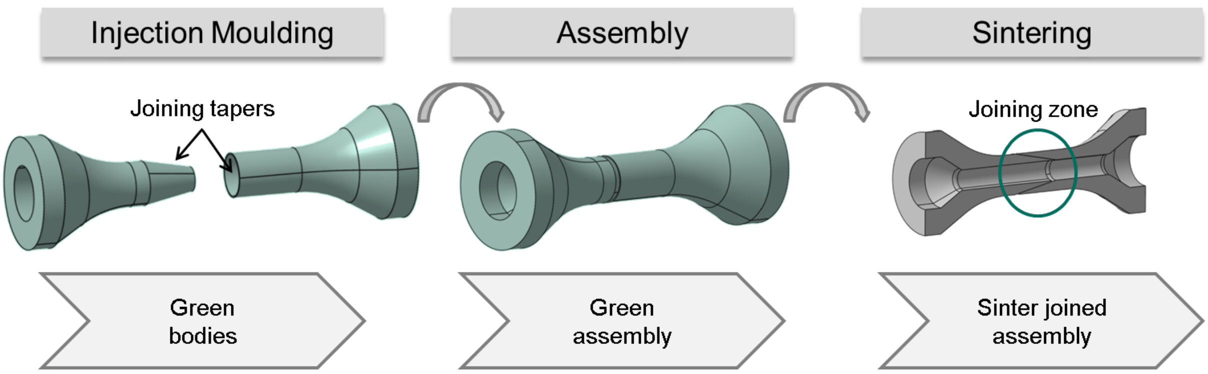

Figure 2: Principle of sinter joining by the example of the developed tensile sample

Materials and methods

Test planning and preparation

In the previous studies at the wbk it could be shown that dimensional and shape accuracy as well as surface quality of the green joining surfaces have an impact on the connection quality. This is due to the fact that they influence the gap distance in the joining zone significantly which is responsible for the taking place of diffusion processes and therefore for closing the seam [7, 9]. Within the scope of the studies, first reference values for the required joining surface parameters could be determined in order to achieve the high connection quality [7].

On the basis of these results the dimensional accuracy of the cone angle and the roundness of the cones to be joined were gradually changed in the present study. The surface quality was kept constant during the test series and lies in the range of R_a = 1,01 – 1,39 µm for test specimens with inner cone and at 0,68 – 0,77 µm.

To vary the gap distance only one join partner was changed at a time. The conical joint surfaces of the halves of tensile specimens with outer cone showing high dimensional accuracy with regard to the cone angle φ_{AK} and high shape accuracy in terms of roundness were kept constant. Random measurements at the CMM showed an average cone angle of 22,032°± 0,039 (nominal angle $\varphi_{nominal}$ = 22°) and a shape accuracy regarding the roundness of the cone to be joined $t_{AK} \rightarrow 0$. The cone angle φ_{IK} and the roundness deviation t_{IK} of the test specimens with inner cone, however, were varied in three factor levels by the use of different mould cores. Eight charges of the different factor level combinations resulted in this way. The preset factor level combinations are illustrated in figure 3.

Charge	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
φ_{AK} [°]	22	22	22	22	22	22	22	22
φ_{IK}[°]	21	21.5	22	21	21.5	22	21.5	22
$\Delta\varphi = \varphi_{AK} - \varphi_{IK}$ [°]	1	0.5	0	1	0.5	0	0.5	0
t_{AK} [µm]	→0	→0	→0	→0	→0	→0	→0	→0
t_{IK} [µm]	< 5	< 5	< 5	10	10	10	15	15
Δt	→5	→5	→5	→10	→10	→10	→15	→15

Figure 3: Factor level combinations of the test series concerning sinter joining of conical joint surfaces

Figure 4 illustrates the influence of the varied parameters on the gap distance in the joining zone.

