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Production, Bonding and Application of Metal Matrix Composite Hot Forging Tool Components

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Abstract

Metal matrix composite materials are of high interest for their increased stiffness, strength or wear resistance. Wear resistant composites contain hard ceramic particles to reduce microcutting and grooving of the metal matrix surface. In this paper, a gas atomised hot work tool steel X40CrMoV5-1 (1.2344/AISI H13) was combined with fused tungsten carbide (FTC) particles in order to create forging tools with increased abrasive wear resistance. For that purpose, tool components were manufactured by sinter-forging of stacked powder layers to build up a graded hard phase concentration of up to 10 vol.-%. Subsequently, sinter-forged specimens were combined with basic hot work tool steel components and joined by diffusion bonding to assemble the complete tool. In order to evaluate their performance, the tools were examined in a hot backward can extrusion process of low-alloyed steel. Optical geometry measurements, light microscopy and scanning electron microscopy of the worn tool radii indicated a significant decrease in abrasive wear when using FTC-reinforced tools rather than conventional hardened tool steel.

Keywords: hot forming; sinter-forging; metal matrix composites; wear; diffusion bonding

1. Introduction

Metal matrix composites (MMCs) feature a combination of a metal matrix and a secondary material, thereby achieving new overall material properties of composite. This concept allows the creation of materials which are specifically designed for their application. Possible examples include strong and lightweight aluminum/silicon carbide MMCs or wear resistant iron-based composites [1]. These wear resistant composites exhibit increased grooving resistance due to embedded hard phases. The chemical composition of the hard particles may vary as well as the steel matrix alloy. Particle size, shape and concentration can be adjusted to create the desired properties [2].

The aforementioned parameters can be adjusted relatively easily in a powder metallurgical (PM) production process. If this is applied locally, functionally graded materials can be created. Their local material properties are tailored to the local loads or functionalities of the powder metallurgical part. In hot forming applications, this might be an increase in hardness or general wear resistance of the surface regions [3,4]. A steady hard phase concentration gradient towards the parts volume decreases local stress concentrations and thereby the risk of cracking under mechanical or thermal loads [5].

The general feasibility of hard phase reinforced steel MMCs has been proven in wear tests and some practical applications [6]. A remaining challenge is the production of the wear resistant components. Laboratory scale processes include conventional sintering [7], hot isostatic pressing [8] or hot extrusion [9]. The produced MMCs are more difficult to machine and require increased effort and care in comparison to conventional materials or PM parts [10]. To overcome these problems, wear resistant graded metal matrix composites can be bonded to a solid metal part.

This study aims to produce hot forming tools with a functionally graded metal matrix composite wear surface, to

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test them in this demanding application [11,12]. To achieve this, a feasible bonding strategy needs to be developed. Possible solutions reach from welding techniques to interference fitting or threaded constructions. As any remaining cavities or sharp radii are detrimental to the later usability in a forging process, diffusion bonding techniques are evaluated and compared to interference fitting as reference. Finally, the produced forging tools are evaluated in forging experiments and their wear behavior is examined.

2. Materials and Methods

2.1. Powder Metallurgy

The MMC components were produced via a sinter-forging route. It starts with the cold compaction of the powder followed by a sintering process. After sintering, the process-related residual porosity is reduced by a forging operation.

The steel powder (X40CrMoV5-1 (1.2344)) was gas atomised and is of the same chemical composition as the later bonding partner. The content of the alloying elements is given in table 1, as certified by the producer (TLS Technik, Germany). Futhermore, the powder particle size was examined, with the results shown in figure 1.

Table 1. Chemical composition of the matrix metal powder in wt.-%.

C	Si	Mn	Cr	Mo	Fe
0.4	1.1	4.7	5.1	1.3	Bal.

Specimens with and without carbide reinforcements were created by stacking layers of increasing carbide concentration, up to 10 vol.-% at the later working surface. The bonding zone was kept carbide free. Fused Tungsten Carbides (FTC) were used as hard phases, with their size ranging from 63 µm to 180 µm. To enable the compaction of the powder, 1 wt.-% of microwax (Deurex MA 7050) was added. The individual powder compositions were mixed with the help of a Turbula mixer (Willy A. Bachhofen AG, Switzerland).

