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Increasing the Lightweight Potential of Composite Cold Forging by Utilizing Magnesium and Granular Cores

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Abstract: In this paper a process sequence, that uses forward rod extrusion with cold forged C15 steel cup billets to produce lightweight shafts, is presented. The steel cup billets feature either a lightweight magnesium alloy core or a granular medium core that is removed after forming to obtain hollow shafts without the need of complex tools and highly loaded mandrels. It is shown that composite shafts featuring magnesium cores can be produced for a wide range of extrusion strains. Due to high hydrostic pressures in forward rod extrusion, the forming limit of magnesium at room temperature can be expanded. The observed bond strength between core and sheath is below the shear yield strength of utilized magnesium AZ31 alloy. Hollow shafts are successfully produced with the presented process route by utilizing zirconium oxide beads or quartz sand as a lost core. As the law of constant volume in metal forming is violated by compressible granular media, a simulation approach using a modified Drucker-Prager yield surface to model these materials is validated to provide a tool for efficient process design. Granular cores and magnesium alloy cores offer new possibilities in production of lightweight shafts by means of composite cold forging. Both process variants allow for higher weight savings than composite shafts based on aluminum cores.

Keywords: composite cold forging; granular media; lightweight components

Citation: Gitschel, R.; Kolpak, F.; Hering, O.; Tekkaya, A.E. Increasing the Lightweight Potential of Composite Cold Forging by Utilizing Magnesium and Granular Cores. *Metals* **2021**, *11*, 32. https://dx.doi.org/10.3390/met11010032

Received: 2 December 2020
Accepted: 22 December 2020
Published: 26 December 2020

1. Introduction

Lightweight design in the transportation sector is indispensable nowadays to cut down energy consumption and greenhouse gas emissions, accordingly. Different lightweight design strategies impose different requirements on forming technologies and production engineering in general. Thus the development and adaption of forming processes to the needs of lightweight design and ecological production is an ongoing field of research.

In hybrid lightweight design approaches, materials are applied according to their specific properties and local requirements of a component. The use of multiple materials calls for methodologies to join them. To combine the advantages of hybrid lightweight design with the high precision and high output rate of cold forging, various studies focused on joining materials by means of cold forging processes.

First investigations of composite cold extrusion were conducted by Gumm in 1964 [1]. The author successfully joined aluminum and copper by forward rod extrusion, forward hollow extrusion and backward can extrusion by either a serial or parallel arrangement of the forming partners, as depicted in Figure 1a–c and showed that bonding strength of the two materials is proportional to the surface expansion of the contacting surfaces. Further studies have shown that joining a vast variety of materials by cold forging is feasible. Material combinations of steel/copper [2], steel/nickel [2], steel/aluminum [3] and titan/aluminum [4] were successfully joined by cold forging processes. The bond between joining partners can either be of metallurgical, force-fitting or form-fitting nature. In order to achieve a metallurgical bond at room temperature, the plain materials, that are covered by oxide layers, need to get in direct contact [5]. To achieve such contact in a forming process, high surface expansions as well as high normal pressures are required [6]. The surface expansion leads to cracks in covering oxide layers, through which the material is extruded by the high contact pressure. The contact of micro-extruded material of both joining partners finally results in a cold pressure weld. Further research by Bay has shown that preliminary treatment of joining surfaces for example, by a rotating brush can improve the weld quality [7]. Also the heat treatment condition of the forming partners affects the bond strength [8].

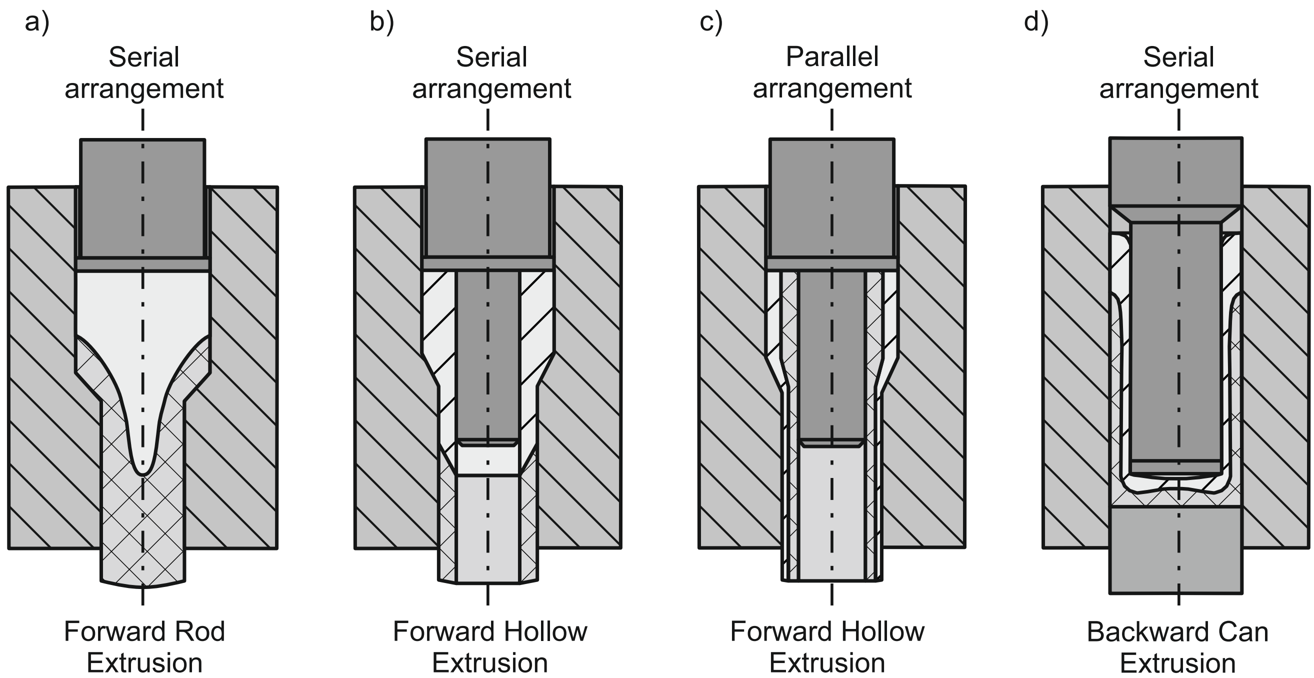

Figure 1. Cold forging processes and arrangement of materials in used composite billets. (**a**–**c**) representing works by Gumm [1] and (**d**) investigations by Wagener and Haats [4].

Ossenkemper et al. [9] presented a composite cold forging process that uses hybrid semi-finished products consisting of a steel cup and a lightweight aluminum alloy cylindrical core. This composite billet is then formed by means of forward rod extrusion, using conventional tools (Figure 2). Ossenkemper et al. [10] showed by means of FEM -simulations that conditions for cold pressure welding are not met in composite forward rod extrusion. Instead a force-fitting bond can be achieved by the residual stress acting on the contact area of core and sheath after forward rod extrusion. The resulting bond strength can be described by an analytical model that takes yield stresses and Young's moduli of the forming partners into account. The model is in agreement with push-out tests of shafts produced by cold forged billets made from backward can extruded steel cups. However, this is only the case for a smooth, as forged, inner surface of the cold forged steel cups. Sandblasting the inner cup surface before inserting the aluminum core results in increased bond strength that even succeeds the shear yield limit of the aluminum core. As a metallurgical bond was rejected as the bond strength governing mechanism by previous studies, a micro form fit induced by aluminum flowing into the indents of the sand-blasted steel cup was identified as the pertinent mechanism [11]. Apart from that, the authors also implemented a macroscopic form-fit in tangential direction by using non-round core geometries and corresponding punch geometries in backward can extrusion for production of the steel cups. A form-fit in axial direction can be achieved by applying shaft shoulders on both ends of the shaft.

