Synthesis of a deforming-cutting mill design

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Abstract. The article is devoted to the synthesis of a new threading tool used to form internal threads in products made of aluminum alloys. As a rule, when machining internal threads in complex parts, the manufacture of which is carried out at milling machining centers, thread mills are used. This is due to low reliability of threading operations where classic marking tools are used, which are unacceptable for parts that have high cost at this time. In addition, when processing products made of aluminum alloys, there are features related to the presence of porosity in the material and ‘tears’ on the treated surface, the nature of which is associated with the cutting process. This degrades such an operational parameter of threaded joints as tightness.

To solve these problems, the design of a new tool, a deforming-cutting mill, was proposed on basis of morphological analysis and synthesis, and the combined machining principle was taken as a basis for its creation.

There are many ways to obtain internal threads; they can be divided into cutting, grinding, and deformation [1-5]. The external thread is mainly used on fixing elements and is obtained by rolling [2]. The most common tools for machining internal threads are marking tools [1, 6, 7].

The thread milling process is a processing method for both internal and external surfaces. Thread milling, in relation to other types of shaping, has its own advantages and is often used to produce large-diameter threads, however, world leaders in the tool industry have micromills designed to process internal threads starting from standard size M1,4 [8]. Thread milling is used for a wide range of structural materials – from non-ferrous metals and alloys to hardened steel with HRC, 62 hardness [8].

Thread milling provides a high cutting speed, unlike marking tools, which have speed limits associated with a rigid relationship between the peripheral and axial tool speeds. In addition, a single thread mill can handle a wide range of standard sizes without making changes to the tool design.

Thread milling has become widespread in the manufacture of complex, expensive parts, when, in addition to the requirements for quality and productivity, the requirement is made for the technological operation reliability, and its implementation is carried out at machining centers or on CNC milling machines.

According to the design thread mills are divided into comb shank-type end mills (figure 1) [6, 7, 8, 9], comb shell-type mills and disc mills. Each of this type of tools is used to process a certain type of surface.
An internal thread milling cycle consists of three main stages: 1 – introducing the mill into the hole to be processed; 2 - milling of the thread; 3 – removing the tool from the hole (figure 2). The difference in the kinematics of movements between machining with a marking tool and with a mill is that during threading a tool, in addition to axial rotation and movement along the axis, has to receive an additional planetary movement to ensure its running on the surface of the hole.

In the manufacture of blanks for machine parts in which AK12 (AL2), AK9ch (AL4), AK7ch (AL9) aluminum alloys formed by casting are used, gas porosity is observed [10-12]. The nature of this defect is different: porosity can be related to and formed because of hydrogen contained in the liquid-alloy — hydrogen porosity; it can be formed in the process of shrinkage – shrinkage porosity; it can be mixed – formed due to hydrogen inclusions and developed during metal shrinkage (figure 3).
Presence of porosity in the structure of aluminum alloys impairs mechanical and technological properties of parts. Technical requirements for cast blanks of aluminum alloys provide for their mandatory defect control [13]. However, firstly, control involves overcoming a certain boundary (porosity score) exceeding which classifies the blank as defective, i.e. suitable blanks also have this specified defect, but of a smaller size or dislocation density. Secondly, in real conditions, a selective control of blanks is often carried out, which doesn’t involve checking every blank. The previously mentioned determines that the blanks arriving for machining contain porosity of a larger or smaller size and density in their structure.

The thread milling process also has certain drawbacks. A surface roughness is formed during cutting, which is generally determined by the tool geometry and movement kinematics, mechanical characteristics of the material being processed, dynamic phenomena of processing, and roughness of the mill blades [14]. Often, when machining metals and alloys, ‘tears’ are observed on the treated surface due to microwelding of the material of the part and the tool, presence of build-up, and random phenomena (presence of non-metallic inclusions in the material, chips coming under the tool blade, etc.). These tears are not taken into account when analyzing roughness values, because the calculation method is reduced to averaging the values. The surface roughness control of an internal thread is complicated, therefore, the surface microgeometry obtained by turning [15, 16] is presented as an example, and tears are observed both at low and at high cutting speeds (figure 4).

![Figure 4. Three-dimensional surface image [15, 16]:
(a) V = 21 m/min; (b) V = 155 m/min.](image)

When machining aluminum alloy parts by cutting, the pores present in the material get opened on the thread surface, and tears further reducing the degree of surface uniformity are formed due to milling process. This causes worsening of one of the main operational properties of threaded detachable joints – tightness. Observance and preservation of this property is very important for parts of hydraulic and pneumatic equipment, mechanisms and machines operating in aggressive environments, vacuum, etc. [17, 18, 19].

The aim of this article is to offer a technological solution that ensures the quality of the working surfaces of internal threads.

The goal can be achieved as follows:
- by improving the quality of aluminum alloys through the use of advanced metallurgical technologies or close continuous control of blanks, where an extremely lowered limit of permissible gas porosity is used as a criterion;
- by applying coatings on the machined thread surfaces that would cover the existing pores and tears, for example, a thin layer of polymer;
- by selecting optimal processing conditions that minimize tears on the treated surface;
- by using other types of surface shaping instead of cutting.
Most of these options solve only one side of the problem, i.e. cannot be applied on their own. Thus, selection of optimum cutting modes does not solve the problem associated with defects in the blank’s material, and vice versa, absence of gas porosity does not determine absence of tears during cutting.

