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Citation: *AIP Conf. Proc.* **1383**, 645 (2011); doi: 10.1063/1.3623668

View online: <http://dx.doi.org/10.1063/1.3623668>

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# Influences on the Molding in Hydroforming Using Granular Material as a Medium

Martin Grüner<sup>a\*</sup>, Marion Merklein<sup>a</sup>

<sup>a</sup> Chair of Manufacturing Technology, University Erlangen-Nuremberg,  
Egerlandstrasse 13, 91058 Erlangen, Germany

\* Phone: +49 9131/85-28317, Fax: +49 9131/85-28866, E-mail: m.gruener@lft.uni-erlangen.de

**Abstract.** The need of lightweight construction for the body in white of modern cars increases due to legal restrictions of CO<sub>2</sub> emissions and the passenger's wishes of safety and low fuel consumption. One approach of lightweight construction is the use of high and ultra high strength steel, to reduce the weight of the single parts, another approach is the use of modern forming technologies, e.g. hydroforming with the possibility to create undercuts, to produce complex parts and thus to reduce the number of parts, the number of joining operations and the weight. The mentioned ultra high strength steels show a poor formability at room temperature and the necessary process forces are high compared to standard deep drawing steels. Warm forming operations can help to reduce the process forces and to increase formability [1]. To combine the benefits of warm forming and hydroforming new forming media are necessary to overcome the problem of temperature stability of fluids, which is limited to about 350 °C [2]. Beside gases, which tend to leakage and which are highly compressible, granular material like small ceramic beads can be used as a forming medium. First results of forming operations using this medium were presented in [3]. The experimental tool used for those tests pressurizes the medium by a punch.

To divide the effects caused by temperature and steel grade from the other effects experiments were carried out at room temperature using the well known deep drawing steel DC04. Influences of the ceramic beads diameter, the number of repetitions, the punch geometry as the punch position, determining the volume of media, on the forming are presented.

**Keywords:** Hydroforming, Granular Material, Elevated Temperatures

**PACS:** 81.20.Hy, 45.70.Mg

## INTRODUCTION

The use of modern steel grades and production technologies for the body in white allows fulfilling the consumers request on cars with reduced fuel consumption and increased passengers safety. Using high and ultra high strength steel grades, e.g. dual phase steel, complex phase steel, martensite phase steel and hot stamping steel, for the body in white is state of the art. The increase of the percentage of these steel grades in modern cars raises since the 1980's [4, 5]. Studies like the Ultralight Steel Automotive Body (ULSAB) show the possibility of a weight reduction of 25% and an increase in stiffness of 80% by using 90% of high and ultra high strength steel [6]. Beside these benefits of those steel grades there are also disadvantages like poor formability and high process forces. A common way to overcome these challenges are warm forming operations allowing to decrease the flow stresses and to increase the formability of the material [1]. Whereas deep drawing processes at even very high temperatures, e.g. hot stamping, are state of the art, hydroforming processes at elevated temperatures suffer from problems of an appropriate medium. Considering the benefits of hydroforming like complex part geometries, the possibility to form tubes or create undercuts additional lightweight potential of the mentioned steel grades is accessible at elevated temperatures. The challenges to overcome for hydroforming at high temperatures are the standard hydroforming fluids being only temperature stable up to about 350 °C [2] and the compressibility of gases as the problem of leakage. This leads to the use of gases for high temperature tube hydroforming where leakage can be neglected and blank draw in is not essential. The use of gases for sheet hydroforming is not common due to high blankholder forces being necessary to avoid leakage but limiting blank draw in. The use of granular material as a medium for hydroforming at elevated

temperatures is a possibility to avoid leakage at low blankholder forces, increasing the blank draw in and also to realize high temperatures of at least up to 600 °C and high pressures of at least up to 1000 bar. Appropriate granular materials are small ceramic beads with diameters of 63 microns up to 850 microns commonly being used in shot peening process. Previous work focused on methods for material characterization, material modeling in the numerical simulation using ABAQUS, the validation of these material models as modeling elastic tool deformation of an experimental hydroforming tool in the numerical simulation [7, 8, 9, 10]. One of the main results out of this work is that a complete forming of the blank into the die can not be achieved, even at temperatures of 600 °C and a pressure of 1000 bar. The here presented work focuses on the influence on the molding according to the used hydroforming medium and changes in the experimental setup using the standard deep drawing steel DC04 at room temperature to separate these effects from thermal effects.