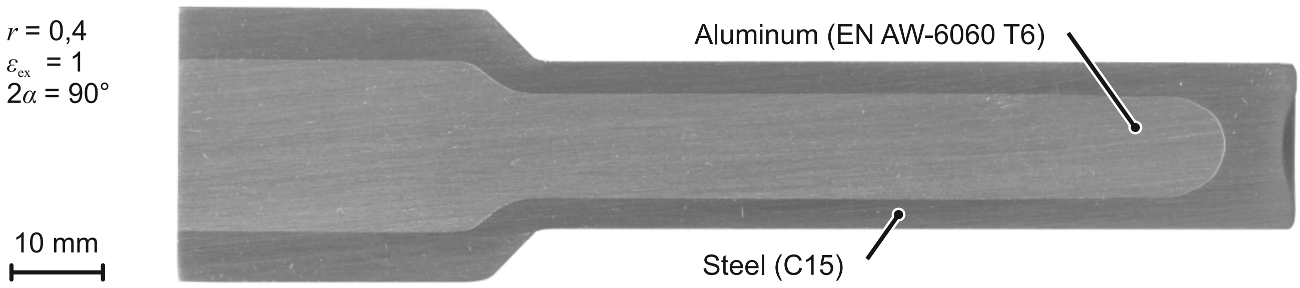

Figure 2. Composite shaft, produced by forward rod extrusion of a backward can extruded steel shaft with an aluminum core, according to [9].

The presented method is especially suited for the production of gear shafts, as the parallel arrangement of steel and aluminum allows for weight reduction with only small losses in torsional and bending stiffness, which are needed to withstand torque and axial forces during service life of a gear shaft.

The goal of this paper is to further increase the lightweight potential of the composite cold forging process. The use of magnesium as a core material as well as granular media cores that are removed after forming are investigated. Figure 3 compares the lightweight potential of magnesium-steel composite shafts and hollow shaft to aluminium-steel composite shafts.

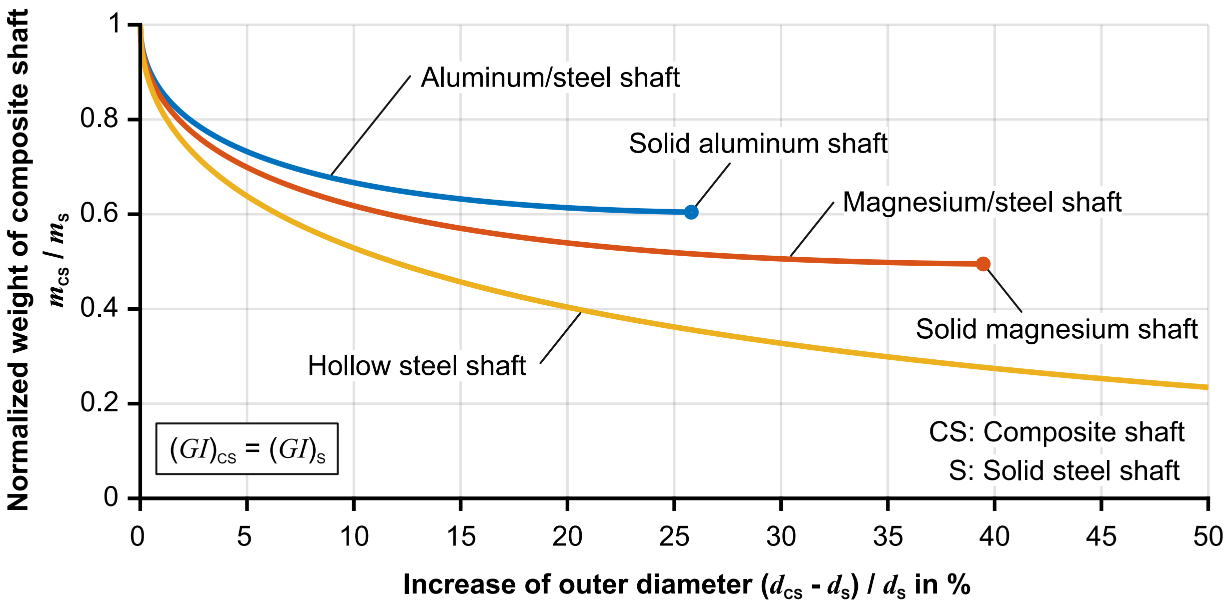

Figure 3. Mass savings for substituting a solid steel shaft by composite shafts with aluminum core, magnesium core and hollow shafts with identical torsional stiffness.

A solid steel shaft with given diameter d_S and torsional stiffness $(GI)_S$ is considered. This shaft is substituted by a composite or hollow shaft with identical torsional stiffness. To achieve the same stiffness, the outer diameter of the composite or hollow shaft needs to be increased due to the weaker shear moduli of the core materials. For an increasing cross sectional area share of the core material, weight reduction increases at the expense of further increase of the outer diameter of the composite shaft. Hollow shafts and composite shafts with magnesium core are superior to aluminum-steel composite shafts in terms of weight reduction. Thus the limiting conditions of manufacturing such shafts by means of composite cold forging are studied numerically and experimentally in this paper.

2. Materials and Methods—Magnesium-Steel Composite Cold Forging

2.1. Process Route

The process route for the production of steel-magnesium composite shafts is shown in Figure 4. The steel cups are produced by means of backward can extrusion, where a cylindrical punch indents the billet which is surrounded by a die. The material flows in the opposite direction of the punch displacement, forming the ring-shaped wall section of the cup.

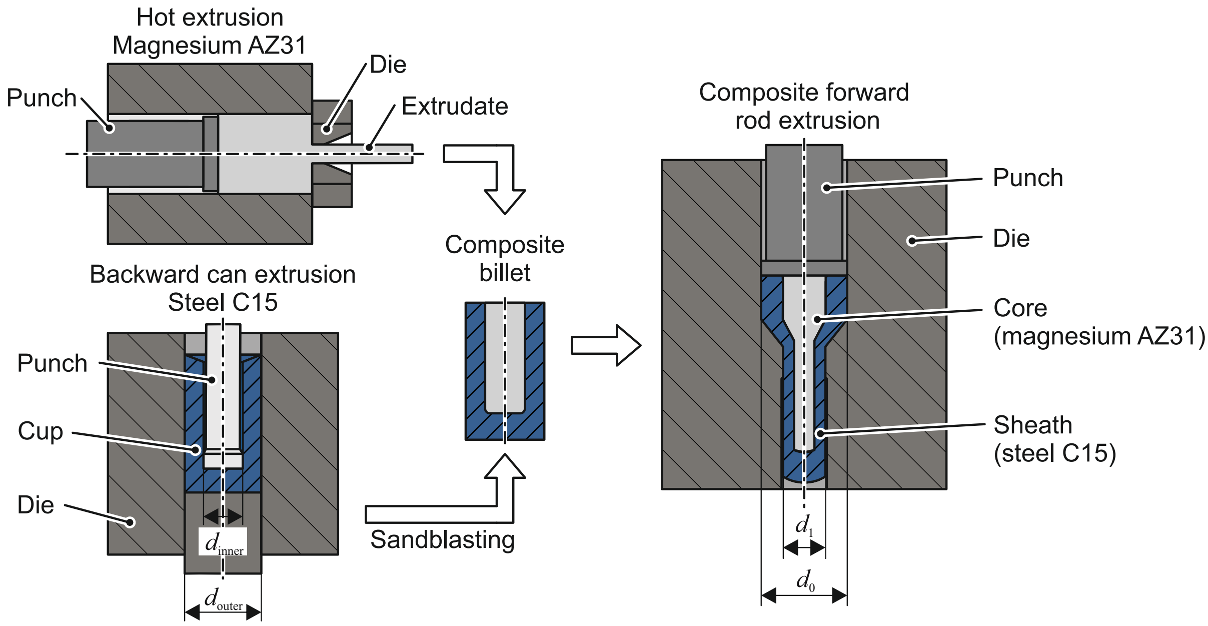

Figure 4. Process route for production of composite shafts with magnesium core. The composite core, consisting of a backward can extruded steel cup and a hot extruded magnesium core is formed to a shaft by composite forward rod extrusion.

The process is specified by the reduction ratio r, expressed by

$$r = \frac{d_{\text{inner}}^2}{d_{\text{outer}}^2}, \tag{1}$$

where d_{inner} denotes the inner and d_{outer} the outer diameter of the produced cup. Due to local plastic strains of up to $\varepsilon = 5$ during backward cup extrusion, the produced cups exhibit increased work hardening. In this paper cup geometries with reduction ratios $r = 0.2$, $r = 0.4$ and $r = 0.6$ are considered. Corresponding inner diameters d_{inner}, initial billet diameter and bottom thickness of the cup are given in Table 1. Aiming for the micro form fitting bond, observed by Ossenkemper et al. [10], the inner surface of the cups is sandblasted and cleaned in an ultrasonic bath before inserting the cores.

The core of the composite billet is produced by direct hot extrusion with flat-face dies. Round profiles with diameters matching the inner diameters of the three cup geometries are produced. The magnesium AZ31 alloy extrudates are cooled at air, cut to length and cleaned in an ultrasonic bath before they are inserted into the steel cups.