The only overall technological solution is the option of switching to another type of shaping. Thread can be obtained by deformation (extrusion) of the blank’s material. In this type of shaping, pores are not opened and crushed, and the process itself does not cause tears on the working surface. However, the use of marking tools narrows the technological capabilities of modern CNC machines, requires specialized equipment and reduces the technological operation reliability. These conditions provide the basis for new technological solutions.

For machining internal threads in aluminum alloys, the deforming-cutting mills were proposed [20, 21]. Their operation mode coincides with the operation mode of traditional marking tools, but due to differences in design has its own characteristics. An intake part of a marking tool contains deforming and cutting teeth [20, 21]. Firstly, the deformation of the machined surface, i.e. a change in its properties, takes place; secondly, cutting of the modified material occurs. However, these tools are also characterized by previously mentioned disadvantages.

A future technological solution can be based on the combined processing principle used in deforming and cutting marking tools — recurrent and consistent deformation and cutting of the material. Application of this principle will solve the problem of porosity in the blank’s material and tears on the treated surfaces. Based on it, a threaded deforming-cutting mill was proposed. A morphological analysis was carried out to determine the design of the future tool. The morphological analysis requires preparation of a morphological matrix with possible options for implementation of structural solutions for tool elements.

The main components and design parameters of the mill and the method of forming the machined surface are selected as elements:

- mill body material;
- type of a mill’s shank end;
- shaping type;
- number of cutting and deforming plates;
- attachment method of cutting plates;
- backing-off of the deforming part;
- chip channels;
- work part material.

After filling the matrix (table 1) and assigning each of the options its own code, we will carry out the synthesis of possible designs of a threaded deforming-cutting mill. By way of presenting the option variety, we draw up a diagram of the tool elements’ links (figure 5).

Based on the number of tool elements and their implementation options, the total number of embodiments of the deforming-cutting mill comes up to 6912 designs. Of course, among these options there are not feasible and not workable designs. To determine the best design, we will assign a numerical value in the range from 0 to 1 to each of the indicated implementation options, where 0 is an unrealizable or not workable solution, 1 is the best and optimum option. Mill’s body material $K_1$: cast iron - 0.5; structural steel - 0.7; tool steel - 1; non-ferrous alloy - 0.3. Type of shank end of the mill $K_2$: conic - 0.8; cylindrical - 0.9; cylindrical flatted (of WELDON type) - 1. Method of surface shaping $K_3$: deformation - 0.8; cutting - 0.9; combined - 1. The number of plates $K_4$: two cutting and two deforming - 0.7; one deforming and one cutting - 0.8. Method of cutting plates’ attachment $K_5$: welding - 0.5; mechanical - 0.6. Backing off of the working part of plates $K_6$: radial - 0.7; axial - 0.6. Chip channels $K_7$: straight - 0.8; screw - 0.7. Material of the working part $K_8$: tool steel - 0.5; high-speed steel - 0.7; hard alloy - 0.9. Application of lubricants $K_9$: absence of channels for supplying lubricants - 0.4; supply of lubricants only to the cutting plates - 0.6; supply of lubricants only to the deforming plates - 0.6; lubricant supply to all plates - 0.9.
Table 1. Morphological matrix of a threaded deforming-cutting mill

| Tool element                                | Implementation options |
|---------------------------------------------|------------------------|
| 1. Mill body material – X₁                 | 1.1 Cast iron – X₁₁   |
|                                             | 1.2 Structural steel – X₁₂ |
|                                             | 1.3 Tool steel – X₁₃   |
|                                             | 1.4 Non-ferrous alloy – X₁₄ |
| 2. Type of mill’s shank end – X₂           | 2.1 Conical – X₂₁     |
|                                             | 2.2 Cylindrical – X₂₂ |
|                                             | 2.3 Cylindrical flatted (of WELDON type) – X₂₃ |
| 3. Shaping method – X₃                     | 3.1 Cutting – X₃₁     |
|                                             | 3.2 Deforming – X₃₂   |
|                                             | 3.3 Combined – X₃₃    |
| 4. Number of cutting and deforming plates – X₄ | 4.1 Two plates, one of them is cutting, another – deforming – X₄₁ |
|                                             | 4.2 Four plates (2 cutting and 2 deforming) – X₄₂ |
| 5. Method of cutting plates’ attachment – X₅ | 5.1 Welding to the mill’s body – X₅₁ |
|                                             | 5.2 Mechanical screw fixing – X₅₂ |
| 6. Backing-off of plates’ working part – X₆ | 6.1 Radial – X₆₁ |
|                                             | 6.2 Axial – X₆₂ |
| 7. Chip channels – X₇                      | 7.1 Straight – X₇₁ |
|                                             | 7.2 Screw – X₇₂ |
| 8. Working part material – X₈               | 8.1 Tool steel – X₈₁ |
|                                             | 8.2 High speed steel – X₈₂ |
|                                             | 8.3 Carbide – X₈₃ |
| 9. Usage of lubricants – X₉                 | 9.1 Absence of channels for supplying lubricants to the cutting zone – X₉₁ |
|                                             | 9.2 Supply of lubricants only to cutting plates – X₉₂ |
|                                             | 9.3 Supply of lubricants only to deforming plates – X₉₃ |
|                                             | 9.4 Supply of lubricants to all plates – X₉₄ |

Figure 5. Diagram of possible structural options for the tool design.

