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EVALUATION OF TITANIUM ALLOY THREAD QUALITY DURING CUTTING

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Abstract

This article concerns a new method of assessing the thread cutting process and the quality of the formed thread using the method of optical observation of the workpiece during machining. A series of digital images of the thread profile was taken in transmitted light for each tool infeed. Such images, obtained with high resolution for three angular positions, were binarized, with the space between ridges taken in successive infeeds identified as "void", and its projection was then parameterized. Two of these parameters, area of void and aspect ratio, were used as indicators of the technological quality of the thread. The suitability of the selected parameters for technological description of the thread was verified using the example of titanium alloy thread turning under ambient and cryogenic conditions.

Keywords: process evaluation, thread measurement, titanium and its alloys, liquid nitrogen.

1. Introduction

According to current standards, the dimensional accuracy of thread is evaluated based on dimensional and shape tolerance. The measurement and evaluation of metric screw thread quality with the use of a direct optical method is the most common approach, based on a machine vision instrument and image processing. Different implementations of evaluation and error compensation are used in different systems. For example, Min in [1] presents a method of screw thread geometric error compensation when machine vision is used for measurements. It was observed that there were many factors which influence measurement error, such as interference of outside light sources, adjustment of focal length of the microscope, and lens distortion. Even if all factors affecting the measurement are included in the compensation equation, as indicated in [2], only 2D information will be obtained about a three-dimensional object. It is possible to use 3D measurement with computed tomography, as in [3], or an optical measurement method as in [4], but computational time is required to obtain layered images and perform parametric evaluation. In [5] a comprehensive evaluation of the measurement system is presented, where the metric screw thread is assessed with regard to the fulfillment of geometrical requirements during the manufacturing process. With the vision system, basic geometrical parameters such as thread angle, thread diameter and thread pitch are calculated based on a cross-sectional image of the thread.

Measurements confirm the quality of workmanship, but the quality itself is created in the manufacturing process. For sequential manufacturing, fractal methods are used for modeling, as described in [6]. They make it possible to take into account heat transfer [7] and system vibrations [8]. Nevertheless, when modeling the cutting process, the variable temperature field changes significantly the material properties. The occurrence of plowing force, uncut chip thickness or continuous changes on the tool edge causes imperfections in threads. To obtain the best possible thread accuracy, the machining parameters should take into account the specific properties of titanium alloys, such as the change in the elastic deformation of the workpiece induced by the change in cutting force, tool wear, increasing thermal distortion, formation of a built-up edge, and increasing radial spindle error.

The deformation energy used during thread cutting is transformed into heat energy near the cutting edge of the tool. The increased heat can cause not only rapid wear of the tool, but also dimensional changes in the part being machined. In the research presented in [9], microstructural sub-surface changes of the Ti–6Al–4V alloy were observed without Ti phase transformation. Crystallographic observations, together with residual stress analysis, indicated the layered structure of the material sub-surface. The analysis of the microstructure of the segmented chip presented in [10] shows that the length of the undeformed surface in the segmented chip is independent of the cutting speed and the depth of cut, but increases with feed rate.

The analysis of experimental data presented in [11] indicated that in the machining of titanium alloys, plowing forces exist in all conditions, significantly contributing to the total forces. This is convergent with the research described in [12], where the plowing effect was measured and modeled for a wide range of materials, taking into account the material properties and tool edge radius. In [13] it was also confirmed that with an increase in residual stresses in the machined surface, the probability of burr formation also increased.

This article deals with quality analysis in successive thread feeds. The optical method of direct observation of the thread profile in transmitted light was used. During machining, the surface perpendicular to the thread profile at the height of the outer diameter is taken as the base measuring surface. Performance of measurements in successive infeeds enables the analysis of material loss and of the formation of space between successive crests of the observed thread. The following chapters contain a description of the method of measurement, the results of the measurements, and discussion of those results. The sensitivity of the method was assessed by examining how a change in the material properties affects the values of the assessment parameters (area and aspect ratio).

2. Materials and methods

2.1. Experimental procedure

External thread M-ISO M7×1 (ISO 68-1: 1998) tests were performed for two different titanium alloys: commercially pure titanium Grade 2 (CP Ti), and $\alpha\beta$ titanium alloy Grade 5 (Ti-6Al-4V), in ambient and cryogenic conditions. For cutting in ambient conditions the labels “Ti Grade 2, dry” and “Ti Grade 5, dry” were used; for cryogenic machining (with cooling of the workpiece for 5 minutes before machining) the labels were “Ti Grade 2, LN2” and “Ti Grade 5, LN2”.