The composite billets are finally cold forged, using conventional forward rod extrusion tools. A punch pushes the the billet through a die shoulder, reducing its initial diameter to a desired shaft diameter. The extrusion strain ε_{ex} equals the plastic equivalent strain at the middle axis of the formed shaft and is given by

$$\varepsilon_{\text{ex}} = \ln\left(\frac{A_0}{A_1}\right) = 2\ln\left(\frac{d_0}{d_1}\right), \tag{2}$$

where d_0 and d_1 denote the initial radius of the billet and the shaft radius, respectively. During the simultaneous extrusion of core and sheath, the sheath behaves similar to an inner die with a reduced diameter. As the principle of constant volume holds, the inner diameter of the magnesium core $d_{\text{core},1}$ after forming, and thus also the wall thickness of the sheath, can be determined analytically by:

$$d_{\text{core},1} = \frac{d_{\text{core},0}}{\sqrt{\exp(\varepsilon_{\text{ex}})}}, \tag{3}$$

where $d_{\text{core},0}$ denotes the initial core diameter.

To investigate the process' limits a variety of extrusion strains ε_{ex} = 0.3 to ε_{ex} = 1.5 is considered (Table 1).

Table 1. Investigated parameters in composite cold forging with magnesium core billets.

Varied Parameters						
Reduction ratio *r*		0.2	0.4	0.6		
(corresponding inner cup diameter)		(13.4 mm	19 mm	23.2 mm)		
Extrusion strain ε_{ex}	0.3	0.5	0.7	1.0	1.2	1.5
Fixed Parameters						
Cup material	Steel C15 (1.0401)					
Core material	Magnesium AZ31					
Inner cup surface treatment	Sandblasting					
Billet diameter	30 mm					
Cup bottom thickness	12 mm					

2.2. *Materials*

Magnesium features a low density and high specific strength [12]. Due to its hexagonal close packed lattice structure and resulting low ductility magnesium is unfavourable for forming applications at room temperature. However, its formability can be increased by superposing hydrostatic pressure [13]. Forward rod extrusion exhibits appropriate hydrostatic pressure, especially for high extrusion strains [14], and thus offers the prerequisites for the forming of magnesium up to high strains at room temperature. In this paper, the frequently used magnesium alloy AZ31 is investigated. For the outer steel sheath the case-hardening steel C15 is utilized.

3. Results and Discussion–Magnesium-Steel Composite Cold Forging

3.1. *Process Limits*

Figure 5 shows parts produced by forward cold extrusion of cold forged cups with inserted magnesium cores. Parts that do not show macroscopic defects at the outer surface are cut in half to examine the inner core. Two types of failure occur, which are cracks at the inner surface of the steel sheath and cracks along the whole thickness of the sheath. The former is present for small extrusion strains in combination with high cup wall thicknesses. The onset of each crack can also be observed in the process force, as shown in Figure 6, where each crack leaves a characteristic drop in the force-displacement curve. Periodic internal arrow-shaped cracks at the central axis, also called chevron cracks, are a common process failure in conventional forward rod extrusion with small extrusion strains. They can be often identified by the concave shape of the front face of the extruded shaft. These chevron cracks occur due to hydrostatic tensile stresses in the forming zone [15]. As shown in Figure 5, parts with internal cracks also feature a characteristic concave front face. However, the cracks do not initiate at the magnesium core, but at the inner surface of the steel sheath. It is observed that cavities in front and behind the core develop, which implies a relative motion between core and sheath, such that it acts like a moving mandrel.

This prevents high tensile stresses from being transmitted to the magnesium core, which is why the core does not show any failure. As stress conditions for chevron cracks are absent at the edge region of an extruded shaft, composite shafts with high reduction ratio in backward can extrusion, meaning low wall thicknesses, do not show any chevron cracks.

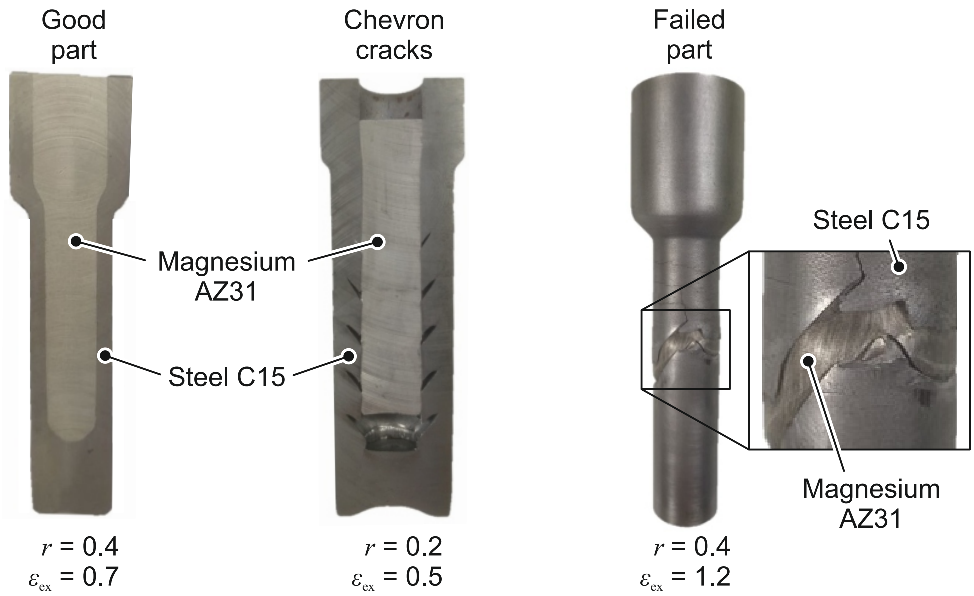

Figure 5. Parts produced by magnesium-steel composite forward rod extrusion.

For high extrusion strains and high area reductions, macroscopic cracks over the entire sheath thickness are observed. These defects occur during ejection after forward rod extrusion, as no force drop is observed during the forward rod extrusion process. As ejector forces increase and the cross sectional area of the shaft decreases for higher extrusion strains, the shaft is more prone to upsetting during ejection. This is especially the case for low sheath wall thicknesses, which is why this type of failure is promoted by the use of steel cups with high reduction ratios.

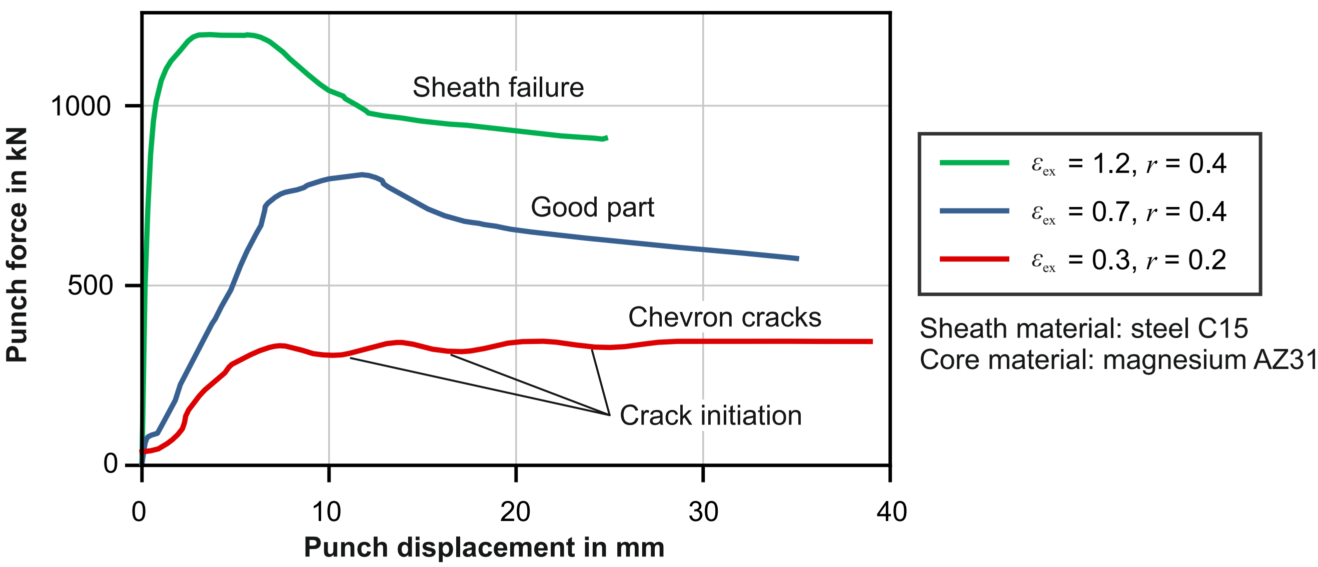

Figure 6. Punch forces in magnesium-steel composite forward rod extrusion.

