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*CNC processing,*
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# MACHINING STUDY OF A PART CONSISTING OF A SPHERE INSIDE A CUBE

This paper pertains to the execution of a part consisting of a sphere situated inside a cube on a CNC milling machine tool. The sphere is freely situated, i.e. it has full freedom of movement within the cube. However it is not possible to remove it from the cube, because its diameter exceeds the length of the cube wall. The hypothesis posed in this paper is that optimal utilisation of technological processing capabilities in combination with geometrical and technological problem analysis enables a significant expansion in the range of details acknowledged as possible to produce. A method of analysis of a technological problem posed in this way was proposed, as a result of which the technology for production of this part was developed, and the final effect presented in the form of the produced detail. This paper shows that the condition for success is the proper selection of technological factors (machine tool, tools, method of fastening) and conceptual and informational factors (geometrical analysis, correct use of CNC control, optimal utilisation of CAD/CAM software for generation of the control program).

## 1. INTRODUCTION

Cutting was and still is the primary method of processing. Its importance is not diminishing despite the introduction of new techniques.

In the Framework Programme of CECIMO (European Association of Machine Tool Industries), the role of machine tools in production was described as follows:
*Machine tools are the motor of technical progress. The machine tool industry reflects the production capacity of the economy; machine tools determine the living standard of a society to a large degree. Machine tools are needed today, and they will be needed and irreplaceable tomorrow.*

The application of CNC control has made it possible to improve the efficiency and accuracy of processing. These controls, along with the application of multi-axial machine tool structures, have enabled significant improvement in technological capabilities. Increasingly complex elements require the application of increasingly advanced machining methods. Contemporary machine tools make it possible to produce details much more complicated than those usually produced on conventional machine tools. The selection of the processing method is largely dependent on the type and structure of the machine tool.

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For this reason, continuous development of machining techniques, stimulated by the increasing demands of customers and recipients, is being observed. The effect of these trends is that designers can now design more and more complex parts, because the ongoing development of machining techniques enables their production.

This article concerns analysis of the production of a part consisting of two solids, an internal sphere and an external skeletal cube, in such a way that the sphere cannot fall out of the cube. This problem, seemingly technologically difficult, can be solved with deeper analysis of the kinematic capabilities of modern machine tools and support from advanced CNC controls and application of the appropriate CAM software [1].

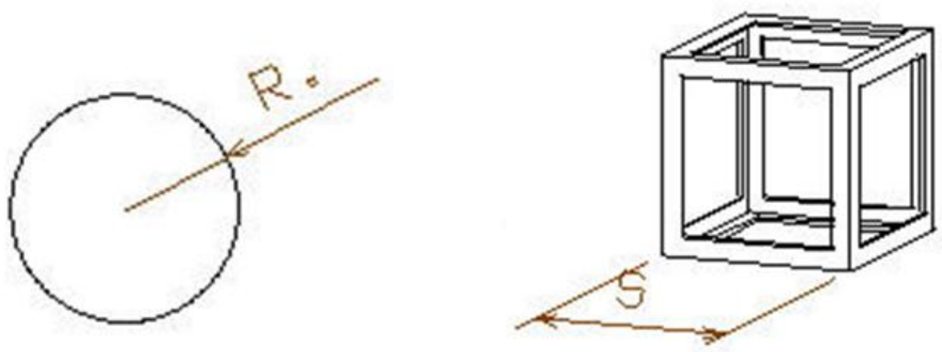
## 2. ASSUMPTIONS

The element is to be produced on a CNC milling machine tool from a uniform solid material. The internal sphere is solid; the external cube has no walls and is, with the exception of the sphere, empty. It is assumed that the external surfaces of the cube are to be processed during the semi-finished-product phase.

During analysis, two types of limitations will be considered: geometrical and technological. Geometrical limitations concern the dimensions of solids and their mutual relations; technological limitations account for such factors as the shape of applied cutting tools, their diameters and lengths, method of mounting and the limitations resulting therefrom, and finally, the method of basing and mounting the machined solid.