A total of 32 samples were prepared, 40 mm in length, with a diameter of 7 mm. Two different tool materials were used for cutting at ambient temperature (PVD TiAlN, 3ER 1.0 ISO VTX Carbide Threading Insert Vardex [14]) and in cryogenic cutting (Carmex 16 ER 1.0 ISO P30 [15]). Cutting parameters were pre-optimized for the tool life criterion. Finally, cutting tests were performed for the following parameters: feed rate 1 mm, cutting speed 22 m/min (rotational speed 1000 rev/min), successive infeeds: 0 – 0 mm, 1 – 0.1 mm, 2 – 0.1 mm, 3 – 0.1 mm, 4 – 0.1 mm, 5 – 0.1 mm, 6 – 0.06 mm, 7 – 0.05 mm, 8 – 0.05 mm.

2.2. Measurement procedure

The quality of the thread production process was evaluated using a vision measuring system. The measurement procedure consists of three loops shown in Figure 1. For subsequent tool infeed (loop 3 – infeed number 0..8), for three subsequent rotational positions (loop 2 – rotation number position 0...2) and 20 subsequent translational positions (loop 1 – translation number position 0...19) *Measurement master plan* is implemented. Each execution of the *Measurement master plan* causes a change of the measurement system setting and measurement of the thread in the position offset by the set value. In this way, a set of measurements along the thread was carried out at a given length with a given offset (20 measurements). Then the thread position relative to the measuring system was changed by 120°, and measurement was carried out in the displaced system. Measurements were made for all states in sequence. After all state changes were completed while the system was running the measurement procedure for a single thread was completed.

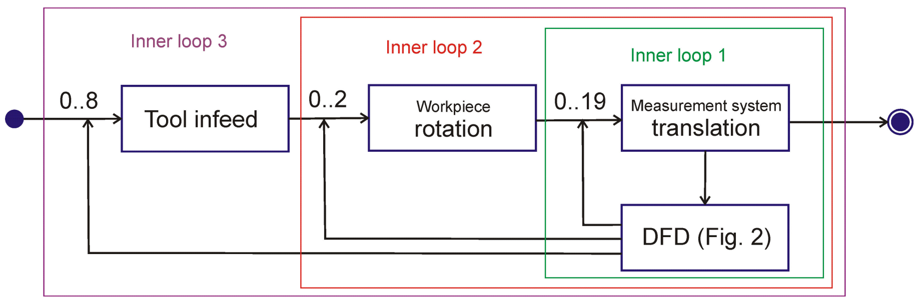


Fig. 1. Measurement state transition diagram of producing a single thread.

A single measurement was carried out in accordance with the data flow diagram (Fig. 2). For each infeed, a measuring system was set up in accordance with the *Measurement master plan*. The details of implementation of the plan were recorded in *Measurement plan details* as another record of the measurement being carried out (unique measurement number, tool infeed, rotary position, translational position, other related data). The completed measurement (a single thread image) was saved in *Thread images*. At the same time, further analysis of the image was carried out in accordance with the adopted algorithm in *Data processing*. The results of image data processing were sent to the *Inference System*, which exchanged the thread measurement results with control data, which in turn were processed into a measurement task in the *Measurement task generation* process.