The cold compaction was carried out on a hydraulic powder press (SMS Meer, Germany) with controlled movement of the upper and lower punches within the die. This allowed for equal compaction pressures on the upper and lower surface of the green compact. The gas atomised powder showed a high tap density of 4.5 g/cm³ but poor pressability with a density of 6.2 g/cm³ at 600 MPa.

The green compacts with a height of 35 mm and diameter of 36 mm were then sintered using a hot wall vacuum furnace (Xerion, Germany). Sintering temperature was 1150 °C, which was held for 40 min. In previous work, it was found that the FTC particles dissolve at sintering temperatures of 1200 °C and higher. Therefore, the sintering temperature was lower than the usual values for highly alloyed tool steels. The weight of the specimens was measured by a precision scale KERN EG620 (Kern & Sohn, Germany) before and after sintering. A weight loss of 1 wt.-% was detected, which is attributed to the burn off of the microwax.

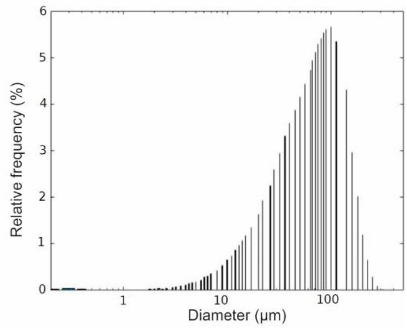

Fig. 1. Particle size distribution of the MMC matrix powder, gas atomised X40CrMoV5-1 hot work steel

Subsequent to sintering, the specimen were heated in a batch furnace for 20 min to 1150 °C forging temperature. The sinter-forging operation was carried out on a screw press (LASCO, Germany) and was designed to minimize material flow. Thus, the gradient structure of the FTC particle concentration is preserved. The sinter-forged specimen were then annealed to allow machining in the next process step.

2.2. Bonding Strategy

The bonding of the PM components with conventional base material was developed without carbide reinforcements to facilitate easy machining of the specimens. The area near the bonding zone would stay carbide free as well for the MMC components. Therefore, an application of the same bonding strategies should be possible.

The aim was to achieve a strong bond, that withstands the high compressive forces required for forging tools. Thus, a diffusion bonding process was chosen, as it uses the part´s full cross section without any cavities or sharp edges. Its parameters were based on literature [13] and verified in try-out tests with conventional (rolled bar stock) steel cylinders. The geometry of the diffusion bonding specimens is given in figure 2 c.

It features a smooth bonding surface and the ends are of increased diameter to allow threading and safe fixation in the testing machine. These specimens were machined from PM cylinders produced by sinter-forging and from conventional bar stock. The bonding surface was ground and roughness measurements showed a surface roughness below R_z 1.5. The PM parts were then each paired up with a conventional one and these stacks were diffusion bonded with help of a hot sintering press (Dr. Fritsch, Germany).

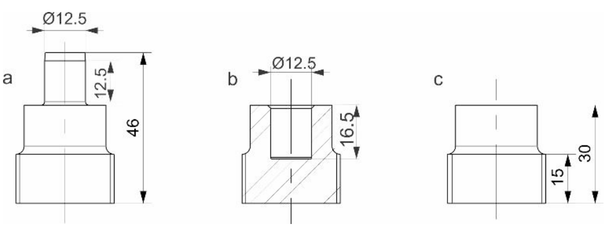

Fig. 2. Different geometries for bonding test specimens: (a) conventional interference fit part (b) PM interference fit part (c) diffusion bonding part

Three specimen stacks were placed in the vacuum chamber of the hot sintering press and processed simultaneously. Graphite electrodes on top and bottom provided electric current and applied the bonding pressure, see figure 3a. The temperature was measured optically by a pyrometer Metis M316 (Sensortherm, Germany) attached to the hot sintering press. The bonding temperature was 1200 °C and a bonding pressure of 14.7 MPa was used, as higher values lead to excessive deformation of the stacked bonding parts. The holding time at bonding temperature was 30 min. In addition to the plain steel-steel diffusion bond, a pure nickel interlayer with 0.1 mm thickness between the steel parts was also tested.