## 3. GEOMETRICAL LIMITATIONS

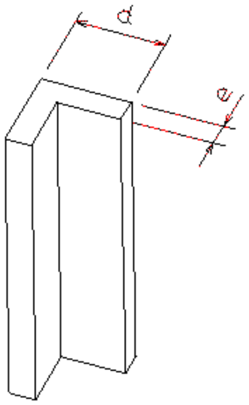
The characteristic quantities of the component solids were input for analysis of the geometrical dependencies of the case under consideration. The quantity of the sphere is its radius; of the cube, the length of its edge (Fig. 1).




**R** – sphere radius **S** – edge of cube

Fig. 1. Characteristic dimensions for component solids

Two variants of the task are set in this paper. In the first, the edges of the cube form a rectangular cross-section. In the second, the edges forming the skeleton form the cross-section of an angle section, where *d* stands for the width and *e* for the thickness of the cube's skeleton (Fig. 2).




d – width of the cube's skeleton
e – thickness of the cube's skeleton

Fig. 2. Characteristic dimensions of the skeleton of the external cube

For the external solid to make sense in physical terms, the width of the skeleton, *d*, must be greater than its thickness, *e*.

All of the dependencies shown below were derived in reference to the sphere's radius *R* as the characteristic parameter of the internal figure, which geometrically limits the dimensions of the external cube. These dependencies were derived using mathematical tables.

Figure 3 shows the geometrical dependencies between the sphere and the external cube.

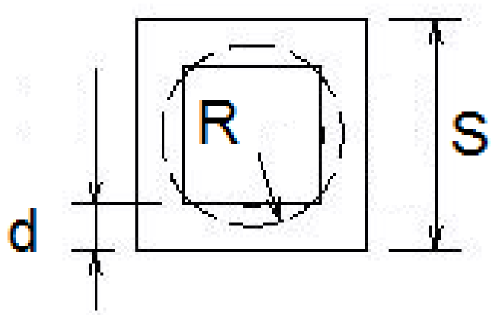



Fig. 3. Dependencies pertaining to the sphere placed in the cube

In order for the sphere to be situated within the cube, and at the same time for it to be impossible to remove the sphere from within the cube, the following conditions must be fulfilled:

1. $R_{min} = \frac{S}{2} - d$

2. $R_{max} = \frac{S}{2}$

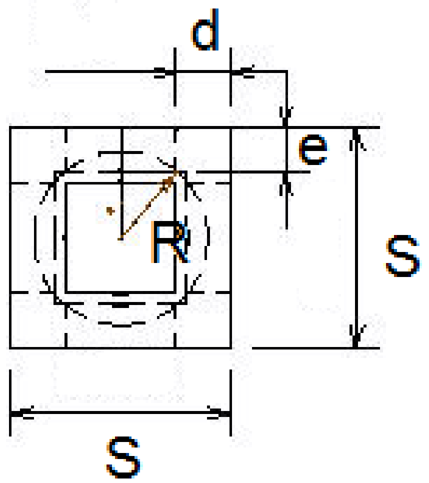



Fig. 4. Dependencies pertaining to the sphere situated in the cube with regard to the width and thickness of the skeleton

In the case of a skeleton in the shape of an angle section, additional geometrical limitations must be formulated (Fig. 4):

$$R^2 = (\frac{S}{2} - e)^2 + (\frac{S}{2} - d)^2$$

$$R_{max} = \sqrt{(\frac{S}{2} - e)^2 + (\frac{S}{2} - d)^2}$$

## 4. TECHNOLOGICAL ANALYSIS OF THE PROBLEM: TOOLS

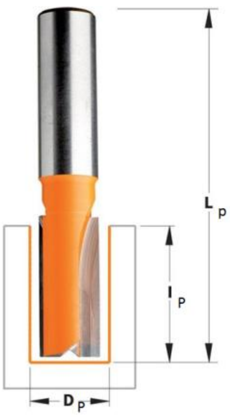
According to the assumptions, the external form is treated as machined, and so only machining of the sphere and of the interior surface of the cube will be subject to further analysis. For this reason, the tool for machining of flat surfaces, the face milling cutter, can be abandoned at the onset.