## EXPERIMENTAL SETUP

The following chapter describes the materials for the blank and the granular material being used for the experiments, the standard experimental setup as the modifications of the experimental setup.

### Used Materials

For all presented experiments the standard deep drawing steel DC04 is used as blank material. Circular blanks with a diameter of 180 mm and a sheet thickness of 1.5 mm are investigated. As granular forming medium ceramic beads Zirblast distributed by SEPR Keramik GmbH & Co.KG are used. These ceramic beads are commonly used for shot peening processes like cleaning and finishing operations. The main physical properties of this material are given in Tab.1. For the experiments three different diameter distributions (SDD) of the spheres are used. The coarse one with sphere diameters from 600 microns up to 850 microns, the medium one with sphere diameters from 250 microns up to 425 microns and the fine one with sphere diameters from 63 microns up to 125 microns are used. One of the most important properties that have to be taken into account is the breaking of some of the beads to fine powder during the processes. Beside realignment processes this contributes to the compressibility of the medium.

**TABLE 1.** Physical properties of the granular material being used [11]

Specific density	3.85 g/cm <sup>3</sup>
Bulk density	2.3 g/cm <sup>3</sup>
Young's-Modulus $E$	200000 N/mm <sup>2</sup>
Hardness	60 – 65 HRC
Low plastic deformations / breaking to fine powder	

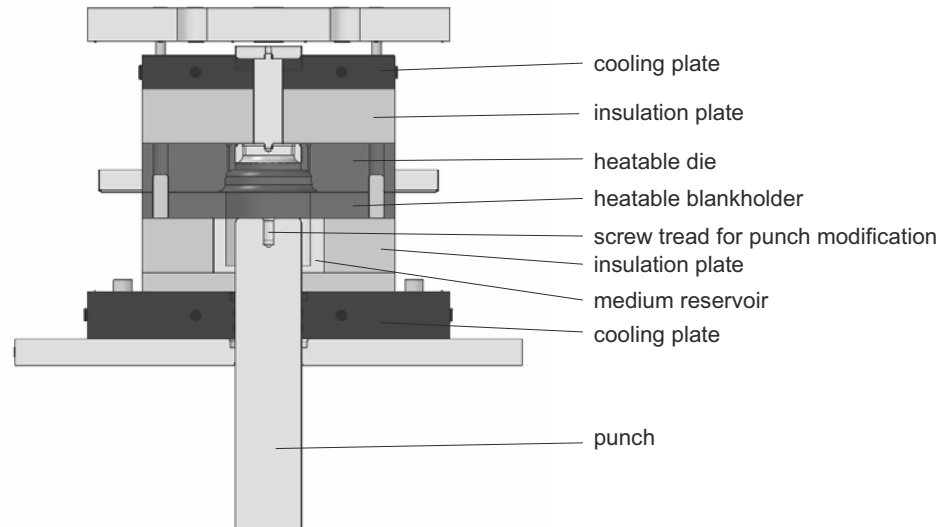
### Experimental Hydroforming Tool and Process Cycle

The experimental tool for hydroforming using granular material as a medium consists of an upper tool containing the die, the lower tool containing the medium reservoir and the blankholder as the punch pressurizing the medium. The schematically construction of the tool is shown in Fig. 1. The blankholder as the die are each equipped with eight heating cartridges that allow heating this components up to 500 °C. All tool components that might suffer extensive wear by a relative movement between blank and tool components or ceramic beads and tool components are made out of hot-working steel 1.2343. This steel obtains a hardness of at least 54 HRC at temperatures up to 500 °C. Additional insulation plates and water cooled cooling plates prevent a heating of the hydraulic press the tool is deployed in.