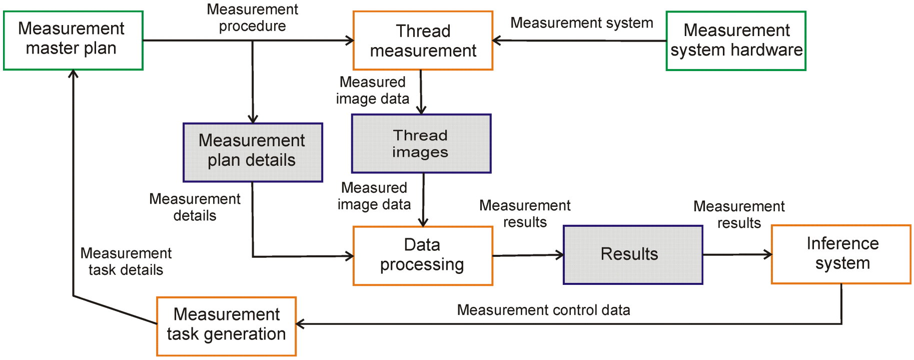
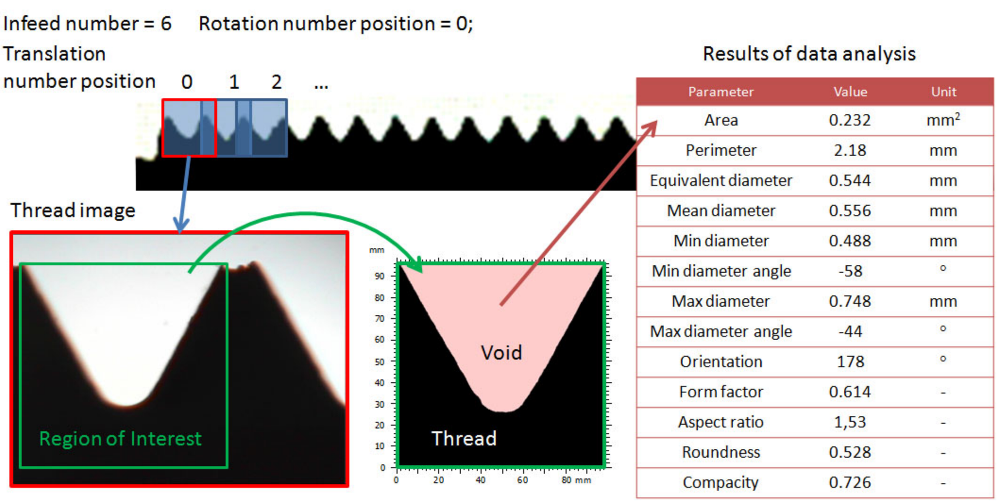


Fig. 2. Measurement data flow diagram (DFD).

2.3. Data acquisition, processing and analysis

The measuring system allows obtaining a single image of the thread profile. For a stationary system, the measuring system has been earlier described in [16]. The core of the system is a single digital camera with an optical system. Two main requirements were set for the measuring system: 1) the field of view should allow observation of at least a single thread profile, and 2) the thread lighting system should allow the thread profile area to be distinguished. An optical system was designed that fulfilled these requirements and enabled the recording of images with a field of view of 1.33 mm^2. A back lighting system was applied, in which transmitted light images were recorded. The system for positioning the thread relative to the optical axis and the lighting system was set to obtain the correct focus of observation of both thread faces (Fig. 3 Thread image).

To better identify the effect of burr formation for a subsequent infeed of the thread, geometrical contour parameters were calculated. For the series of acquired images a pre-processing procedure was applied, consisting of noise removal and contrast improvement. The enhanced images were then subjected to a segmentation procedure. The binary images were characterized with the use of object parameters (Fig. 3).



Parameter	Value	Unit
Area	0.232	mm^2
Perimeter	2.18	mm
Equivalent diameter	0.544	mm
Mean diameter	0.556	mm
Min diameter	0.488	mm
Min diameter angle	-58	°
Max diameter	0.748	mm
Max diameter angle	-44	°
Orientation	178	°
Form factor	0.614	-
Aspect ratio	1,53	-
Roundness	0.528	-
Compacity	0.726	-

Fig. 3. Example of measurement and analysis of thread quality parameters.

The identified object (the void between two ridges/crests/flanks) was characterized by such parameters as area, perimeter, equivalent diameter, mean diameter, minimum diameter, maximum diameter, aspect ratio, roundness and compactness. Detailed analysis of these parameters showed that some of them were linearly correlated. The area parameter was linearly correlated with perimeter, equivalent diameter, mean diameter, minimum diameter and maximum diameter, while the aspect ratio was correlated with roundness and compactness. Finally, only two parameters were selected for further analysis: area and aspect ratio.

– Area is defined as the horizontal area covered by the object. It is measured by summing all pixels belonging to the object. The significance of this parameter relates to the free space for interaction with the internal thread of the nut. It is required that the area be not less than the nominal value.
– Aspect ratio is defined as the ratio between the maximum diameter (maximum horizontal diameter of the void) and the minimum diameter (maximum vertical diameter of the void). If the value is close to 1, the form of the object is close to that of a disk. If the value is high, the grain is oblong. The significance of this parameter relates to the technological quality of the thread. It is required that the ratio be not less than the nominal value.