Three types of milling cutters will be required for machining:

– end mill – Fig. 5,

– ballnose milling cutter – Fig. 6,

– T-slot cutter – in the case of machining the interior surface of the skeleton in the shape of an angle section (for d > e) – Fig. 7.

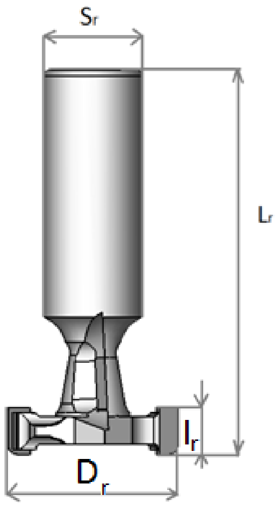



$D_p$ – cutter diameter
$L_p$ total cutter length
$I_p$ – length of cutter blade

Fig. 5. End mill [3]


$S_k$ – milling arbor diameter
$L_k$ – total cutter length
$R_k$ – radius of the spherical milling cutter

Fig. 6. Ballnose milling cutter [3]




$S_r$ - milling arbor diameter
$L_r$ – total cutter length
$I_r$ – length of cutter blade
$D_r$ - cutter diameter

Fig. 7. T-slot cutter [3]

## 5. TECHNOLOGICAL ANALYSIS OF THE PROBLEM: MACHINING

The theoretical limitations necessary for fulfilment of the considered case of a sphere within a cube were formulated above. The basic limitation determines the dimension of the sphere's radius, which must be greater than the side of the 'empty' wall of the external cube.

It should also be ensured that the sphere and skeleton do not come into contact. Only then is it possible to machine the interior of the cube. According to the optimisation of the machining plan, a symmetrical location of the sphere in the centre of the cube is assumed.

The first step is coarse machining of the space between the cube's skeleton and the sphere. An end mill or ballnose milling cutter can be used for this purpose. For technological reasons, the selection of the latter is more favourable.

Machining is to be performed successively from six sides for each wall. In order to provide access for the cutter from each side, the length of the cutter's blade must fulfil the following condition:

$$l_p > \frac{S}{2} - R\sin 45^o$$

Alternatively, during the second step, the interior surface of the skeleton can be machined in the shape of an angle section (when d > e) (Fig. 4). Machining is to be done using the T-slot cutter. In this case, an additional condition for the length of the blade of the cutter must be fulfilled:

$$l_r < \frac{S}{2} - R - e$$

As in the previous step, machining is to be carried out for each wall in turn.

The final step is finishing the sphere's surface using the ballnose milling cutter, performed from the side of each wall. In this case, a blade with the appropriately small radius $R_k$ should be selected, which will make it possible to finish the entire surface of the sphere.

Finishing of the sphere's surface can be performed in two ways:

1. with the use of linear axes of machine tool only (Fig. 8)
2. with the application of linear and rotary axes of machine tool (Fig. 9).

In both cases, it is advisable to use a milling cutter with a radius $R_k$ as small as possible.

In the analysis of the machining plan, one more condition concerning the skeleton machined with the T-slot cutter must be formulated (Fig. 10). In this case, the greatest value of the internal sphere's radius is equal to:

$$R\max = \sqrt{|AB|^2 + |BC|^2}$$

where $$|AB| = \frac{S}{2} - d - 2(d-e) - S_r$$

$$|BC| = \frac{S}{2} - e - I_r$$

$$R\max = \sqrt{\left(\frac{S}{2} - 3d - S_r + 2e\right)^2 + \left(\frac{S}{2} - e - l_r\right)^2}$$