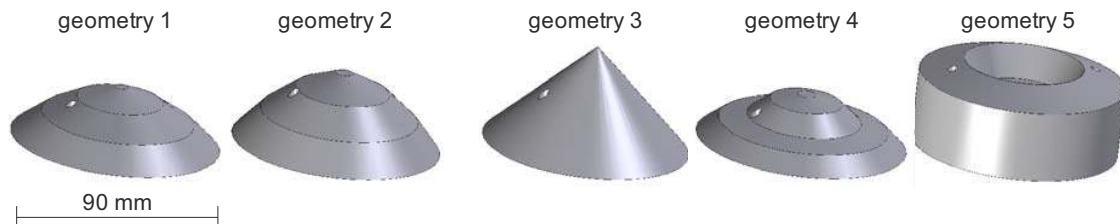
The die is designed to form round cups with a diameter of 120 mm, die radii of 10 mm and cup bottom radii of 10 mm. The punch has a diameter of 90 mm and a flat top with an additional screw thread. This screw thread allows modifying the punch geometry by adding top pieces shown in Fig.2. In standard configuration the top of the punch is about 90 mm below the top surface of the blankholder. The maximum punch force is dimensioned for forces up to

1500 kN resulting in a pressure of about 23 00 bar on the top of the punch. However preliminary experiments showed that pressures higher than 1000 bar significantly increase the amount of broken beads.

The process usually starts with filling the reservoir with ceramic beads and placing the blank on the blankholder. Afterwards the upper tool is displaced by the ram against the lower tool and the blankholder force is applied. Shortly after the blankholder force is applied the punch is displaced upwards into the ceramic beads in the reservoir and pressurizes the medium. The medium passes the pressure to the blank and the forming takes place.



**FIGURE 1.** Sketch of experimental tool for hydroforming with granular material used as a medium



**FIGURE 2.** Top pieces used for punch geometry modification

## Experiments

First experiments forming a cup using granular material as a medium showed that the molding of the cup bottom radii is in complete. Theoretically it should be possible to form the cup bottom radius using a liquid as forming medium. According to this four different kinds of influences were investigated systematically.

The first influence being investigated is the size of the ceramic beads being used for the forming operation. For these experiments the standard configuration of the experimental tool without top pieces on the punch and the standard initial position of the punch described above are used.

The second effect being examined is the possibility of multiple use of the granular material without removing the powder resulting from broken spheres and the effect of this mixture of powder and spheres on the molding.

The third influence being investigated is the punch geometry that is modified with top pieces. By varying the geometry of the punch the pressure distribution inside the granular material should be changed. Extensive numerical simulations were carried out to determine effective geometries of the top pieces. These numerical simulations showed only smaller improvements in the molding so only the five most effective geometries, shown in Fig. 2, out of more than forty were manufactured and tested in reality. Geometry 1 to geometry 4 target pressurizing the cup bottom radii, geometry 5 targets discharging the cup bottom center where first contact with the die takes place. For a

better understanding of these approaches it is necessary to know that pressure distribution inside granular material is not hydrostatic but depends on the direction the medium is pressurized.

The fourth effect on the molding being analyzed is the initial position of the punch. For these experiments the punch without top pieces and with the five different top pieces is used reducing the initial position of the punch from 90 mm below the blankholder top surface to 60 mm, 50 mm and 40 mm below the blankholder top surface.

## RESULTS

### Influence of Sphere Diameter Distribution

Experiments carried out show an influence of the different sphere diameter distributions of the granular material as the number of repetitions (Rep.) without removing the powder of broken beads on the molding. Each series of experiments is repeated at least three times and the geometry of the formed cups is measured by sliding caliper and radius gauges. These measurements show only very small deviations. This allows measuring the inner contour (IC) and outer contour (OC) of representative single parts on a coordinate measurement machine (CMM). The results of the CMM measurements are shown in Fig. 3 – Fig. 7 and Fig. 10.

If unused granular material or granular material where the powder from broken beads was removed is used for the forming operation the coarse medium shows the best molding followed by the medium and fine one as shown in Fig. 3. The results in forming in the cup bottom radii differ by about the sheet thickness comparing the cups formed by coarse medium and by fine medium. Anyway a complete molding of the cup bottom radii of 10 mm can not be achieved.