3. Results and discussion

3.1. Thread measurement results

To evaluate the turning process, the thread was measured and analyzed for each infeed. The results for Ti Grade 2 and Ti Grade 5 are presented in Fig. 4 and Fig. 5. Differences in the

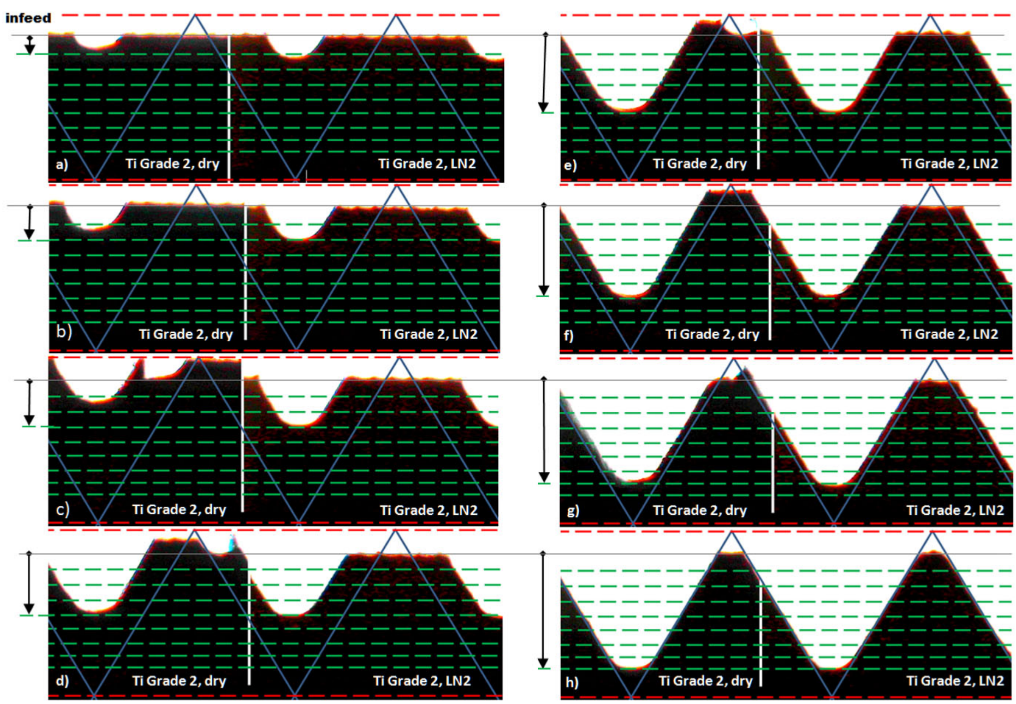


Fig. 4. Optical images of the thread contour for Ti Grade 2 in dry and cryogenic tests.

formation of the thread are visible especially in the case of Ti Grade 2 dry, where the problem of burrs is clearly noticeable.