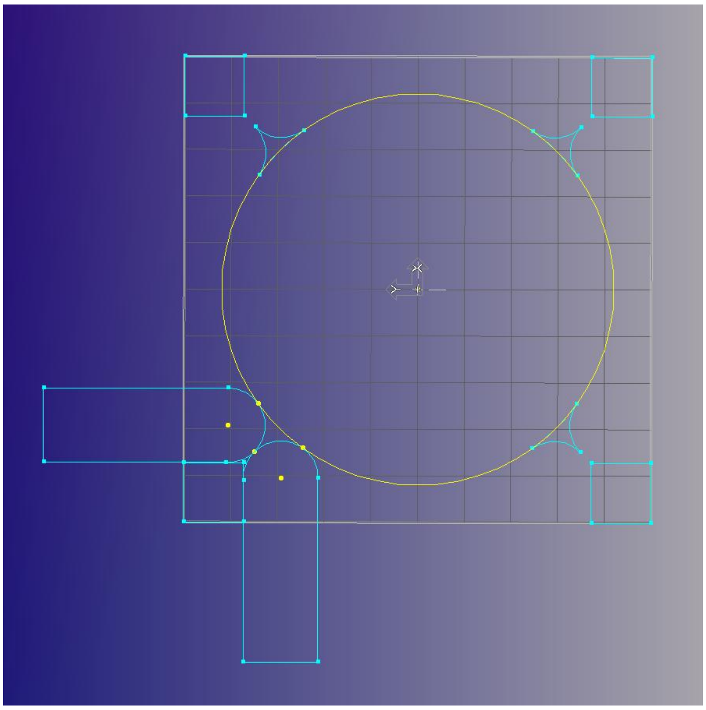


Fig. 8. Illustration of the machining case with the application of linear axes

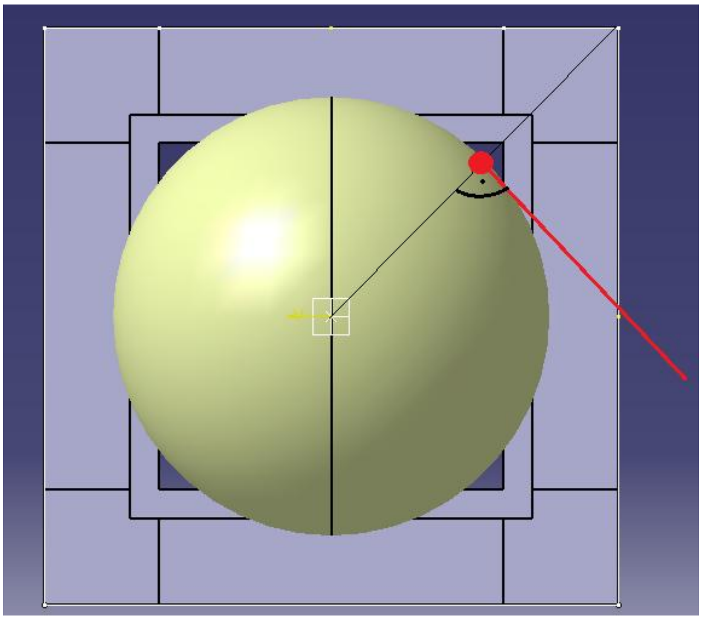


Fig. 9. Illustration of the machining case with the application of axes of rotation