The complete process window for magnesium-steel composite forward rod extrusion is depicted in Figure 7. It is shown that the process is applicable for a wide range of parameter combinations. The hydrostatic pressure in the forming zone for high extrusion strains allows to form the magnesium core to strains of up to ε_{ex} = 1.2. As failure only occurs in the steel sheath, the process is not limited by the low forming limit of magnesium at room temperature.

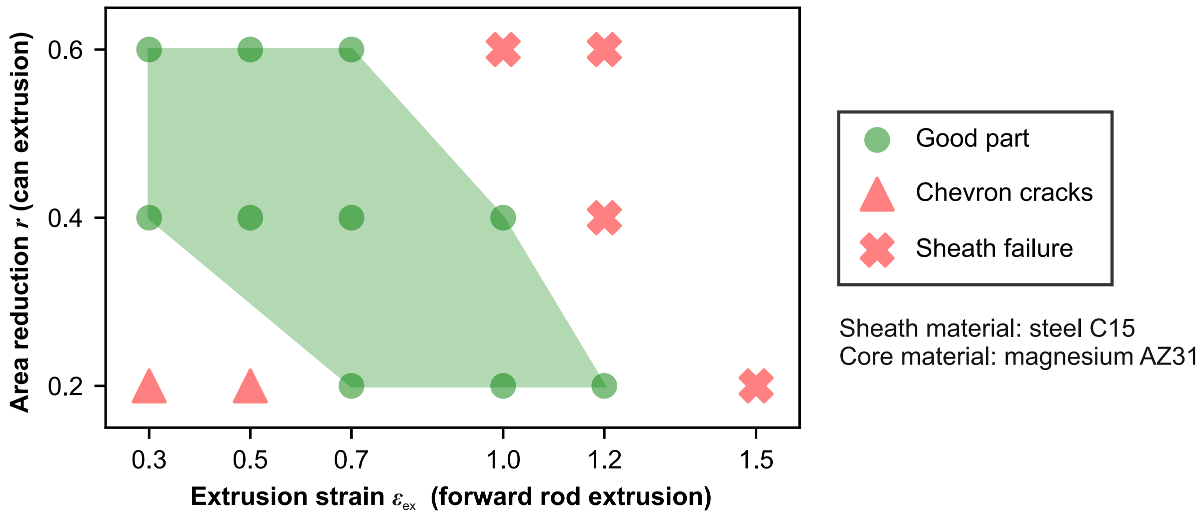

Figure 7. Process window of magnesium-steel composite forward rod extrusion.

3.2. Bond Strength

To asses the bond strength between magnesium cores and the steel sheath, push-out tests are conducted. A 5 mm thick disc is extracted from the area of homogeneous plastic strains of the cold forged composite shaft. During the push-out test, the outer ring of the specimen is supported by a die, while a punch pushes the core out of the specimen, as depicted in Figure 8. The punch force and displacement are recorded on a Zwick Z250 universal testing machine. The force-displacement-curves exhibit a distinctive peak at the time of initial slip of the core. The force at this point is used for evaluation of the bond strength, given by

$$\tau_{\text{bond}} = \frac{F_{\text{P}}}{A_{\text{contact}}} = \frac{F_{\text{P}}}{\pi\, d_{\text{core, 1}}\, h_{\text{specimen}}}, \tag{4}$$

where $d_{\text{core, 1}}$ denotes the core diameter after forward rod extrusion and h_{specimen} the height of the specimen.

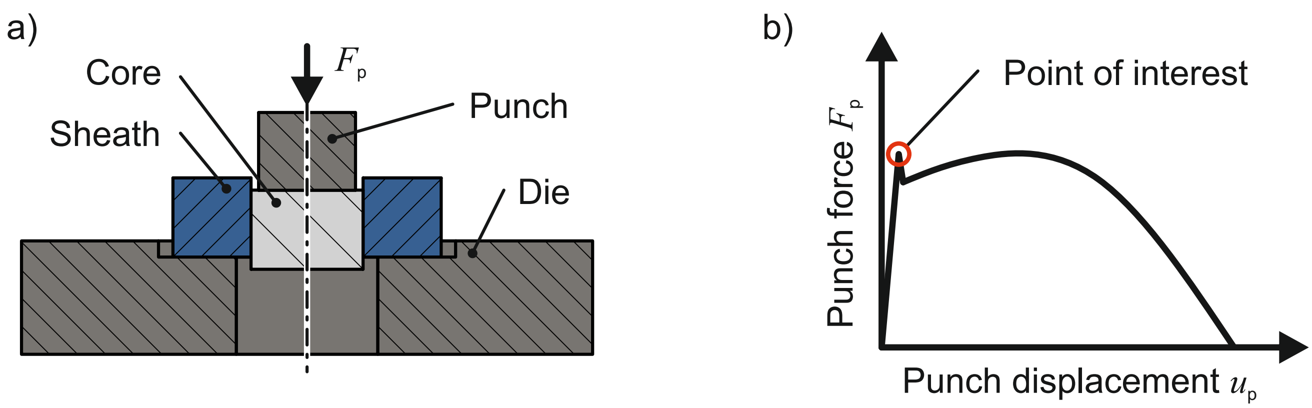

Figure 8. Principle of push-out testing: (**a**) tool set up and (**b**) evaluation of obtained force-displacement-curve.

Figure 9 shows the bond strengths obtained by means of push-out tests of the successfully produced shaft geometries. The bond strength increases for higher extrusion strains. For the extrusion strain of 0.7 higher reduction ratios lead to an increase in bond strength, which is not observed for the other extrusion strains. An increase of bond strength for thinner sheath thicknesses is beneficial as regions of the shaft closer to the edge encounter higher stress under bending and torsion during service life. However, the achieved bond strengths are low compared to the initial shear yield stress of the magnesium core of $\tau_{y,0}$ = 71 MPa, which was determined by upsetting tests and application of the Tresca yield criterion. A micro form fit that Ossenkemper et al. established for aluminium cores [10] cannot be achieved for magnesium cores. This can be traced back to magnesium's lower formability, preventing the core material to flow into the micro indents induced by sandblasting, which was validated by light-microscopy investigations. This is especially the case for low extrusion strains, where the lowest bond strength is observed.

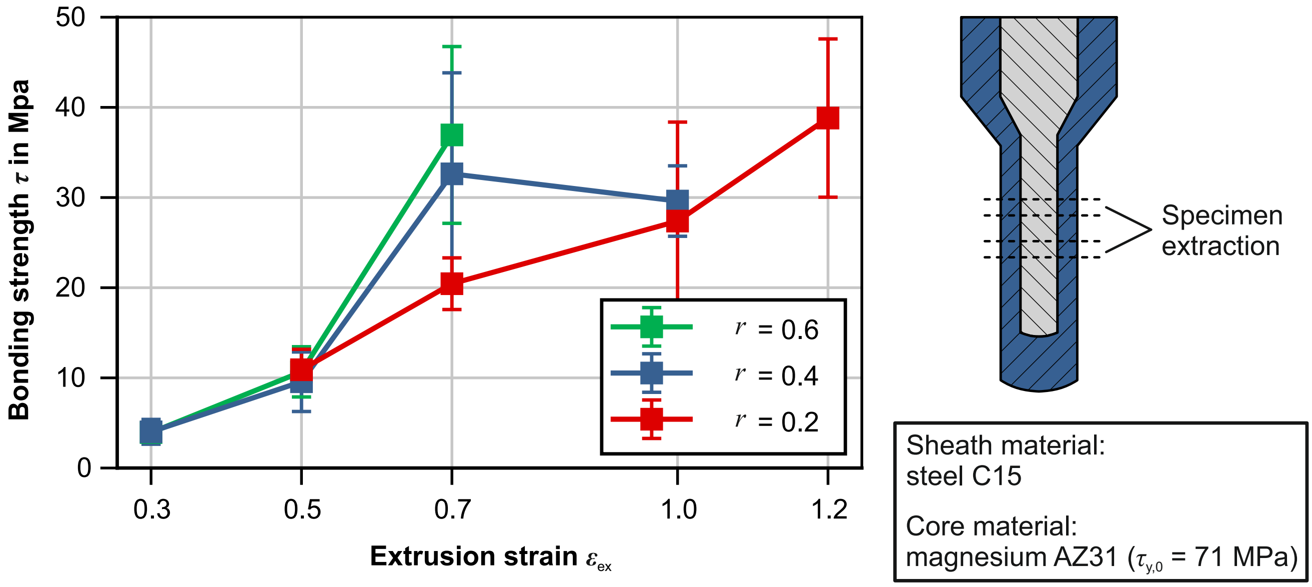

Figure 9. Bond strength of magnesium core and steel sheath, obtained by push-out testing and location of specimen extraction.