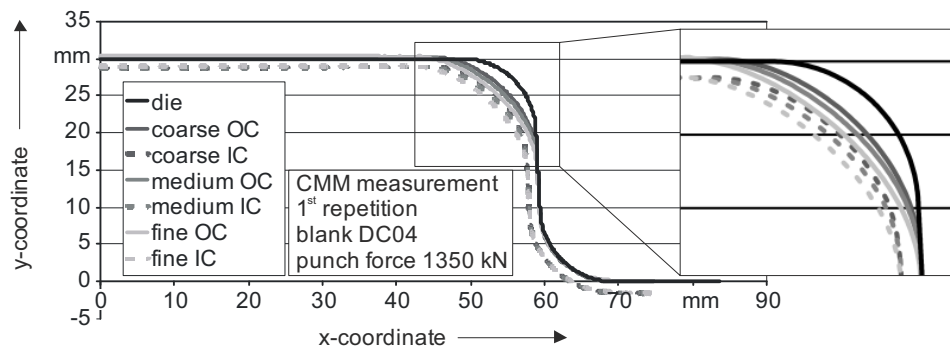
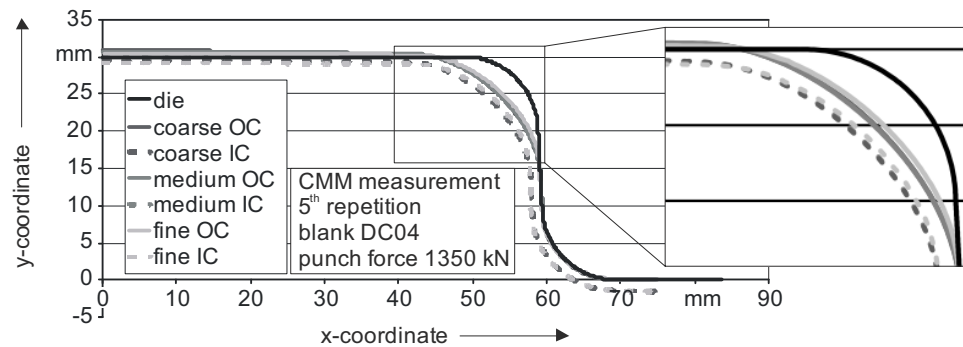


FIGURE 3. Resulting cup geometries in the first repetition using different sphere diameter distributions

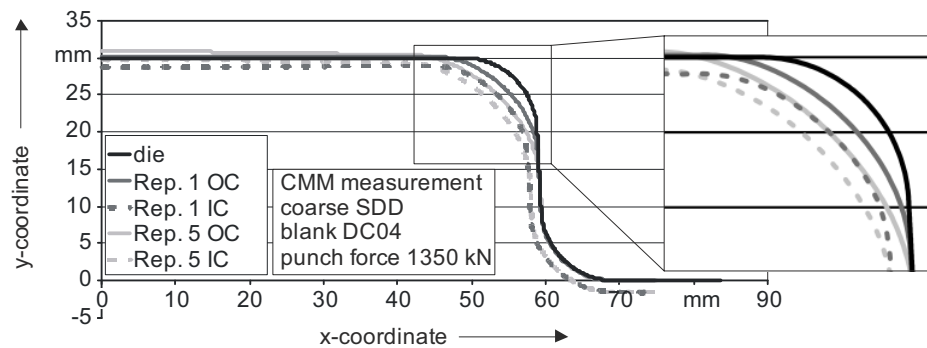
### Influence of Multiple Use of the Granular Material

Using the granular material several times without removing the powder resulting from broken ceramic spheres leads to smaller differences in molding for the three sphere diameter distributions being used for the forming operation. The geometries of the cups in the fifth repetition formed by granular material with different sphere diameter distributions show only slight differences as presented in Fig. 4. The cups formed using the coarse, the medium as the fine sphere diameter distribution show almost the same geometry in the cup bottom radii. It seems that the resulting geometry of cups formed by the coarse medium degrades stronger than the resulting geometry of cups formed by ceramic beads with medium or fine diameter distribution. This leads to the necessity to have a closer look on the changes in forming for the three sphere diameter distributions separately.