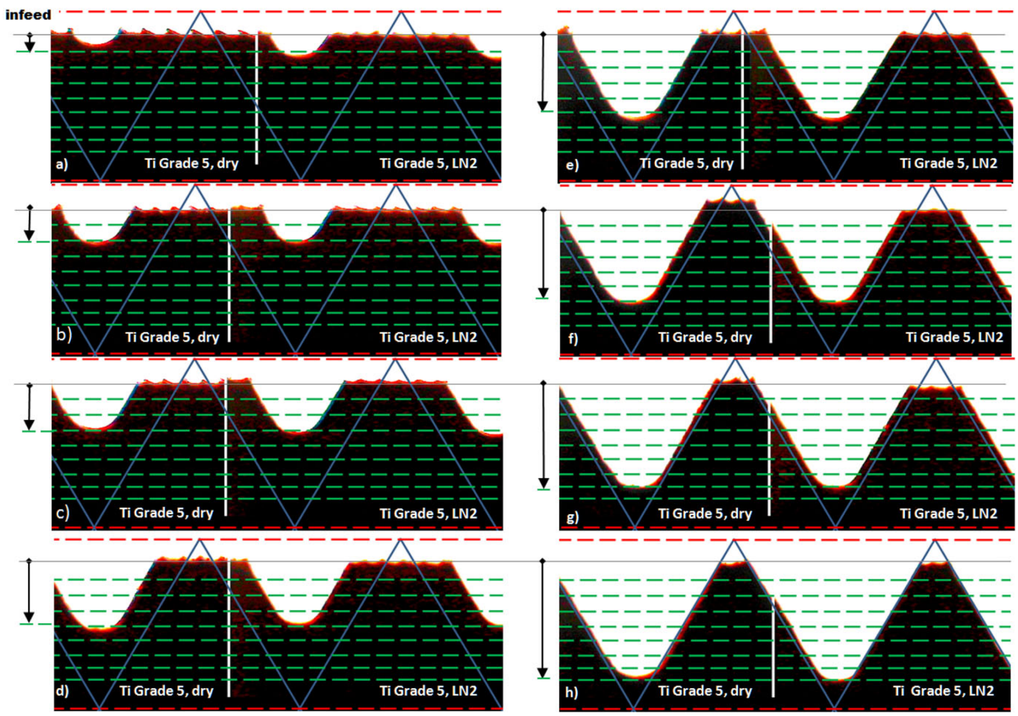


Fig. 5. Optical images of the thread contour for Ti-6Al-4V alloy in dry and cryogenic tests.

The burr formation mechanism for titanium alloys was described by Dornfeld *et al.* [17]. In their research, involving Ti-6Al-4V drilling tests, four types of burrs were investigated: uniform burr, lean back burr, roll back burr, and roll back burr with widened exit. In the research presented in [3] a qualitative analysis of burrs was made, with entrance burrs acquired using SEM. The authors reported no evident differences in burr shape and size for all of the tested cutting conditions.

In this study, two types of burrs were observed during machining: burrs with a strongly rolled-back shape, and burrs with a relatively small height and widened exit. In the initial stages of the process the material is displaced sideways. This causes a change in the outside diameter and the appearance of burrs, first longer and thinner, gradually becoming short and thick. These types of burrs are produced due to thermal effects in dry cutting. According to the author's own research and the results reported in [17], burrs gradually disappear at lower cutting temperatures. The final accuracy of the thread geometry is satisfactory. In the case of cryogenic cutting, visible burr marks are no longer observed. The thread images in Fig. 4 and Fig. 5 confirm this. Cryogenic cooling provided a remarkable benefit in reducing the visible burrs, and had a significant positive effect on thread accuracy. The thread error caused by increasing flank wear and thermal expansion as the workpiece temperature increases during machining was reduced in the case of cryogenic cutting.

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3.2. Analysis of area of void

Measurements based on image analysis refer to the quality determined in pixels. These values are converted into units corresponding to the value of the measured quantity. The area of the void is measured by summing all pixels belonging to the object (the void between ridges). For a nominal thread, the value of the cross-sectional area of the void between the crests of the thread is fixed for successive infeeds. Comparison of the measured value with the nominal value provides an indication of the course of the thread cutting process.

The results of tests of Ti-6Al-4V alloy during turning at ambient and cryogenic temperatures present a properly cut external thread. Observations during cutting confirm the good machinability of the material. The measurements of the final product lie within the assumed tolerance range. In Fig. 6b the surface area of the removed material (void) is given as a function of the nominal area. For both threads, the surface area values are similar. It may be observed for dry machining that the area of the void is slightly higher for infeeds 4, 6, 7 and slightly smaller for the third infeed. The pattern is similar to that obtained for Ti Grade 2 (Fig. 6a). However, in the case of Ti Grade 2 the differences are much greater, and it is hard to describe the machinability as good. In the range of infeeds from 3 to 7, disturbances in the outline of the thread resulting from burrs, the high level of plastic deformation, and the non-constant uncut chip thickness are also observed.