As reference an interference fit was designed to join the PM component and the conventional material. The interference fit was designed according to DIN 7190 with an interference between 22 µm and 51 µm on a cylindrical surface with 12.5 mm diameter. The aim was to achieve the highest possible pull-out strength without risking material fracture. The real interferences during the experiment were 50 +/-20 µm. The outer part (PM component) was heated to 450 °C and both were swiftly pressed into each other.

The three different variants were then tested on a tension testing machine (Dynamess, Germany). Of the diffusion bond without interlayer 7 specimens were tested, for the other two variants 9 specimens could be tested.

With the experience from the tensile specimens, forging tools were produced by diffusion bonding a graded MMC component to a conventional tool steel (1.2344) base part, see figure 3c. The sinter-forged MMC components were annealed, machined and then diffusion bonded to the machined base parts from rolled bar stock material. The bonding parameters were identical to the tensile specimens with interlayer. After diffusion bonding, the combined parts were annealed again and machined to their final geometry before final heat treatment to a hardness of 48-50 HRC of the steel matrix.

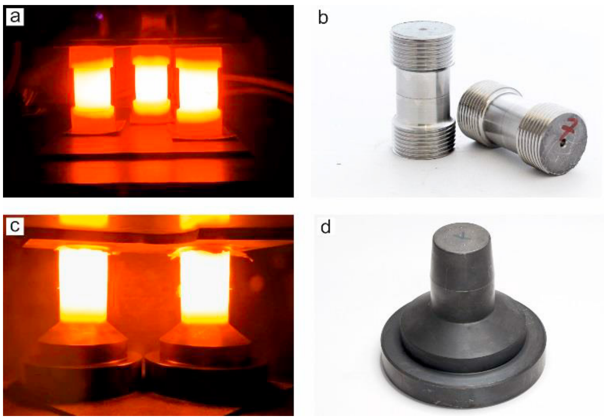

Fig. 3. Diffusion bonding procedure (a) for the tensile specimens (b) and the bonding (c) of MMC component and tool (d) complete tool after machining and hardening with a height of 80 mm

2.3. Forging Application

The forging tests were conducted on a screw press (Weingarten, Germany). The chosen backward can extrusion process was designed to result in significant abrasive wear of the tested tools' radii, see figure 4. The material used during the forging trials was the common low alloy steel 42CrMo4 (1.7225) and was heated to 1100 °C forming temperature. The upper punch and the lower forging die were lubricated with a commercial graphite spray Con Traer G300 (Fuchs Lubritech, Germany).

In total, five punches were tested in the forging experiments, of which two contained reinforcing particles. One was produced by the same sinter-forging route but contained no hard phases (PM) and one was machined completely from bar stock material (Ref), see table 2.

Table 2. Overview of the punch variants tested in the forging experiments

Designation	Quantity	Diffusion Bonded	FTC	Tested Cycles
Ref	1	No	No	100
PM	1	Yes	No	50
FTC	2	Yes	Yes	100

The Geometry and surface roughness of the punches were measured before the forging experiment and after 10 and 50 cycles. Three punch variants were also investigated after 100 cycles. The geometric measurement was performed with a wide-area 3D measurement system VR-3200 (Keyence, Japan). For the roughness measurements the system T8000-RC (Hommel, Germany) was used.

After the completion of the forging tests all punches were investigated with a digital light microscope VH-55 (Keyence, Japan). Selected punches were closer examined using a scanning electron microscope SUPRA 55VP (Zeiss, Germany). Sections of the tool radii and bonding zone were cut by Electric Discharge Machining (EDM) and inspected with a light microscope POLYVAR MET (Leica, Austria).

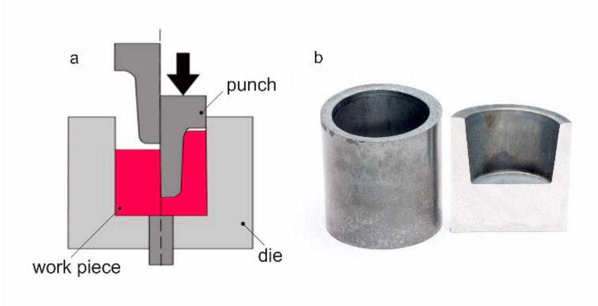

Fig. 4. (a) Schematic representation of the backward can extrusion process (b) geometry of the forged part

3. Results and Discussion

3.1. Bonding Process

The diffusion bonding tests resulted in valuable information on the general parameter requirements and feasibility of the concept itself.