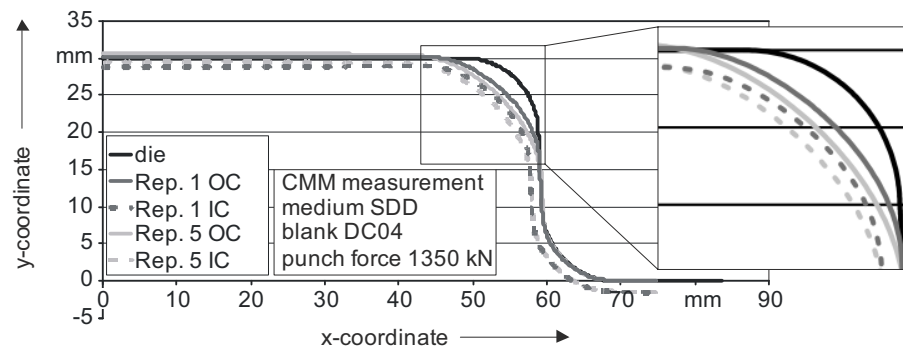
**FIGURE 4.** Resulting cup geometries in the fifth repetition using different sphere diameter distributions

The measurement of cups after the first and the fifth repetition formed with the coarse medium show a decrease in forming of the cup bottom radius. The decrease in forming is about one sheet thickness. The resulting cup bottom radius of cups formed with the coarse medium in the fifth repetition is similar to the radius of cups formed with the fine medium in the first repetition. This effect is due to the fine powder resulting from broken beads. In the first repetition the fine powder still trickles in the hollow spaces between the relatively big spheres. With increasing number of repetitions the percentage of powder increases and fills the hollow spaces. This leads to a higher bulk density of the forming medium and to lower movements of the beads against each other.



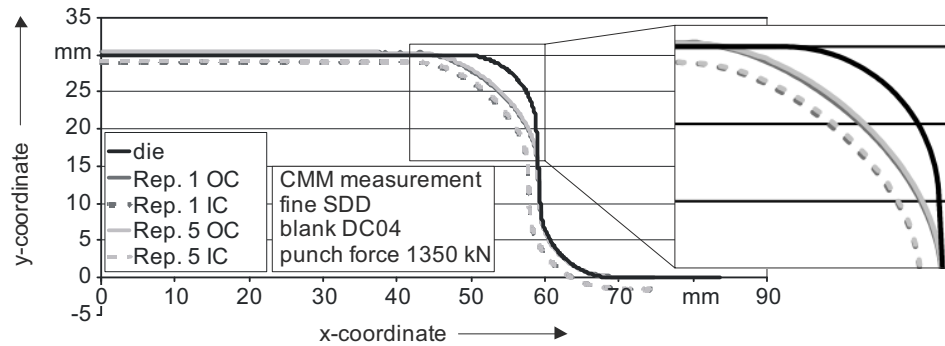
**FIGURE 5.** Changes in cup geometry for multiple use of coarse sphere diameter distribution

The changes in geometry of the cups between the first and the fifth repetition using the medium sphere diameter distribution of the granular material are smaller than for the coarse medium. For the medium size spheres the difference in the cup bottom radius is about three fourths of the sheet thickness shown in Fig. 6. According to the smaller sphere diameters the Trickling of powder through the beads is reduced and even the small amount of powder occurring in the first repetition reduces the forming.



**FIGURE 6.** Changes in cup geometry for multiple use of medium sphere diameter distribution

Fig. 7 shows that there is almost no decrease in forming between the first and fifth repetition if the fine medium is used for the forming operation. Taking small deviations during the forming operation into account, e.g. friction and process forces, no significant differences can be observed. Due to the small sphere diameter of the spheres of down to 63 microns powder and unbroken spheres show almost the same behavior. The powder almost does not trickle into the hollow spaces and the bulk density does not increase. Thus the forming results of the first and the fifth repetition do show no differences.



