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Multi-sensor measurements of titanium alloy surface texture formed at subsequent operations of precision machining process

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ABSTRACT

The paper presents the issues concerning difficult-to-machine materials along with machining process and technologies used to measure surface topography. Thorough research comprising precision machining process and multi-sensor measurements enabled multi-scale analysis of surface texture.

The subjects of the study were titanium alloys TiAlSiZr. The semi-finished products were subjected to precision abrasive machining process which consisted of preliminary grinding, precision grinding, lapping, and polishing. The surface texture obtained after each operation of machining process was measured using a white light interference microscopy, a scanning electron microscopy and an atomic force microscopy.

The measurement results obtained from the multi-scale analysis show differences in the surface texture of titanium alloys, resulting mainly from machining conditions including the applied tools (grains and micrograins of diamond).

Surface defects, e.g. grinding cracks (preliminary grinding), dales of different geometry (precision grinding), scratches and the distribution of dales/dents (lapping and polishing) influencing surface functional properties were discussed.

1. Introduction

Titanium alloys, depending on a chemical composition, can have a single-phase α structure, a single-phase β structure, or a two-phase $\alpha + \beta$ structure. The single-phase α alloys of titanium exhibit excellent corrosion and oxidation resistance, high weldability, fracture toughness, and creep strength. The single-phase β alloys of titanium, compared to α alloys, offer improved strength, ductility, and cold formability. The $\alpha + \beta$ alloys of titanium, containing up to 50% of the β phase, are obtained by adding stabilizing alloying elements to the α phase. The most widely used alloying additive aimed at stabilizing and strengthening the α phase is aluminum (Al) which increases the heat stability, while reducing the density of the titanium alloy. The $\alpha + \beta$ alloys of titanium possess good strength, ductility, corrosion resistance, moderate creep strength and oxidation resistance, and weldability [1].

Titanium alloys belong to difficult-to-machine materials [2]. Low thermal conductivity causes that the heat generated during the machining process is concentrated on the cutting edge and the rake face of the tool. The generated temperature (more than 1000 °C) can lead to intensive wear - deformation and the dulling of the cutting edges of the tool. Progressive tool-wear results from the high reactivity of titanium alloys at high temperatures [3].

An inability to dissipate heat (high temperature) generated in the machining zone can lead to the strengthening of a machined material, and may thus cause geometric errors at macro- (form error and dimensions), meso- (surface waviness and defects,) and micro- scales (surface roughness), thereby reducing the performance of the workpiece (e.g. fatigue strength manifested by visible cracks on the machined surface).

Factors exerting a negative influence on the behavior of titanium alloys during manufacturing process can be minimized by selection of an appropriate type and parameters of machining process.

Within subtractive manufacturing, the most universal machining processes that are applied to difficult-to-machine materials are abrasive operations performed with a grinding wheel (grinding) and loose abrasives (lapping and polishing) [3–5].

The aim of carrying out a machining operation with a grinding wheel is to obtain the required form and dimensions of a machined material; whereas a machining operation performed with loose abrasives is aimed at producing the surface exhibiting desired surface functional properties.

In subtractive manufacturing, an important role is played by surface damages resulting from the impact that abrasive grains

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Nomenclature

Ra	arithmetic mean deviation of the profile, [μm]
Sa	arithmetic mean deviation of the surface, [μm]
Sq	root mean square (RMS) deviation of the surface, [μm]
Sz	maximum height of the surface, [μm]
Sp	maximum peak height of the surface, [μm]
Sv	maximum valley depth of the surface, [μm]
Ssk	skewness of surface height distribution, [–]
Sku	kurtosis of surface height distribution, [–]

have on the workpiece. This is attributed to the mechanism of material separation occurring in the process of micro-cutting. Defects that emerge over the course of a machining operation performed with a grinding wheel (grinding) can be minimized or entirely eliminated at the machining operation carried out with a loose abrasive (lapping and polishing). Lapping begins with paste (a mixture of an abrasive material and a medium comprising, among others, stearin, paraffin, or silicic acid) containing thick micrograins (with the diameter ranging from 60 to 20 μm), gradually moving to paste with increasingly smaller micrograins (the smallest diameter ranging from 1 to 0 μm). At each stage of abrasive machining process, it is essential to eliminate the defects derived from the previous operation, thus removing the material layer the thickness of which corresponds to the size of the largest abrasive grains or micrograins.

The shape of a workpiece (including functional properties of a surface [6–8]) at each stage of machining/manufacturing process should be assessed based on the results received from research on surface topography. This will enable better understanding of changes concerning the stereometry of the machined surfaces and prediction of their potential properties.