The tensile testing of the three differently bonded specimens showed clearly that diffusion bonding with the nickel interlayer is superior to diffusion bonding without interlayer and to the interference fit (see table 3). The achieved pull-out strengths of the interference fit is in agreement with the design calculations.

Table 3. Tensile strength of the tested bonding strategies

	Interference fit	Diffusion bond	Diffusion bond with interlayer
Mean tensile strength (MPa)	39.55	85.11	117.82
Standard deviation (MPa)	12.72	24.68	27.59

Subsequent metallographic examination of the failed bond showed for both diffusion bonding strategies a fracture within the PM part. Two specimens with interlayer tolerated the maximum tensile stress of 150 MPa. The regions near the bonding surface show porosity and weak sintering of the particles even in the specimens that remained intact, see figure 5. The low strength of the PM parts during the tensile tests is attributed to this incomplete sintering and densification. A possible explanation is the low sintering temperature of 1150 °C. It is necessary to avoid melting of the steel matrix near the FTC particles and the subsequent dissolution of them. Regularly, tool steel powders are sintered at higher temperatures, even using Liquid Phase Sintering (LPS) processes [14,15]. A possible solution to this problem is the use of pressure assisted sintering technologies such as Hot Isostatic Pressing (HIP). These have lower temperature requirements for the successful densification of tool steel powder [16].

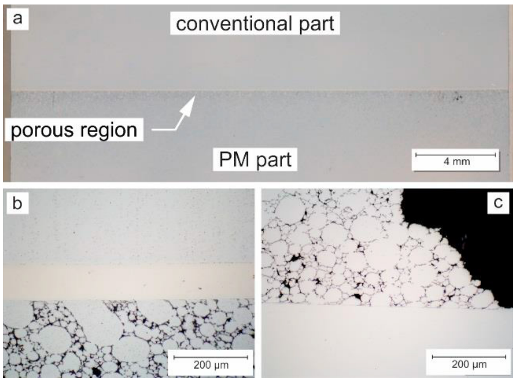

Fig. 5. (a) Metallographic images of the bonding zone of an interlayer diffusion bonding specimen after tensile testing (b) magnified image with the conventional part, the nickel interlayer and the porous PM part (c) PM material remnants at diffusion bonding zone (without interlayer) after fracture

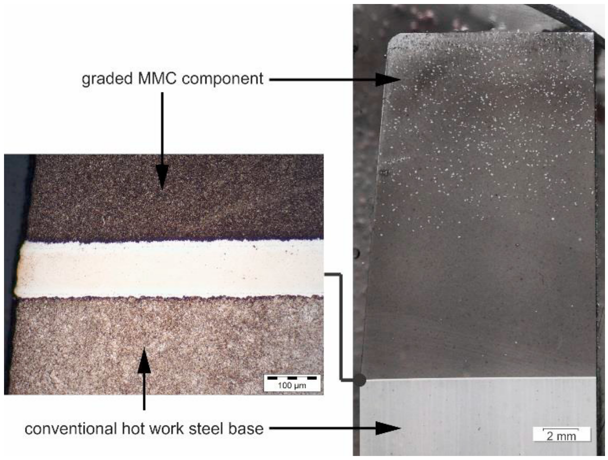

Fig. 6. (a) Metallographic image of the diffusion bond of the machined MMC part (dark) with the Ni interlayer (white) and the conventional tool base (brown) (b) contrasted image of a section through MMC component (dark with white FTC particle) and base steel component (grey)

The fact that the nickel interlayer had a significant impact on the fracture stresses of the PM component might be explained by residual stresses due to the diffusion bonding process. These are reduced to some extend by the ductile nickel layer and therefore the PM components can sustain higher loads compared to the bonding processes without an interlayer [17,18].