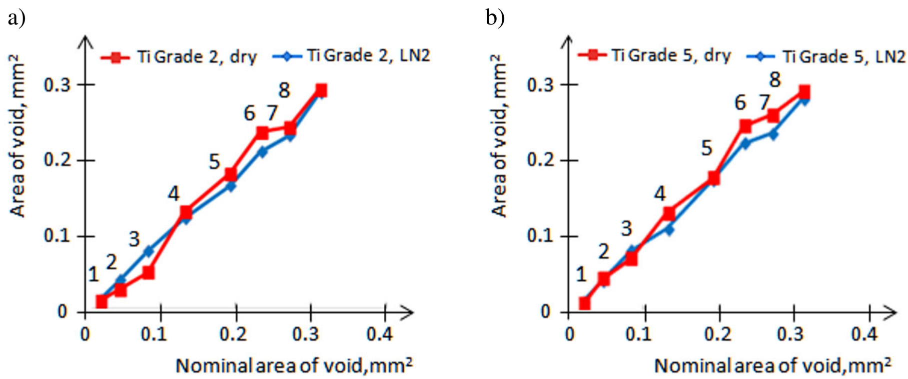

Fig. 6. Measured area of void vs. nominal area of void in thread turning tests of Ti Grade 2 (a) and Ti-6Al-4V alloy (b).

The following assumptions were adopted for analysis of the void area:

1. The nominal value is known.
2. Due to the tolerance of the thread, the difference between the measured area and the nominal area cannot be negative.
3. The difference between the measured area and the nominal area is related to the tolerance and should not exceed the permissible value.

In the case of Grade 2 dry (Fig. 7a), it may be observed that in the initial stages of thread cutting the relative difference between the measured area and the nominal area of the void (nut) is substantial, and for the first three infeeds it is even negative. In the case of Ti Grade 2 LN2 (Fig. 7b), the value of the area is close to the assumed value. In this case the accuracy of the thread is greater.

In the case of Ti Grade 5 dry and Ti Grade 5 LN2 (Fig. 7c and Fig. 7d) the results are close to the nominal value of the removed material. In cutting of Ti Grade 5 cooled with liquid nitrogen, better accuracy was obtained for each infeed.

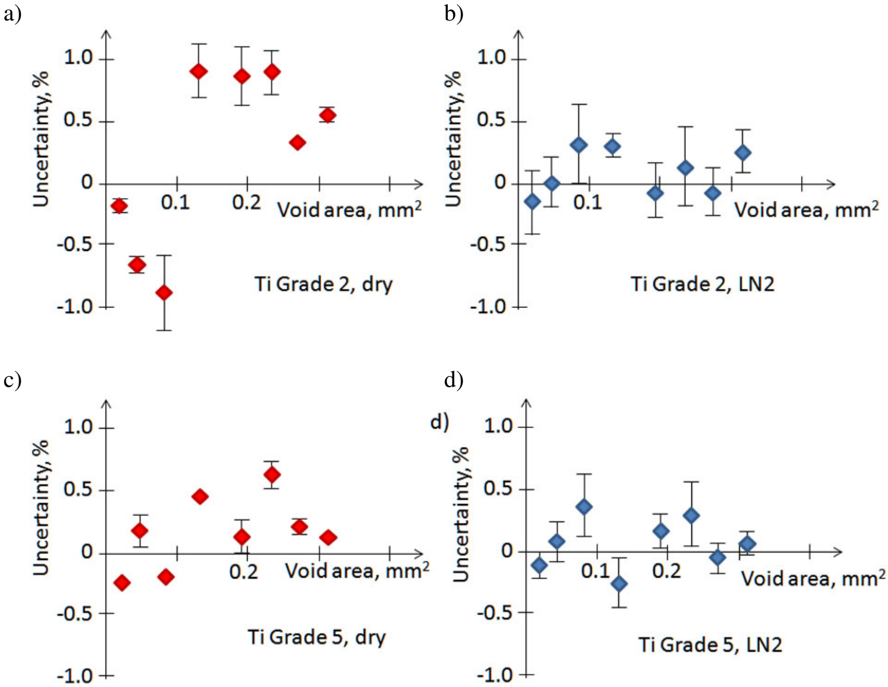

Fig. 7. Uncertainty of measured void area vs. nominal void area (for successive infeeds).

3.3. Analysis of the aspect ratio

The second analyzed parameter of the thread is the aspect ratio of the area of the void. It is calculated as the ratio of the thread width to its height (the ratio of the maximum horizontal diameter of the void to its maximum vertical diameter). The aspect ratio describes the accuracy of the thread. If its value is too large or too small, the thread should be corrected in *close loop manufacturing* (CLM). Zawada-Tomkiewicz *et al.* discuss in [5] a set of actions taken within the quality system to ensure that a product fulfils quality requirements. The quality of the product is guaranteed by application of the concept of a cyber physical system For the development of the measurement model, an optical measurement system has been developed to measure the characteristics of the workpiece on the basis of the subject's image in passing and reflected light. The measuring system was analyzed in screw thread measurement, and its measurement capability was checked at the same time. The model of the manufacturing system was developed, and the influence of factors affecting technological quality assurance of the product was analyzed. A more thorough analysis was made to assess the effect of tool flank wear on the accuracy of the metric screw thread in the manufacturing process model. At the same time, capacity analysis was performed for the entire manufacturing system.