Coefficient $K_c$ determining the optimality of a particular design of the mill is based on the following:

$$K_c = 1 - \sum_{i=1}^{n'} (1 - K_i') / n'$$  \hspace{1cm} (1)

where $K_i'$ is the numerical value of an implementation option; $n'$ is the number of implementation options.

As a result of calculating the coefficient according to expression (1), the following structural options that have the highest value of coefficient $K_c$ were identified:

$$K_{c1} = X_{13} \rightarrow X_{23} \rightarrow X_{33} \rightarrow X_{44} \rightarrow X_{52} \rightarrow X_{61} \rightarrow X_{71} \rightarrow X_{83} \rightarrow X_{94},$$

$$K_{c2} = X_{13} \rightarrow X_{23} \rightarrow X_{33} \rightarrow X_{44} \rightarrow X_{52} \rightarrow X_{61} \rightarrow X_{71} \rightarrow X_{83} \rightarrow X_{94},$$
\[ K_{c3} = X_{13} \rightarrow X_{23} \rightarrow X_{31} \rightarrow X_{42} \rightarrow X_{52} \rightarrow X_{61} \rightarrow X_{72} \rightarrow X_{83} \rightarrow X_{94}, \]

and each of these options amounts to:

\[ K_{c1} = 1 \rightarrow 1 \rightarrow 0.8 \rightarrow 0.6 \rightarrow 0.7 \rightarrow 0.8 \rightarrow 0.9 \rightarrow 0.9 = 0.85, \]
\[ K_{c2} = 1 \rightarrow 1 \rightarrow 0.8 \rightarrow 0.5 \rightarrow 0.7 \rightarrow 0.8 \rightarrow 0.9 \rightarrow 0.9 = 0.81, \]
\[ K_{c3} = 1 \rightarrow 0.9 \rightarrow 0.8 \rightarrow 0.6 \rightarrow 0.7 \rightarrow 0.7 \rightarrow 0.9 \rightarrow 0.9 = 0.78. \]

The most important option is \( K_{c1} = 0.85 \), which contains nodes and characteristics that allow to create a tool that meets all operational requirements and can be implemented on basis of available technologies, however, the use of deforming plates in the mill design is a new solution.

The deforming-cutting mill design, developed on basis of structure option \( K_{c1} \), is shown in Figure 6.

The leading structural element of the proposed tool is a one-piece body 1 (figure 6) made of U8 tool steel. On the shank end of the body 1 there is a flat 2 for installation in a WELDON type chuck, which contributes to the correct positioning of the tool and facilitates the search for problems encountered during processing. Neck 3 is made on body 1 to facilitate grinding of the shank end and the working part of the tool. It also acts as a stress concentrator, so that in case of an error in the program or deficiencies associated with the blank, a broken tool does not damage the blank itself, the chuck or machine elements. As a rule, in this case, the working part of the tool remains in the hole, and the shank end remains clamped in the chuck.

![Figure 6](image_url)

**Figure 6.** Model of a universal multi-start deforming-cutting end mill with interchangeable plates.

The working part of the tool consists of two straight chip grooves 5, with slots for installing multi-start threaded plates 6 and 7. In the axial direction plates 6 and 7 are offset relative to each other by the amount of thread rise, which is done so that the plates’ teeth could enter the thread cavities. The possibility of supplying lubricants into the cutting zone is provided, channels 8 are located in the upper part of the chip groove. The location and size of the chip grooves ensure that there is no possibility of clogging them with chips and processing products.

A feature and a novelty of this mill is combined processing. This result can be achieved due to two plates 6 and 7, realizing shaping of different types. One of the plates is a standard representative of
multi-start comb cutting plates for mills made of coated hard alloy (figure 7, a). They are produced in a wide range of sizes, selected according to the thread pitch and embodiment, and they are common and affordable.

![Figure 7. Working plates: a) cutting plate; b) deforming plate.](image)

The second is a modified cutting plate (figure 7, b). The modification consists of re-sharpening of cutting teeth by backing-off - giving them a different geometry, which determines the absence of cutting during tool operation, replaced by plastic deformation. When placing the plate, the design of the mill’s body provides for its offset by the amount of backing-off in order to place both cutting and deforming teeth on the same diameter.

The design of the proposed deforming-cutting mill will solve the problem of porosity in the blank’s material and tears on the formed surface.

Further research with the use of deforming-cutting mills can be carried out in the field of identifying features, refinement and optimization of threading cycles implemented on CNC machines.

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