After machining of the imperfect regions, fully functional tools were produced and tested. Metallographic examination of these bonds show fully densified microstructure and full interlayer contact. This is shown in figure 6, which also shows the hard phase concentration gradient towards the working tool surface.

3.2. Forging Experiments

The forging experiments functioned as a test of the MMC components integrity and the bond between MMC and base tool under realistic loading conditions. During the tests, no preliminary failure of either was observed. The diffusion bonding strategy left no detrimental weak points in the tool´s structure and the compressive and tensile forces during the forging process were tolerated. The MMC components produced by sinter-forging achieved nearly full densification. The matrix tool steel showed similar hardening properties and microstructure to the reference material.

During the forging tests the surface roughness of the punch front area is increasing at a similar rate for all tested variants, see figure 7. The light microscopic images of the punches´ frontal face and radius confirm this, see figure 8. The freshly machined surfaces showed remaining micro grooves from the machining operation. After 10 forging cycles both, the surfaces of the reference and the MMC material, show radial grooving due to abrasion by the formed material. The grooving of the punches increases with the forging cycles, as shown in images 8d-f.

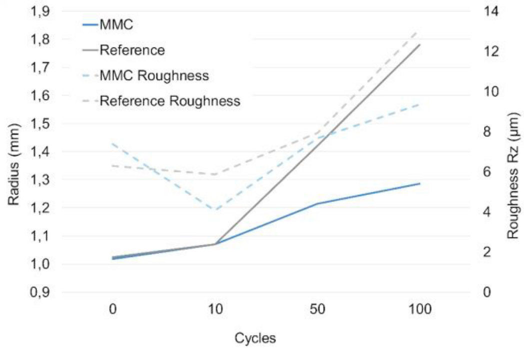

Fig. 7. Development of punch radius and front face roughness for the MMC punches (mean of the two FTC) and the reference punches (mean of Ref and PM)

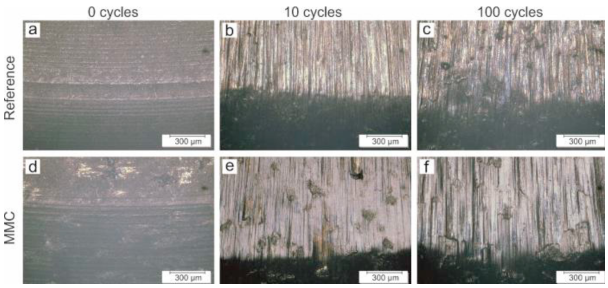

Fig. 8. Microscopic images of the reference material punch radius and front face (upper row) and the MMC punch radius and front face (lower row) before the forging tests (a,d) after 10 (b,e) and after 100 cycles (c,f)

Based on these results, the PM production and the addition of the FTC particles have no significant impact on the roughness of the punch front area. However, the optical measurements of the punch radius profiles indicate a rougher, more irregular surface of the worn MMCs´ radii over the reference. Figure 9 shows a comparison of the initial tool profile and the worn radius profiles of the MMC and reference tools after 100 cycles. The material loss is significantly reduced and therefore the increase in punch radius is smaller with the MMC components. The profile of the MMC punch radius shows the rougher, more wavy appearance compared to the smooth, gradual surface of the reference.

These differences are very clear in the SEM images in figure 10. While the hardened 1.2344 abrades evenly, the hard particles in the composite punches protrude from the surface thereby cause the rough surface. The BSE images clearly identify the surface elevations as the FTC particles, as they appear white in contrast to the dark grey matrix steel.

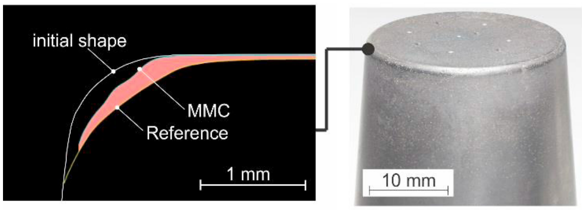

Fig. 9. Comparison on the initial punch radius profile and the worn profiles of MMC and reference punches after 100 cycles