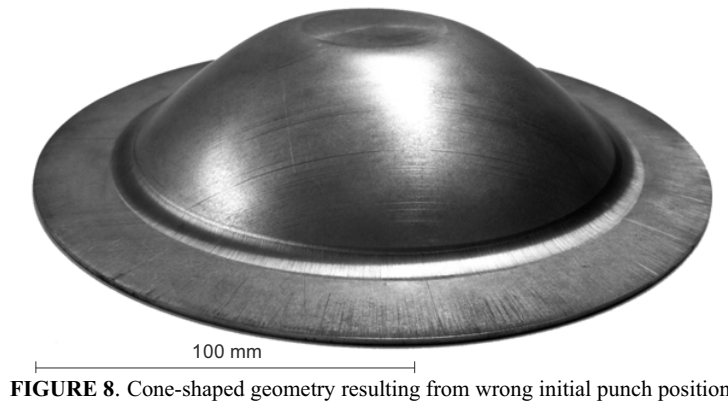
**FIGURE 7.** Changes in cup geometry for multiple use of fine sphere diameter distribution

The observed differences for the three used sphere diameter distributions between the first and fifth repetition go along with the compressibility of the three different sphere sizes due to the size of the hollow spaces and the possibility of the fine powder to fill these. Uniaxial compression tests conducted with these materials also showed great changes in compressibility for the coarse medium and small changes in compressibility for the fine medium by multiple repetitions. It can be concluded that a higher compressibility of the medium coming along with the possibility of the powder to trickle into the hollow spaces and by this to preserve the rearranging of the spheres leads to better forming results.

### Influence of Top Pieces and Punch Position

The modifications of the punch by top pieces show almost no influence on the resulting geometry of the cups. The differences of the cup bottom radii are so small that they are not significant and can be contributed to process and material deviations. Numerical simulations show that the stress distribution especially in the cup bottom radii can not be influenced by top pieces.

However a great influence of the punch position on the resulting geometry of the formed cups can be observed. According to the geometry of the top piece the molding gets very poor if the distance between the top surface of the punch and the top surface of the blankholder falls below a certain value. This value is about 50 mm up to 60 mm according to the geometry of the top piece. Fig. 8 shows the result of the forming operation if this value is exceeded. Most of the force applied by the punch to the granular material concentrates at the center of the bottom of the cup and the pressure in the radii of the cup is very low which leads to a cone-shaped geometry of the formed cup.



**FIGURE 8.** Cone-shaped geometry resulting from wrong initial punch position

## Stress Distribution in Granular Material and Arching Effects

For a better understanding of the effects taking place during the forming operations it is necessary to have a closer look at the stress distribution inside the granular material. Fig. 9 shows the distribution of v. Mises stress at the end of the forming operation. The results are taken from numerical simulations in ABAQUS using the Drucker-Prager-Cap material model to describe the behavior of the granular material. These results show very low values of v. Mises stress in the granular material at the cup bottom radius and high v. Mises stresses at the skirt and the bottom of the cup. Taking into account that high stresses come along with high densities of the granular material and thus a higher strength of the material in this area the reason of incomplete molding can be identified. Having a look at the lines separating the areas with similar v. Mises stress that connect the mentioned high stress areas the incomplete molding can be contributed to the effect of arching [12, 13]. This effect is well known from soil engineering and powder mechanics. The arch of compressed higher strength material shields the cup bottom radius from being pressurized. The main problem of the arching effect for the forming is that it is a self-amplifying effect. With increasing loads the areas building the arch are compressed which leads to an increase of the stability of the arch. This leads to a decrease of forming improvement with increasing punch forces and ends with equilibrium of forces.