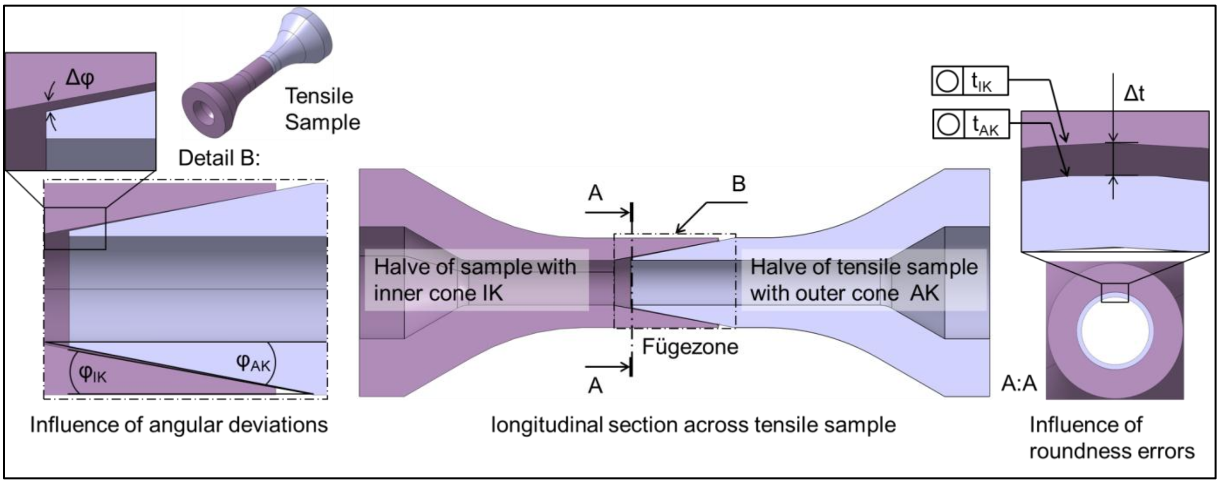

Figure 4: Simplified representation of the influence of angular deviations and roundness errors on the gap distance in the joining zone

From each charge the moulded green compacts were measured at random at a coordinate measuring machine (CMM) in order to guarantee a reproducibility of the cone angle and the roundness during moulding. The measurements showed that the values for φ_{IK} deviated from the nominal values from figure 3 by at most 0,75 % and for t_{IK} by at most 3 µm. Thus, a sound reproducibility of the test specimens is guaranteed.

Test specimen preparation

Per charge 18 carbonyl iron test specimens were produced at a time within the automated process chain. Figure 5 shows from left to right a green pair of test specimens, a green mounted assembly and a sinter joined assembly. To illustrate the dimension of the tensile specimens a scale was included into the figure: in the sintered state the specimens have a total length of approx. 13,92 mm, a maximum diameter of 5,07 mm and a minimum diameter of 2 mm in the sinter joined waistline.

Figure 5: Tensile specimen for sinter joining: green pair of test specimen, green mounted assembly and sinter joined assembly

The torsion position of the green test samples halves to each other was kept constant by means of markings on both test specimens which were identified optically and aligned to one another during the automated assembly. In the course of each automated assembly process the mounting force was detected by means of a pressure sensor to identify mounting force variations which could damage the component assembly. Figure 6 shows the test specimens during the automated assembly in the assembly machine Häcker Vico Placer.