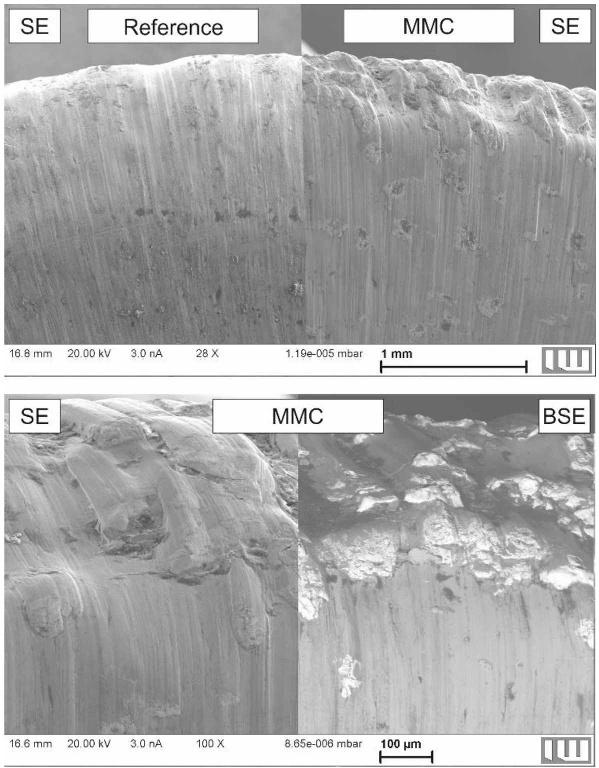

Fig. 10. SEM images of the worn tool radii. The secondary electron (SE) images show the topography of the surface. The back scattered electron (BSE) images contrast the material density and show the FTC particles in white.

The FTC particles provide abrasion protection to matrix material directly behind them (in the direction of material flow). Grooves running up to the FTC particles are stopped.

With these observations, the fundamental mechanism of abrasion resistance in wear resistant MMC reported in the literature [2] could be confirmed. The concept of hard particles hindering the indentation and grooving of the MMC´s surface by abrasives and thereby reducing abrasive wear is applicable in hot metal forming tools. This is further reinforced by the metallographic examination of section through the worn radii of MMC and reference punches shown in figure 11. The surface profile of the worn tool radius is pushed outwards in regions were hard phases are present causing the wavy profile shown previously in figure 9. In contrast, the radius of the reference punch showed a smooth worn surface and plastic deformation.

Both, the light microscopic and the SEM examinations revealed cracks between hard phase particles. These did not lead to tool failure, but question the longevity of the components. The sharp edges of the blocky FTC particle might act as local stress risers and the ductility of the matrix is too low to stop crack growth. Adaptations of hard phase shape, size and matrix hardness are likely to reduce these problems.

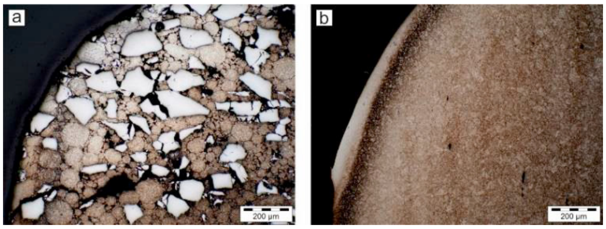

Fig. 11. Metallographic image of the worn MMC (a) and reference (b) punches after 100 cycles

4. Conclusion

The presented results show a promising approach to reducing abrasive wear in forging processes by the use of wear resistant MMC components in forming tools. A diffusion bonding process with direct heating was used to combine MMC and base tool components. The produced tools showed increased abrasion resistance and further examination revealed the wear protection mechanism to be similar to that of wear resistant MMCs in other tests and application. Thereby, the study was able to demonstrate the successful application of these wear components in hot forming tools.

This provides an alternative wear protection concept to the conventional nitriding or hard coating of hot forging tools. A potential advantage is the increased damage tolerance over surface treatments, as these fail abruptly once the hard surface layer is compromised. The hot forming of abrasive materials like high alloyed steels or even other MMCs might be a potential application. To enable practical applications, further research will be dedicated to investigate fatigue properties and cracking behavior of the wear components in prolonged use.

Acknowledgements

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