There are many surface measurement technologies to choose from (Fig. 1), each providing a different piece of information on the studied surface [9–13].

It should be also emphasized that some of measurement technologies allow for a qualitative analysis (e.g. images obtained using OM, SEM, AFM), while the others - for quantitative one (e.g. the data, or parameters, obtained by using a CMM, WLI, SEM/EDS) [13,15].

Surface topography analysis has a long tradition; for years it has been used for assessing, inter alia, the differences between measuring methods; the machined surface topography (received from various manufacturing processes); the stereometric of the active tool surface (the active surface of grinding wheels); and the worn surface topography (e.g. surfaces obtained after tribological studies, wear products, or mechanisms of wear). The examples of the use of various measurement devices for different aims were given below.

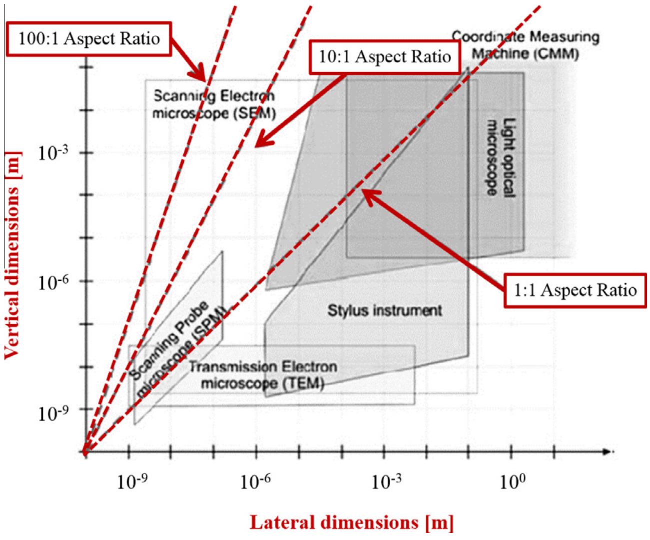

Fig. 1. Surface metrology – surface measurement technologies [14].

Wojciechowski et al. [16] used an optical 3D measurement device to study and analyse various factors affecting the machined surface texture of hardened hot-work tool steel. Niemczewska-Wójcik et al. [17] applied an optical microscope, a scanning electron microscope and a white light interference microscope to assess surface topography of waste basket made of austenitic steel, formed in manufacturing process (taking into account errors of manufacturing process resulting from cutting bores using a laser cutter). Krolczyk et al. [18] used an optical 3D measurement device to assess surface textures obtained by manufacturing process (including turning, milling, grinding, planning, and abrasive blasting process), which is most commonly used in the production facilities. Krolczyk et al. [7], in their research, made use of the same measurement device to assess the influence of clean manufacturing methods (turning for different conditions) on the surface morphology of duplex stainless steel. Nadolny et al. [2] applied a scanning electron microscope to study a non-impregnated grinding wheel active surface as well as an impregnated grinding wheel active surface, and to assess the influence of the type of impregnate on the stereometric features of a grinding wheel active surface after the grinding process of titanium alloy.

Nieslony et al. [19] used a stylus and an optical 3D measurement device to assess the differences between mechanically and electromagnetically measured surfaces after drilling process. Merola et al. [20] used a stylus and an optical 3D measurement device to assess the differences between these two measurement techniques to validate a new protocol for measuring of the surface roughness of medical parts.

Niemczewska-Wójcik et al. [21] used a white light interference microscope and an atomic force microscope to assess the machined surface texture obtained in manufacturing process (three kinds of materials/coatings) and the worn surface texture (including wear tracks) obtained in tribological studies (in different conditions – in a vacuum and in the air). Galda et al. [6] used an optical 3D measurement device to study and assess the influence of geometrical characteristics of the surface texture on the Stribeck curve in lubricating sliding.

It should be mentioned that in order to conduct a thorough assessment of surface topography (in that surface texture) obtained as a result of machining operations, it is important to take a comprehensive approach making use of different measurement techniques, it means multi-sensor measurements. Owing to this, information on surface topography at various scales is collected, which allows to perform multi-scale analysis [22,23].

This paper presents the results of the measurements of surface texture obtained at the subsequent operations of precision machining process of TiAlSiZr alloy. Since it meets the requirements imposed on biomaterials, TiAlSiZr alloy has been applied to medical devices. TiAlSiZr alloy represents a two-phase $\alpha + \beta$