For steel cups with higher reduction ratios and thus thinner walls, the contact surface between core and sheath moves further to the outer edge of the shaft. As radial compressional stress in the forming zone increases towards the edge [16], the bond strength is increasing for higher reduction ratios. The low bond strength observed for magnesium core composite shafts disqualifies their use for applications where shafts are subjected to high static loads. On the contrary, magnesium core shafts benefit from the high damping capacity of magnesium alloys in ultra-high cycle fatigue (UHCF) applications where high loading cycles of more than 10^8 cycles [17] but small stresses are present.

4. Materials and Methods—Granular Media-Based Cold Forging

4.1. Process Route

In order to produce hollow shafts by means of composite cold forging, a steel cup is filled with a granular medium and subsequently formed by means of forward rod extrusion, as shown in Figure 10. The granular medium prevents the cup from upsetting during forward extrusion. After forming, the core is removed to obtain the hollow part.

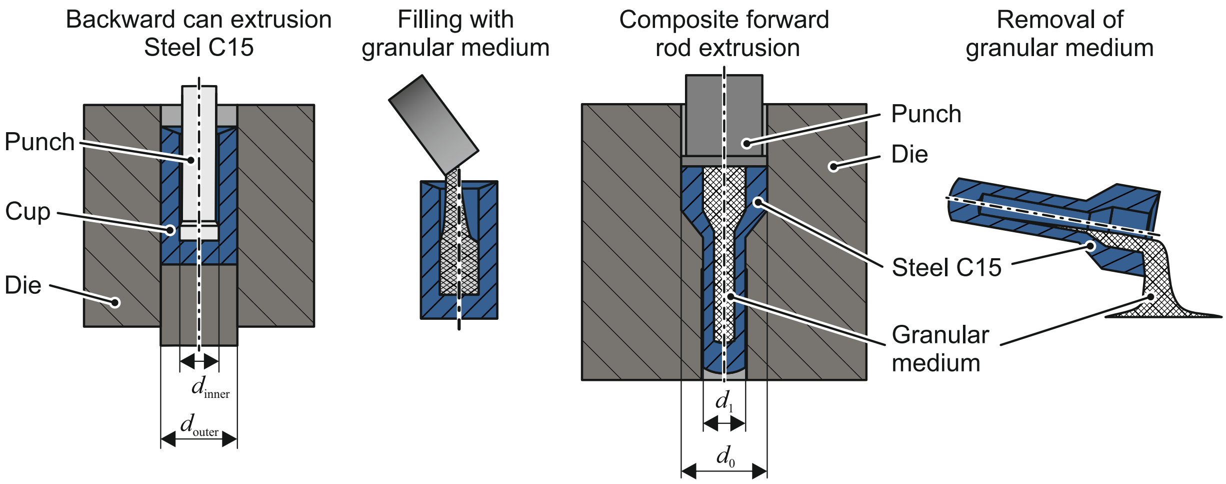

Figure 10. Process route for production of hollow shafts by means of cold forging with granular media.

Kolpak et al. [18] showed the general applicability of the process, using drilled cups filled with granular media. In the present paper, the process is extended by utilizing backward can extruded cups to achieve optimal material utilization. The steel cups are produced in the same fashion, as described in the preceding Section 2.2, by backward can extrusion. The semi-finished can is filled completely with granular media and sealed to allow for easier handling. This billet is then further processed by means of forward rod extrusion. Finally, the granular core is removed manually. The investigated parameter sets are given in Table 2.

Applying cold forging operations on both sides of the shaft makes it possible to produce undercut hollow geometries which are usually formed by radial swagging. In contrast to radial swagging, granular medium based cold forging does not require complex tools, but can be implemented by conventional cold forging dies and punches.

Table 2. Investigated parameters in cold forging with granular media acting as lost cores.

Varied Parameters		
Reduction ratio r	0.2	0.4
(corresponding inner cup diameter)	(13.4 mm	19 mm)
Extrusion strain ε_{ex}	0.5	1.0
Core material	quartz sand	zirconium oxide
Fixed Parameters		
Cup material	Steel C15 (1.0401)	
Inner cup surface treatment	none	
Billet diameter	30 mm	
Cup bottom thickness	12 mm	

4.2. Materials

Granular media offer the ability to withstand high pressures during forming operations and can be easily removed after forming. Thus they are well suited as a lost core in cold forging. The two utilized granular media are quartz sand, consisting mainly of silicon dioxide particles of sharp-edged irregular shape, and sphere-shaped zirconium oxide beads. Both materials are shown in Figure 11. These granular media have already been successfully applied to a tube press hardening process by Chen et al. [19].

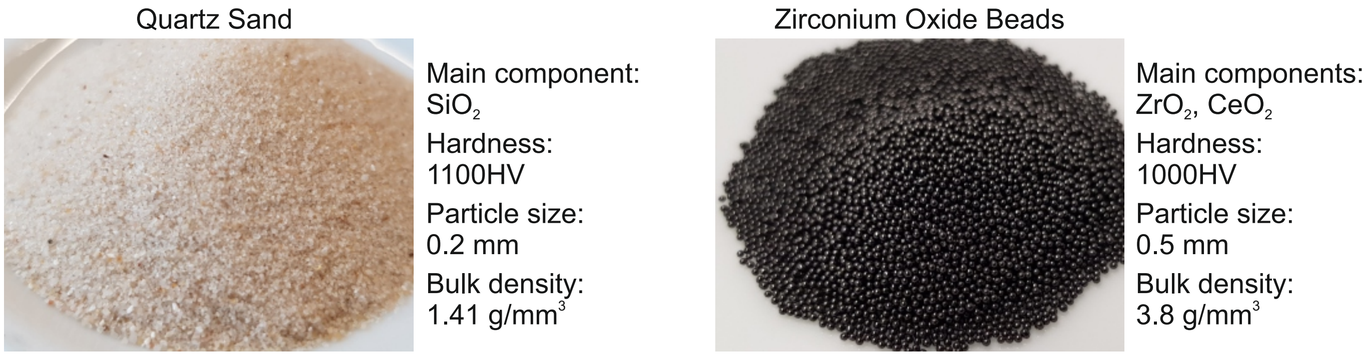

Figure 11. Granular media used as lost cores in cold forging.

Unlike metals, granular media can undergo large volumetric plastic strain. The volumetric hardening behaviour of both materials at hand is shown in Figure 12a. The material behaviour of granular media under shear loads is dependant on pressure acting on the material. Due to the sharp-edged particle shape, quartz sand can transmit higher shear stresses before the onset of plastic yielding, as characterized by Chen et al. [20]. The pressure dependant yield stress of both materials is shown in Figure 12b).

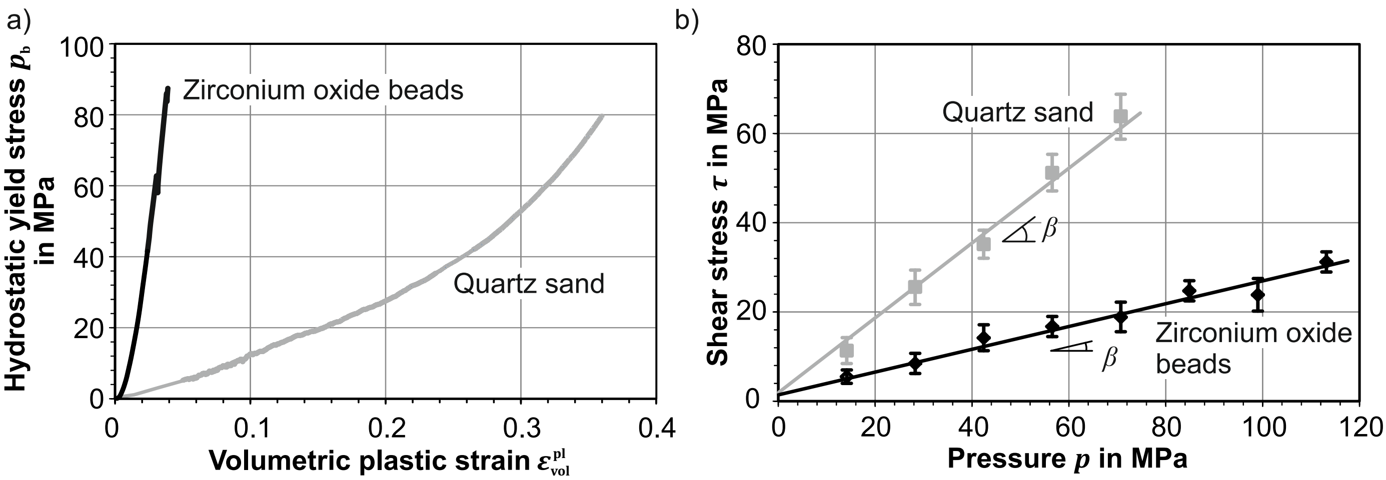

Figure 12. Yield stresses of quartz sand and zirconium oxide beads for (**a**) volumetric compression and (**b**) under shear loading, according to [20].