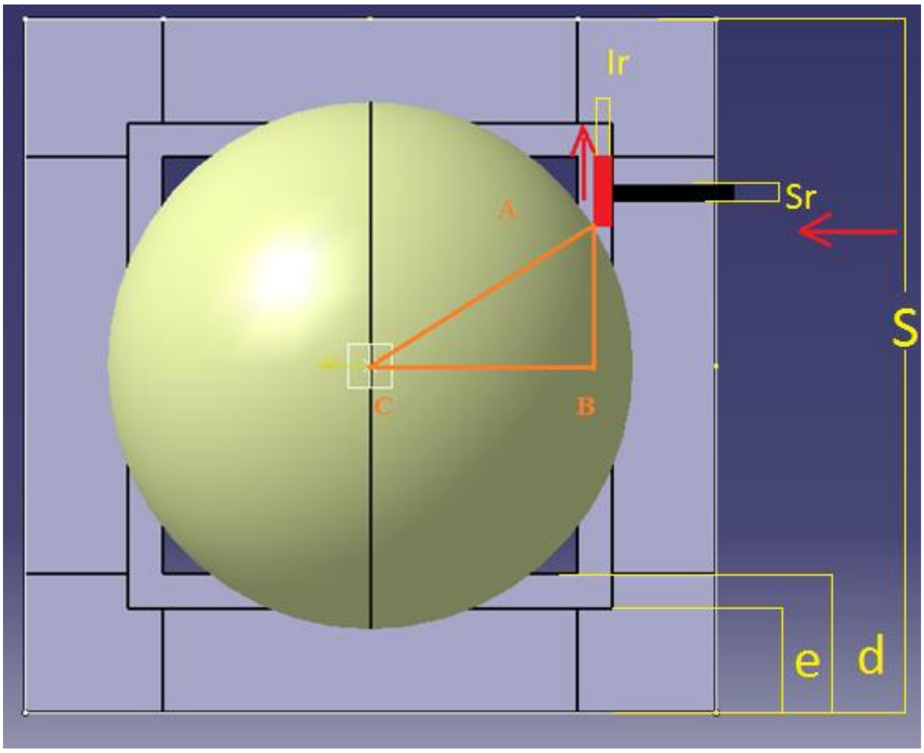



Fig. 10. Illustration of maximum sphere radius enabling cutter entry into T-slots

## 6. MACHINING OF THE PART

Based on the conducted analyses, machining technology for a part comprising a sphere situated inside of a cube was developed. G-code was developed using the GibbsCAM package.

The blank was a block in the shape of a rectangular prism with a outreach sufficient to avoid collisions of the fixture with the tool or spindle. Initially, a round pin was made at one end to enable it to be fastened in a self-centering fixture (Fig. 11).

A Mikron VCE 600 PRO 4-axial vertical milling machine equipped with a 4-axial rotating table was used to perform machining operations. Two cutting tools were applied:
- an end mill with a diameter of 4 mm,
- a ballnose milling cutter with a diameter of 6 mm ($R_k = 3$).

In analysing the various methods of fastening the machined object [2], methods enabling optimal utilisation of the available machine park were used. Machining was carried out in 3 mounting positions:

1. machining of 4 walls with the application of an axis of rotation through fastening in a self-centering fixture (Fig. 12)
2. machining of the remaining 2 walls through fastening in a vise and the application of special brackets making it possible to maintain the sphere in a central position during the final step of machining (Fig. 13).

The final product is presented in Fig. 14.