The following assumptions were adopted for analysis of the aspect ratio:

1. The nominal value for each of the infeeds is known.
2. Due to the fact that the value of the parameter depends on both the maximum horizontal diameter and the maximum vertical diameter of the void, three cases can be considered: 1) the change in the coefficient results from a change in the maximum horizontal diameter (the burr protrudes above the external diameter of the thread); 2) the change occurs as

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a result of a change in the maximum vertical diameter (the burr occurs in the inner space of the void between the ridges); 3) the change occurs as a result of changes in the maximum vertical diameter and the maximum horizontal diameter.

When considering changes in the aspect ratio for successive infeeds, both for Ti Grade 2 and Ti-6Al-4V alloy, it should be noted that the values are increasingly close to the nominal values as the final thread is completed (Fig. 8). At lower temperatures, as in the case of pre-cooling of the workpiece with LN2, the differences are quite small in the final stages of thread turning, both for Ti Grade 2 and Ti-6Al-4V alloy. This indicates the improved machinability of titanium alloys in thread turning tests under cryogenic conditions.

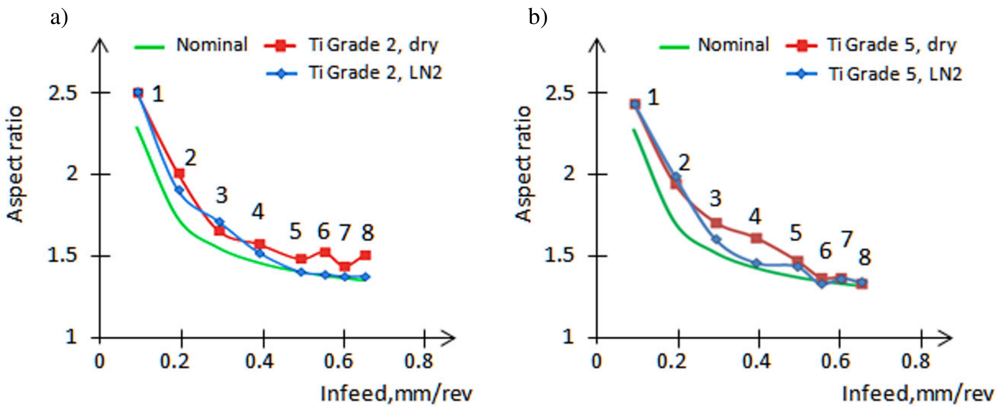

Fig. 8. Measured aspect ratio vs. infeed in thread turning tests of Ti Grade 2 and Ti Grade 5 alloys.

The determined value of the aspect ratio changes for successive infeeds. It should be noted that at the beginning of thread formation, due to the low infeed value, the value is markedly different from the assumed value. After this first significant discrepancy, the results stabilize. In the case of Ti Grade 2 dry (Fig. 9a) the uncertainty is quite significant. For most infeeds the shape of the thread is such that it tends to have a larger width than height. Large fluctuations occur for the third infeed. In this case, the adhesive properties of the material are so large that not only does it stick to the tool, but also the thread outline is dominated by burrs. In the case of Ti Grade 2 LN2 (Fig. 9b) the average uncertainty is smaller. In this case, besides the first infeed, the values indicate that for a given diameter the thread had a width greater than the nominal value. In the case of Ti Grade 5 dry (Fig. 9c) the average uncertainty decreases with each infeed. In the case of Ti Grade 5 LN2 (Fig. 9d) the uncertainty of the thread height relative to its width is similar as in the case of dry cutting; however, for the last infeed, the ratio is close to the expected value, which implies good thread accuracy.