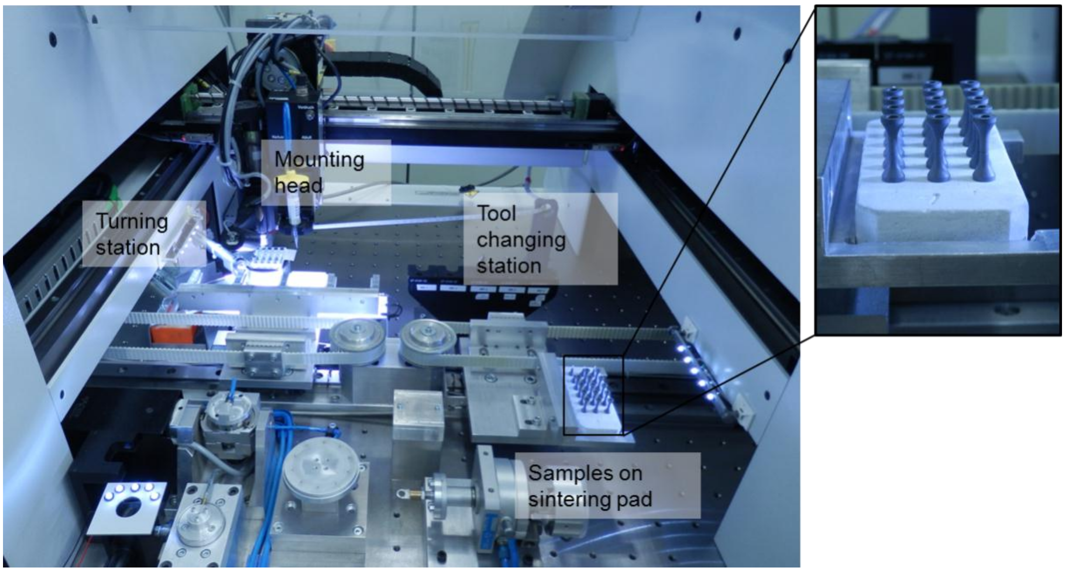

Figure 6: Automated assembly of tensile specimens in the assembly machine Häcker Vico Placer

Three sinter runs with three respectively two sintering boats at a time including 18 test specimens each were sintered. Thus, in this test run the total number of test specimens added up to 144.

The carbonyl iron feedstock used for the tests contains the Clariant binder system Licomont EK 583 (with a binder content of 8 wt%). The test specimens were debound thermally in an argon/hydrogen atmosphere at 540° C. Until this debinding temperature was reached the heating rate was 1.5 K/min, the debinding period was 40 minutes. After the debinding process, the test specimens were heated another time with a heating rate of 15 K/min up to a sintering temperature of 1270°C. The 30-minute sintering cycle took place in a purely hydrogen atmosphere.

Results

The tensile tests were carried out with a tensile testing machine of the Institute of Applied Materials – Materials Science (IAM-WK) at KIT. The boundary conditions of the tensile tests were determined as per DIN 10002-1 [10]. Between 10 and 14 test specimens of each charge were tested. Figure 7 shows the results of these tests. The figure illustrates the respective tensile strengths per charge with standard deviation.

Charge	**1**	**2**	**3**	**4**
R_m [N/mm^2]	203,6±53,8	355,64±46,16	308,00±50,83	239,10±35,15
Charge	**5**	**6**	**7**	**8**
R_m [N/mm^2]	312,00±23,42	271,54±51,81	310,23±57,01	317,21±50,66

Figure 7: Tensile strengths of the sinter joined tensile specimens of different joining surface parameters

Discussion

The maximum tensile strength of the tested sinter joined connections was 418 N/mm^2 and can be considered as high because it already exceeds the tensile strength value for MIM carbonyl iron of 372 N/mm^2 [11] that can be found in the literature. The maximum tensile strength was provided by a tensile specimen of charge 3. Actually, in this charge the highest tensile strengths were measured with a mean value of 355,64 ± 46,16 N/mm^2. The test specimens of this charge showed the minimal roundness errors with a maximum roundness deviation of 5 µm for t_{AK} and tl_K and a cone angle difference $\Delta\varphi$ of 0,5 °. However, not for all test specimens a clear influence of the roundness deviation can be detected. The test specimens of charge 5 with the highest roundness deviation for t_{IK} of 15 µm and a $\Delta\varphi$ of 0° reached on average the second highest tensile strengths of 312,00 ± 23,42 [N/mm^2]. The test specimens of charge 3 with the highest accuracies concerning both examined parameters ($t \leq$ 5 µm and $\Delta\varphi = 0°$) were with 308 N/mm ^{2} on average only slightly above the average of all tested specimens of 290 N/mm^2. Consequently, no clear influence of roundness errors can be noticed below the values of a roundness deviation of less than 15 µm.

The comparison of the cone angle difference $\Delta\varphi$ with the strength of the sintered connection showed that the cone angle difference has a negative influence on the tensile strength from an angle difference of $\Delta\varphi = 1°$. The test specimens of charges 1 and 4 with the highest cone angle difference of 1° achieved the lowest tensile strengths (57% and 67% of the maximum tensile strength reached).

Outlook

The whole relations of the test series shall be analyzed more profoundly by means of a variance analysis. In addition, relations between the resulting maximum gap dimensions, gap volumes and the tensile strength shall be researched. Depending on the results, tests with further factor levels are planned and carried out to assess the relations quantitatively.

Furthermore, there are plans to sinter a full reference tensile specimen produced from the specific feedstock that has been used together with every sinter run in order to receive reliable comparative values and to be able to assess the connection quality more precisely.

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