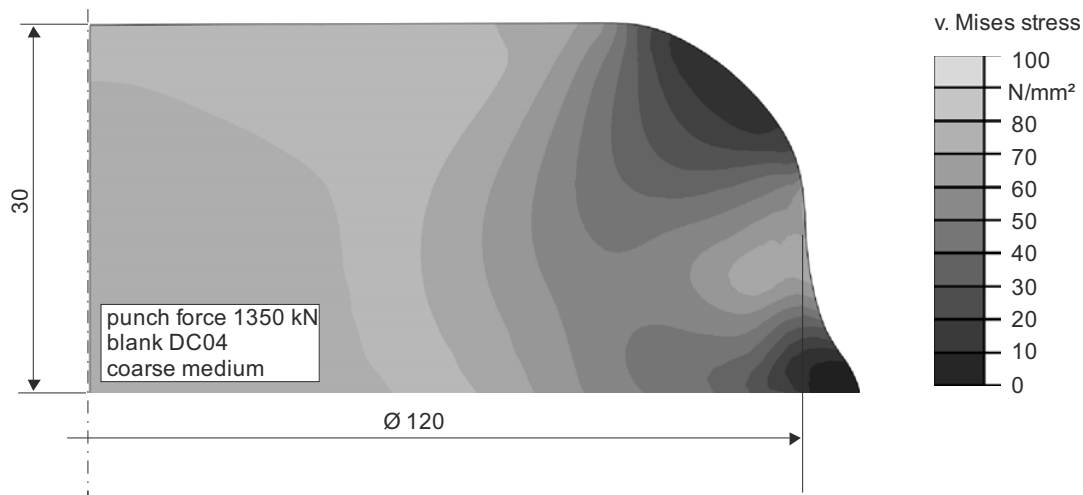


FIGURE 9. v. Mises stress distribution at the end of the forming operation

Experiments showed that a punch force of 600 kN is a good middle ground of molding and wear of the ceramic beads. On the one hand the increase in molding for punch forces higher 600 kN is only small, on the other hand the percentage of broken ceramic spheres increases strongly. Fig. 10 shows the improvement in molding according to increasing punch forces. An increase of the punch force from 200 kN to 400 kN comes along with a reduction of the cup bottom radius by about 4 mm. A further increase by 200 kN from 400 kN to 600 kN decreases the cup bottom radius by only about 2 mm. For an additional decrease of the cup bottom radius by about 2 mm 1350 kN of punch force are necessary.

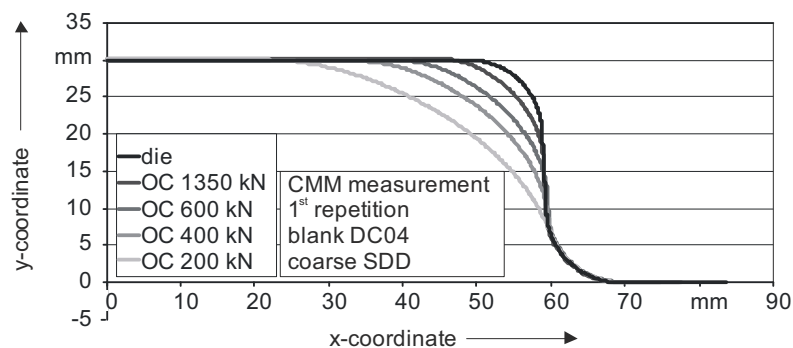


FIGURE 10. Improvement in molding according to increasing punch forces



## SUMMARY

Small ceramic beads can be used as a medium for hydroforming to overcome the disadvantages of gases or fluids especially at high temperatures up to 600°C. To investigate the influence of different sphere diameters as punch geometries on the molding experiments at room temperature were carried out using the well known deep drawing steel DC04. This allows separating mentioned influences from thermal influences. It is shown that beads with coarse sphere diameter distribution are advantageous for the molding but powder from broken beads has to be removed due to a decrease of performance with increasing number of repetitions. The geometry of the punch pressurizing the medium has almost no influence on the forming result but the position of the punch and by this the volume of ceramic beads can negatively influence the molding and lead to cone-shape cups. It is also shown that the effect of arching is limiting the value of the smallest radii.

## ACKNOWLEDGMENTS

The presented results were achieved through investigations within the research project "Warm forming of high strength steel using granular material as a hydroforming medium" which is sponsored by the German Research Foundation (DFG).

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