5. Results and Discussion—Granular Media-Based Cold Forging

5.1. Process Limits

To judge the process success and to reveal the inner surface of the shafts extruded with granular medium core, the components are cut in half after the core is removed. Figure 13 shows the shafts produced with zirconium oxide beads as core material. All of the investigated parameter sets (Table 2) result in workpieces free from macroscopic defects. The inner surface shows indents from the zirconium oxide particles. These indents need to be considered for potential fields of applications, as the hollow section of such parts might be used as additional space for other shafts, data cables or as a cooling channel. Depending on the type of application, additional machining operations are necessary to remove the indented surface area.

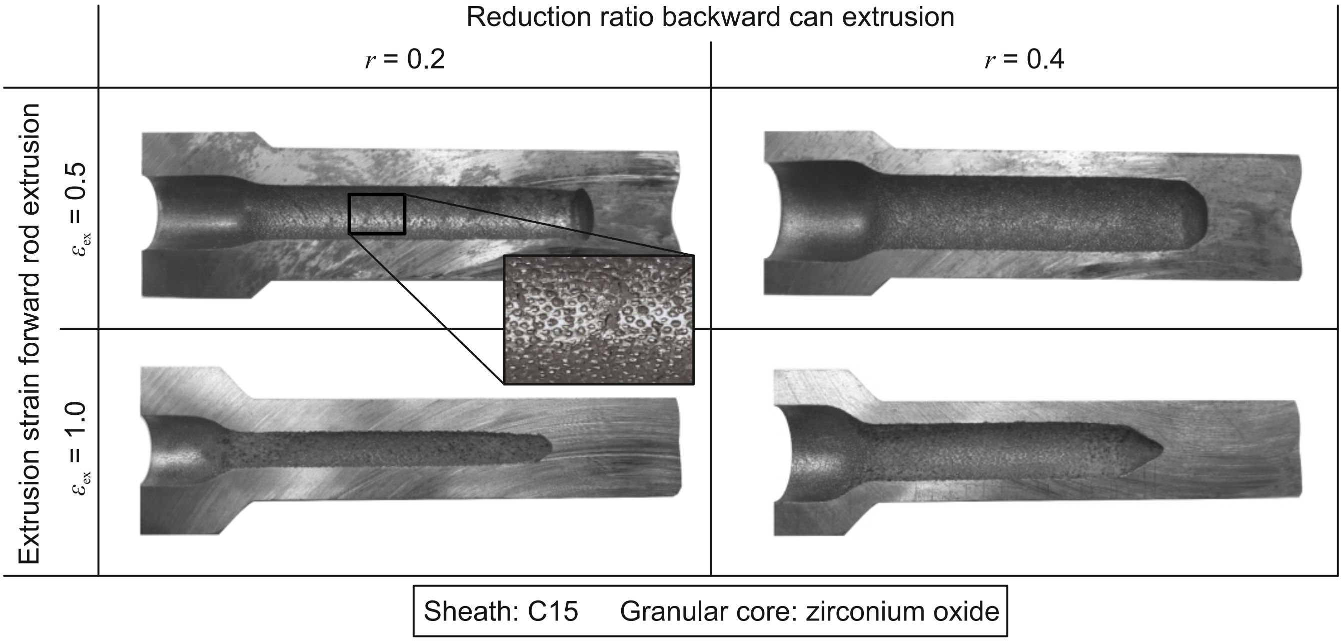

Figure 13. Hollow shafts produced by forward rod extrusion of steel cup billets filled with zirconium oxide, cut open to reveal inner surface.

Figure 14 shows the shafts that were produced utilizing quartz sand as core material. It is observed that the parameter combination with the highest reduction ratio and extrusion strain results in macroscopic failure of the steel sheath. Furthermore, the inner surface of the shaft with $\varepsilon_{ex} = 0.5$ and $r = 0.2$ shows arrow-shaped crack initiations. This is also the case for the shaft with $\varepsilon_{ex} = 0.5$ and $r = 0.4$ at the region close to the bottom where the wall thickness is slightly higher.

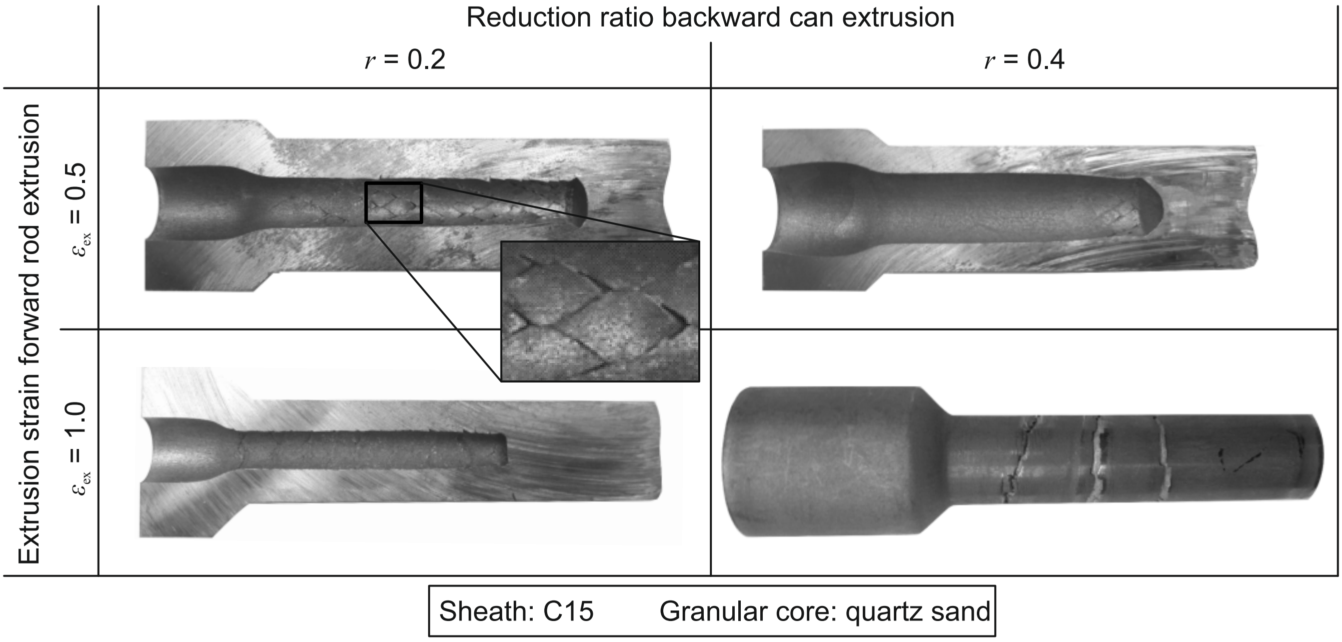

Figure 14. Hollow shafts produced by forward rod extrusion of steel cup billets filled with quartz sand, cut open to reveal inner surface.

The cracks at the inner surface stem at the one hand from the pre-strained material, as they are not observed when using drilled steel cans for the same parameter combinations [18]. Especially the material at the inner surface of the cups exhibits the highest amount of strain hardening during backward can extrusion as shown in the process simulation (Figure 15). At the other hand, also the material behaviour of the granular core plays an important role, as no defects are observed when using zirconium oxide as a core material. As presented in Section 4.2, quartz sand has a higher shear yield limit than zirconium oxide beads, and thus transmits higher loads in axial direction to the steel sheath. As hydrostatic tensile stresses are highest at the centre of the workpiece during forward rod extrusion, the defects only occur for higher wall thicknesses.