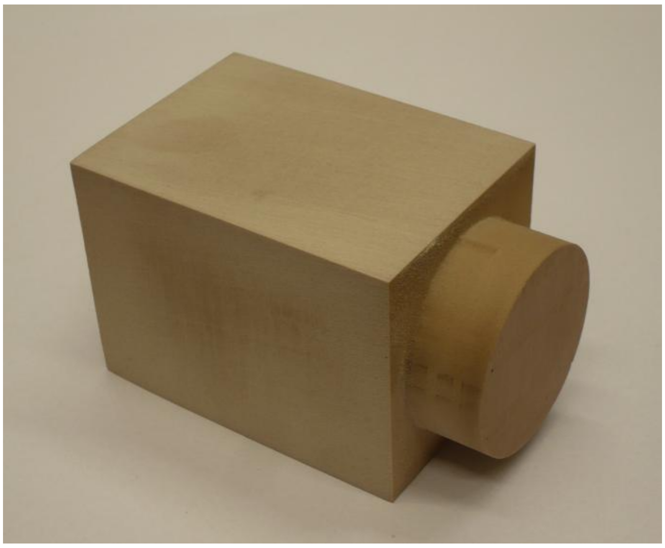


Fig. 11. Blank with visible pin for fastening in the fixture

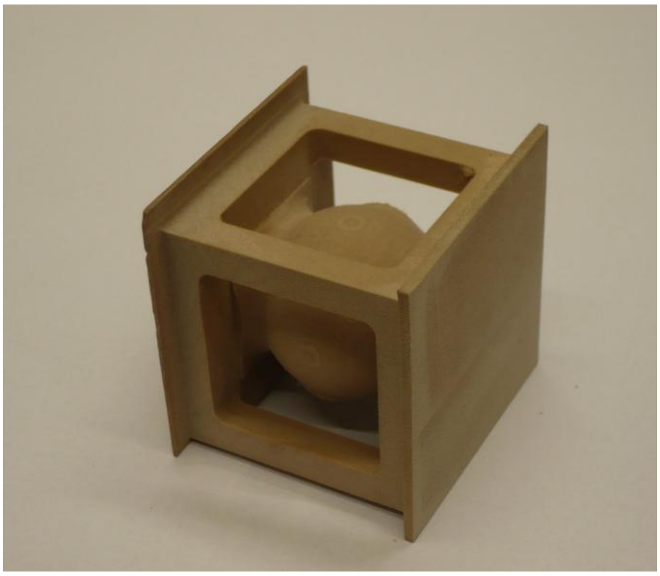


Fig. 12. Part machined from four sides with the application of rotary axis

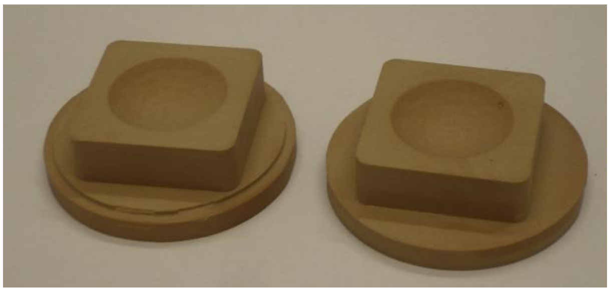


Fig. 13. Special brackets for performance of the final machining step

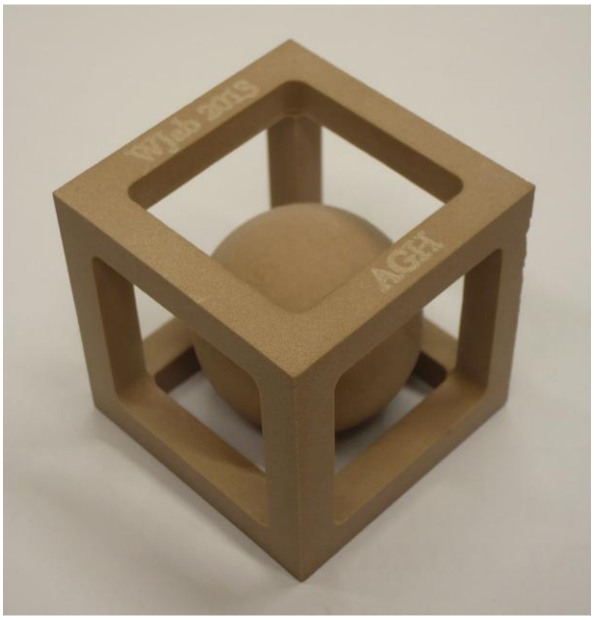



Fig. 14. Final product

## 7. CONCLUSIONS

The task posed in this paper, despite its seeming difficulty, proved possible to complete. There are currently no practical applications for this task; however, the applied methodology turned out to be fully suitable for solving this non-standard technological problem.

Analysis of the capability to produce this detail and others should be conducted with regard to the available machine park and technological equipment. In every case, it is necessary to apply two special fixtures enabling immobilisation of the sphere inside of the cube's skeleton for machining of the final wall in the final step, i.e. when the sphere is separated from the remaining part of the solid.

The number of fastenings depends on the number of controlled axes in the applied machine tool. It should be emphasised that machining can be performed on a 3D and even on a 2.5D milling machine tool; however, this requires 6 fastenings in a machine vise. The application of a 4D miller reduces the number of fastenings to 3, whereas a 5D miller requires only 2.

## REFERENCES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[2] GÓRECKI A., 2009, *Overall technology. Fundamentals of mechanical technologies*, WSiP, Warszawa, Chapter 27.4, (in Polish).

[3] http://www.faba.pl/