The results show that the aspect ratio is slightly larger than its nominal value. This implies that despite cooling of the cutting zone, limited lateral flow of the material still occurred. The material was pushed out and burrs were formed. This was particularly evident when cutting CP Ti Grade 2 at ambient temperature. This is in line with the model suggested in [9], in which the distribution of unit forces on the cutting nose is such that in each case a material side flow effect can be recognized. This effect strongly depends on the thermodynamic conditions in the cutting zone. Freezing titanium alloys prior to machining reduces the effect of lateral flow of the material, which means that in subsequent infeeds an increasingly accurate reproduction of the tool in the workpiece is obtained.

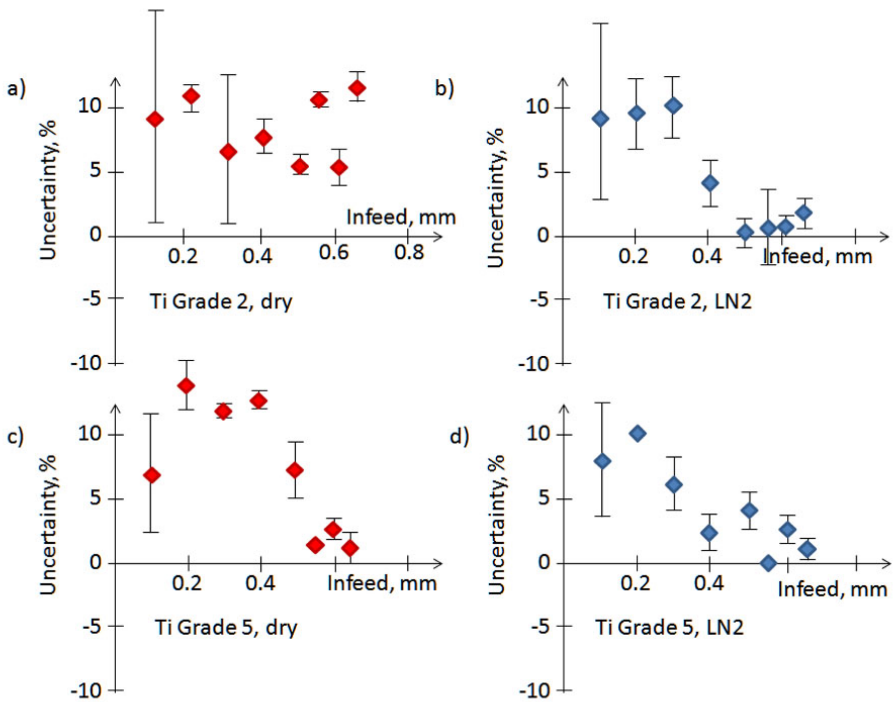

Fig. 9. Uncertainty of the aspect ratio (in relation to nominal) vs. infeed.

4. Conclusions

To evaluate the course of the turning process, the thread was evaluated for each tool infeed. The results for Ti Grade 2 and Ti Grade 5 show differences in the formation of the thread. This was clearly visible in the case of Ti Grade 2 dry, where the problem of burrs was severe. Cryogenic cooling provided a remarkable benefit in decreasing the visible burrs, and had a significant positive effect on thread accuracy.

1. Thread images were acquired for each tool infeed at three settings of the workpiece in relation to the optical axes of the camera of the vision system. The implementation of multiple repetitions of thread measurement for each infeed enabled a reliable assessment of the quality of the thread in the manufacturing process. The measured values were compared with the nominal values, whose uncertainty is summarized in Fig. 7 and Fig. 9. The amount of cut material did not deviate from the nominal value by more than 1% during the process. The final thread quality was within tolerance.
2. Analysis of thread geometric parameters shows that there was lateral flow of the material in all conditions. The material was pushed out and burrs were formed. This was particularly evident when cutting CP Ti Grade 2. Geometric analysis of the empty space between the ridges made it possible to monitor the course of the process. The initial large shape deviation was due to the physical aspects of thread formation, including the properties of the workpiece and the minimum thickness of the cut layer. This is a result of the action of unit forces on the cutting nose, resulting from the rounding of the cutting edge, which makes part of the material move laterally. This effect strongly depends on the thermodynamic

conditions in the cutting zone. Freezing titanium alloys prior to machining reduces the effect of lateral flow of the material, which means that in subsequent infeeds a more accurate reproduction of the tool in the workpiece is obtained.

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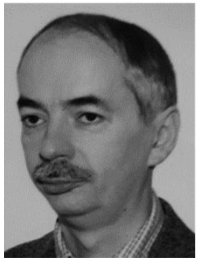

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