5.2. Wall Thickness Determination

The wall thickness of a hollow shaft is, along with its outer radius and material constants, the variable determining the shaft's bending and torsional stiffness. As granular media violate the principle of constant volume, equation (3) is invalid for hollow shafts produced by composite cold forging. In order to provide a tool, that is capable of determining the wall thickness and allows for general process design, a FEM process simulation approach is presented.

Due to different demands to the FEM-code, different solvers are used for backward can extrusion and composite forward rod extrusion. The former exhibits large plastic strains, resulting in unacceptable element distortion. Thus the process is modelled using Simufact Forming, as it provides a robust automatic re-meshing algorithm. Composite forward rod extrusion is modelled using the implicit Abaqus solver instead, as it features an implementation of a Drucker-Prager model with an additional cap yield surface, which is suitable for modelling granular media. To transfer plastic strains and residual stresses from the first process simulation to the second, a Python script is used. As the second process simulation requires a finer mesh to obtain convergent results, an additional mapping of the transferred data onto the new mesh is required. A spatial interpolation from the three nearest neighbor data points is applied (Figure 15).

For both processes a two dimensional, axisymmetric model with linear elements is used. The dies are modelled assuming elastic material behaviour to account for their expansion under high pressures that occur during the cold forging operations. The punches are assumed to be rigid bodies. The C15 steel cup material is modelled by von Mises plasticity with Swift-type hardening. The used material parameters were determined by upsetting tests in [18] and are given in Table 3a.

The granular media are modelled by a Drucker-Prager yield model with additional cap yield surface, presented by Brandt and Nilsson [21], which has successfully been applied by Chen et al. to model granular media based tube press hardening [20]. This model features a cone-shaped yield surface to account for hydrostatic pressure dependent plastic material behaviour and a cap surface closing the cone which allows for volumetric plastic compaction. A third surface defines the material behaviour at the transition zone between the two previously mentioned yield surfaces. The used material parameters are given in Table 3b. Here, β is the opening angle of the cone-shaped Drucker-yield surface, d is the cohesion, R is the cap eccentricity, α is a parameter characterizing the transition surface and a and b parameters describing the cap-hardening behavior. The friction between tools and the steel cup is modelled by Coulomb friction with a coefficient of $\mu = 0.05$. The contact between the granular media core and the steel sheath is assumed to have no relative motion between the contact partners, as particles of the granular media indent the steel sheath due to their higher hardness and establish a form fit.

Table 3. Material parameters for (**a**) C15 steel, identified by Kolpak [18], and (**b**) granular media, identified by Chen [20].

(**a**) Swift

C in MPa	ε_0	n
738	0.128	0.162

(**b**) Drucker-Prager-Cap

Material	β	d in MPa	r	α	a in MPa	b
Quartz sand	47.2°	1.02	0.1	0.48	−44.66	2.313
Zirc. oxide	23.4°	0.65	0.1	0.26	−44.01	24.37

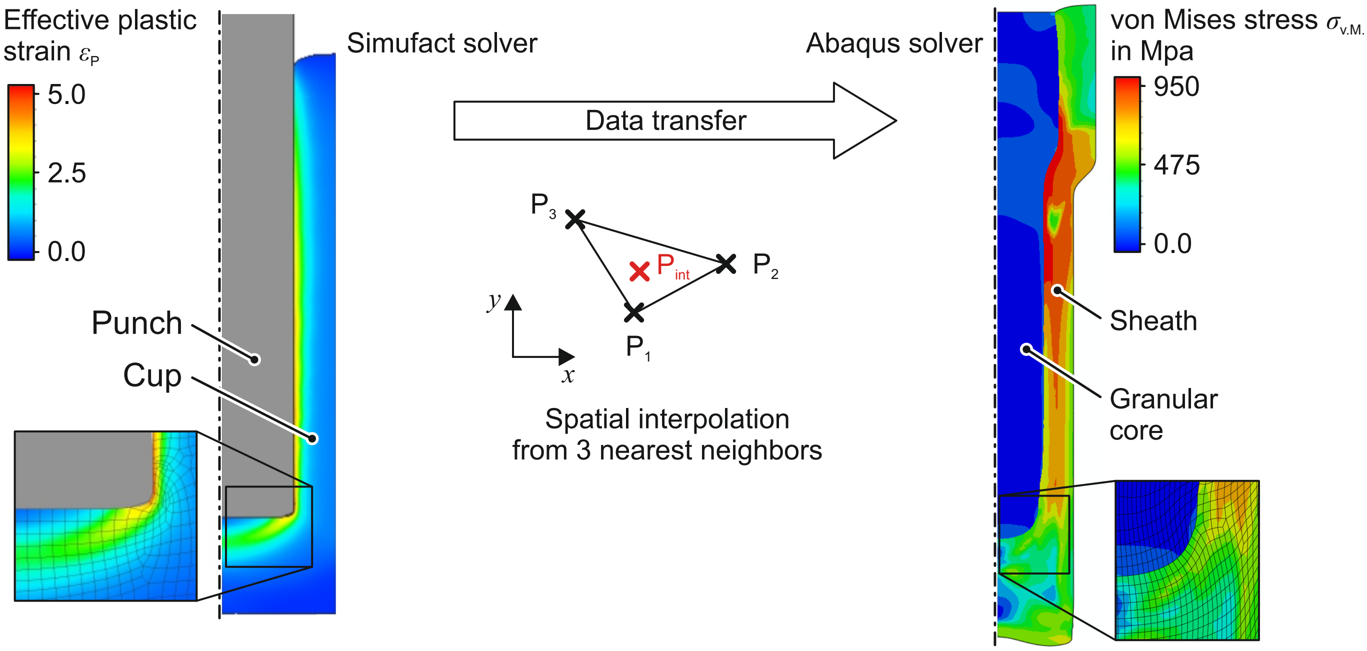

Figure 15. Simulation model for the process chain of cold forging with granular medium based cores. Backward can extrusion is modelled using Simufact forming. The process step of forward rod extrusion is modelled using Abaqus. The data transfer between the two solvers is implemented by a Python script.

The simulation model is validated by comparing the experimentally and numerically determined punch force in composite forward rod extrusion with granular medium core billet. Figure 16 shows the force-displacement-curves from experiments and simulations. Both are in good agreement, so that the presented simulation approach can be used for the efficient design of more complex gear shafts.

The wall thicknesses of the produced shafts are measured at the cut open specimens perpendicular to the outer surface of the hollow shafts. In simulations, corresponding node distances are measured. As shown in Figure 17, experiment and and simulation are in good agreement.

As the numerical model shows precise predictions of process forces and material flow, it can be applied for time and cost effective product and process route design.

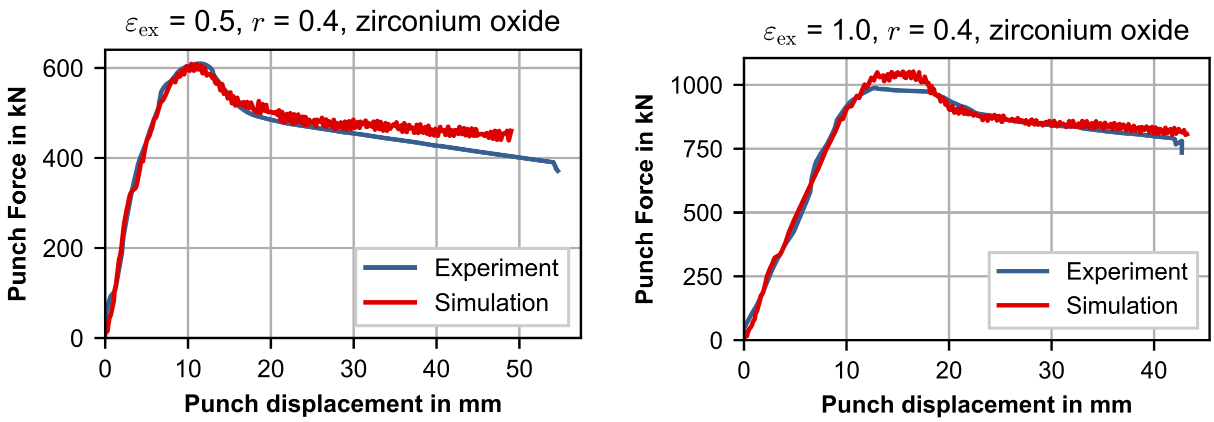

Figure 16. Punch force measured in experiments and obtained from simulation of forward rod extrusion with zirconium oxide core.

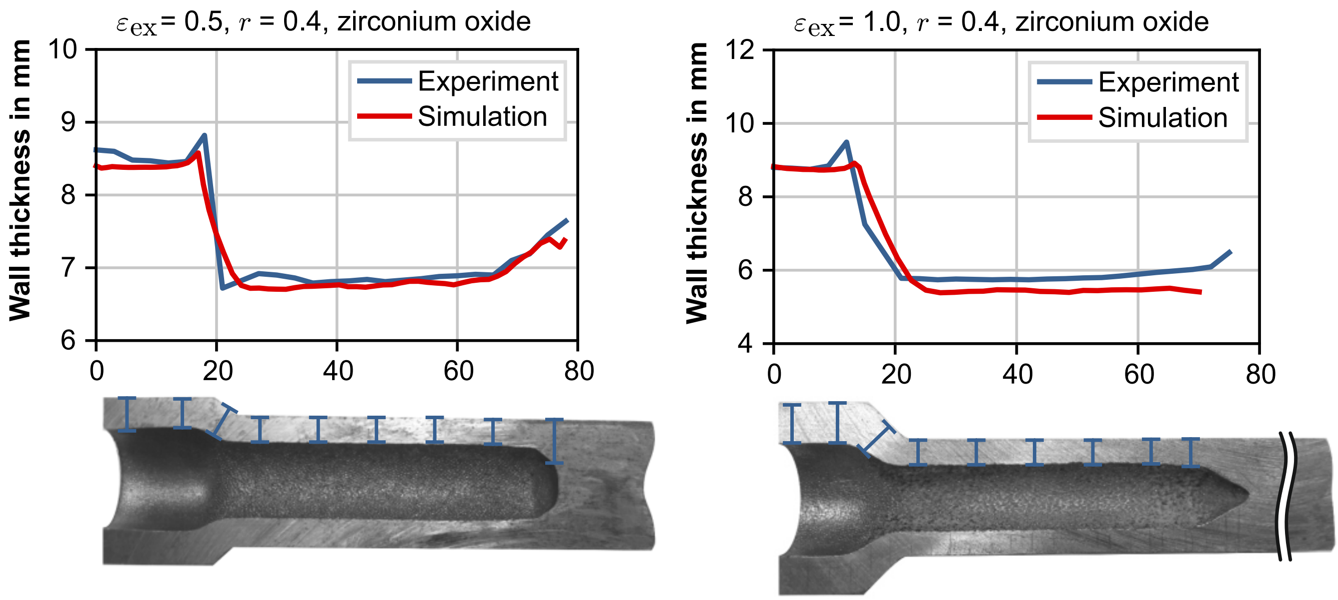

Figure 17. Wall thicknesses measured in experiments and obtained by process simulations.

6. Conclusions

The lightweight potential of composite cold forging can be increased by utilizing magnesium cores or granular medium cores that are removed after forming to obtain hollow shafts. It is shown that the production of such shafts is feasible for a wide range of process parameters. The highest lightweight potential is offered by hollow shafts, but also steel-magnesium composite shafts feature a lower weight in comparison to shafts with aluminum cores. Figure 18 shows examples of weight savings of all three types of lightweight shafts in comparison to a monolithic steel shaft with identical torsional stiffness. Considering an increase of 20% of the outer shaft diameter, weight savings are 39% for an aluminum core, 46% for a magnesium core and 60% for a hollow shaft.

The presented simulation approach of composite cold forging of granular medium filled steel cups correctly models the behaviour of the compressible granular core material. The accurate predictions of process forces and material flow allow for an efficient product and process design.

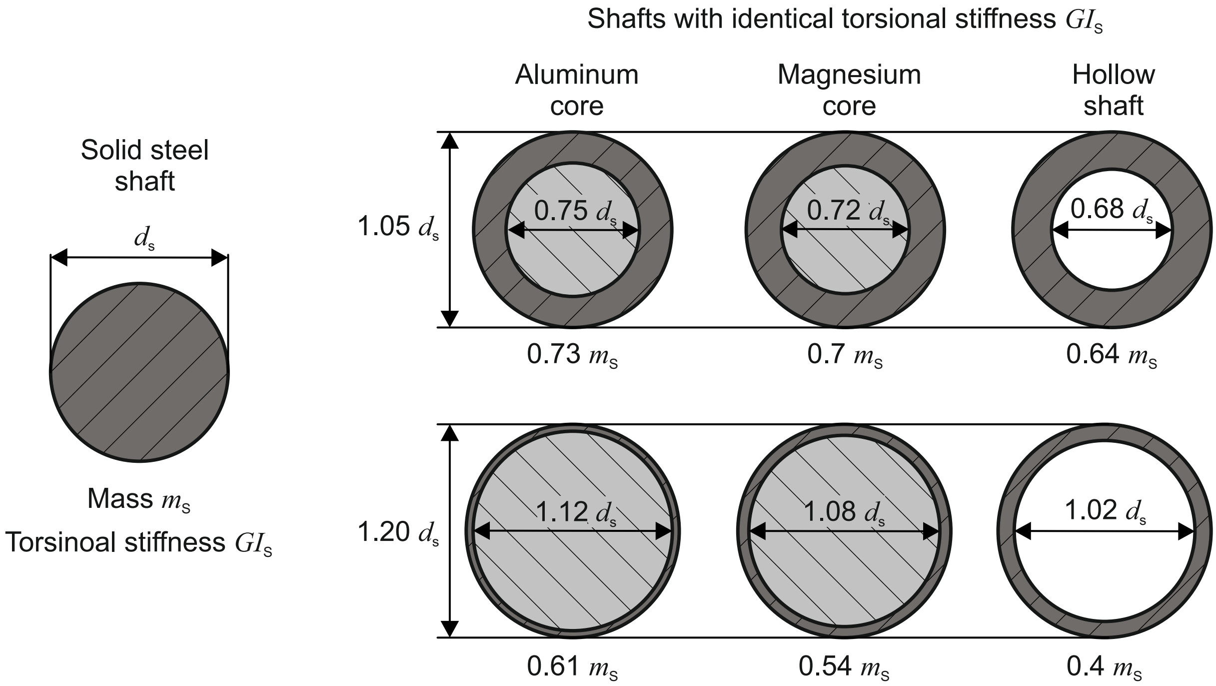

Figure 18. Mass savings for substituting a solid steel shaft by composite shafts with aluminum core, magnesium core and hollow shafts with identical torsional stiffness.

Due to the disadvantages of low bond strength of cold forged magnesium-steel composite shafts and indented inner surface of hollow shafts produced by granular medium based cold forging, each process variant has its favourable fields of application. An overview of characteristics and potential fields of application for the discussed processes is given in Table 4.

Table 4. Characteristics of different core materials used in composite forward rod extrusion.

Core Type	Advantages	Disadvantages	Potential Field of Application
Aluminum	High bond strength	Lowest lightweight potential	General lightweight design for highly loaded parts
Magnesium	Damping properties	Low bond strength	UHCF applications
Granular	Highest lightweight potential	Indented inner surface	Lightweight design for complex geometries

In order to improve the bond strength of magnesium-steel composite shafts, future research will be made on different surface treatment of the inside surface of the cold forged shafts. In addition, the use of non-round core geometries to achieve a macro form fit, as already applied for aluminum cores [11], will be investigated. As magnesium is formed at room temperature to high levels of plastic strain, the process of composite cold forging could also be applied for material characterization of magnesium at high strains. In order to access the potential of producing undercut geometries by granular medium based cold forging, future research will focus on more complex geometries.

Author Contributions: Conceptualization, O.H. and A.E.T.; methodology, R.G. and F.K.; software, R.G. and F.K.; validation, R.G. and F.K.; formal analysis, R.G. and F.K.; investigation, R.G. and F.K.; resources, A.E.T.; writing–original draft preparation, R.G. and F.K.; writing–review and editing, O.H. and A.E.T.; visualization, R.G. and F.K.; supervision, O.H. and A.E.T.; project administration, R.G. and O.H.; funding acquisition, A.E.T. All authors have read and agreed to the published version of the manuscript.

Funding: This work is based on investigations of the research project "Composite Cold Forging of Cold Forged Semi-Finished Parts," funded by the German Research Foundation (DFG, Project number 270149504). Its financial support is greatly acknowledged.

Conflicts of Interest: The authors declare no conflict of interest.

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