www.czasopisma.pan.pl PAN www.journals.pan.pl

ARCHIVES
of
FOUNDRY ENGINEERING

ISSN (2299-2944)
Volume 2020
Issue 4/2020

55 – 60

10.24425/afe.2020.133347

7/4

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

Studies of the Properties of Materials for Foundry Patterns Used in the Production of High-quality Precision Castings

A. Dydak [a, *], **M. Książek** [b]
[a] The Specodlew Enterprise of Foundry Innovation Ltd.,
ul. Rtm. W. Pileckiego 3, 32-050 Skawina, Poland
[b] AGH University of Science and Technology, Faculty of Non-Ferrous Metals,
al. A. Mickiewicza 30, 30-059 Krakow, Poland
* Corresponding author: Email address: artur.dydak@specodlew.com.pl

Received 19.05.2020; accepted in revised form 30.07.2020

Abstract

The paper presents the properties of plastics under the trade names of PMMA and Midas, and of Formowax, Romocast 305 and Romocast 930 casting waxes. Their effect on the quality of foundry patterns used in the manufacture of ceramic moulds for precision casting is also discussed. From the selected materials for foundry patterns, samples were made for testing using the following methods: (i) 3D printing in the case of plastics, and (ii) conventional method based on tooling in the form of metal moulds (dies) in the case of casting waxes.

The most important physico-mechanical properties of materials for foundry patterns were determined, i.e. linear shrinkage, softening temperature, relative elongation and coefficient of thermal linear expansion. Bending tests were carried out on samples of patterns printed and made in metal moulds, including determination of the surface roughness of patterns.

After the process of melting out patterns from the cavities of ceramic moulds in an autoclave, the degree of their melting out was visually assessed (i.e. the residues from pattern removal were evaluated). The ash content after burning out of foundry patterns was also determined. The conducted tests allowed comparing the important parameters of materials used for foundry patterns and assessing the suitability of selected plastics as a material for foundry patterns used in the manufacture of high-quality precision castings.

Keywords: 3D printing, Rapid prototyping, Plastics patterns, Precision casting

1. Introduction

Special-purpose castings with complex shapes and high surface quality are manufactured by the precision casting technology using lost wax patterns, which are responsible for the final shape and dimensions of the finished product. The technological process using lost wax patterns consists of a number of operations, the most crucial one being the manufacture of a wax pattern that should meet the relevant requirements for further technological processes and the possibility of making a high-quality final detail [1]. It is worth noting that the current technology of making patterns, especially prototypes based on soft waxes, does not ensure precise and consistent repeatability of shape and making patterns in a very short time, mainly due to the need to provide additional equipment. Therefore, it was proposed to use appropriate quality plastics for patterns made by 3D printing method, which should guarantee an increase in the quality of the final casting, i.e. obtaining a casting with the highest dimensional and shape accuracy and surface smoothness, as well as its very fast availability in many configurations during the production process.

The basic material for pattern-making in precision casting is wax, which is a thermoplastic material. Modern wax blends are multicomponent mixtures which may contain oligomers, polymers, synthetic wax, natural resins, synthetic resins, and organic filling materials. The wax used to prepare the prototype should have the lowest coefficient of thermal expansion and keep its shape at room temperature. All wax components should be completely burned so that ash residues do not contaminate the foundry mould. Casting wax, however, has two main disadvantages, they are high coefficient of thermal expansion and the possibility of spontaneous deformation of modeled prototypes [2-4]. Physico-chemical properties of waxes depend primarily on the content of individual components and should provide certain parameters, i.e. appropriate mechanical strength and smoothness of the surface, low thermal expansion and, at the same time, low shrinkage, moderate melting point, low viscosity and very low ash content. The wax compositions currently developed are tailored to these requirements. The most commonly used waxes with the addition of fillers facilitate the process of filling the die cavity during injection moulding and ensure dimensional stability of patterns, i.e. mainly low shrinkage value [5-6].

Plastics containing, among others, components such as ethylmethylbenzenesulphonamide derivatives, polyester resins, benzoate derivatives (where the bonding materials are mainly resins), dedicated to the production of foundry patterns using 3D printing techniques, are also characterized by very good parameters. Plastics are characterized by low values of heat of polymerization as well as shrinkage, have greater strength and less tendency to flow than waxes, good dimensional stability and are characterized by residue-free combustion [7]. It is worth noting that the 3D printing technique usually involves precise application of the building material (if required, also supporting material) in the form of individual very thin layers using a printing head until a complete 3D pattern is obtained. The surface of the product can be additionally treated, e.g. by milling off excess material to obtain much greater dimensional accuracy. Supporting materials are often removed by dissolving them in special solutions and then the pattern is washed.

In some methods, the printed pattern is additionally immersed in liquid wax forming a thin layer, whose task is to increase the surface smoothness and improve the properties during melting out in an autoclave [8].

The aim of the study was to carry out comparative research on the physico-mechanical properties of materials used for foundry patterns and to select plastics with the best quality characteristics for the manufacture of foundry patterns using 3D printing technology.

2. Methodology

Samples of the wax patterns were made under industrial conditions (at SPECODLEW) on tooling in the form of metal moulds (dies) using soft Formowax wax supplied by Polwax, designated as M, and hard wax supplied by Romonta, i.e. Romocast 305 and Romocast 930, designated as TWN and TWZ, respectively. Using the 3D printing technique by Powder Binder Jetting, two-component samples designated as DS were made of PMMA, serving as a base material, bonded with PolyPor B resin from VoxelJet (Sand Made) and surface covered with wax. Using the Solidscape method in Smooth Curvature Printing® technology, combining printing by spraying successive layers of Midas wax material with precise milling of the surface of each layer to the appropriate height, samples designated as DL were provided by Lemondim [9-12].

Behaviour assessment during basic technological processes, i.e. the possibility of combining in sets with foundry wax, ease of applying the first ceramic coating on a plastic pattern and an attempt to melt out plastic from the cavity of the ceramic mould was carried out for many printed materials, such as: HAR, PLA, PMMA, SCAST, MIDAS etc., of which only two materials (PMMA and Midas) were qualified for further research, as materials meeting the basic requirements for properties.

The general analysis of the costs of producing prototype models from selected materials in the unit and collective variant was also carried out. For casting waxes price included necessary equipment cost. It has been shown that in the case of producing one piece of a slightly complex shape of a model with a volume of about 25 cm3, the approximately cost will be respectively: for wax M 35001 [u]/pcs, for wax TWN 35002.5 [u]/pcs, for wax TWZ 35001.25 [u]/pcs, for plastic DS 1125 [u]/pcs, for plastic DL 2500 [u]/pcs. For producing 1000 pcs the same pattern the cost will be respectively: for wax M 36 [u]/pcs, for wax TWN 38 [u]/pcs, for wax TWZ 36 [u]/pcs, for plastic DS 100 [u]/pcs, for plastic DL 1250 [u], (where u - the price unit).

The calculation showed that the production cost of unit models from casting waxes is almost the same and associated with high costs due to the need additional equipment, therefore it will be cheaper to make models using 3D printing. However, in the case of large series, wax patterns will be many times cheaper than printed details, and wax price will be of great importance. By increasing the multiple series of prints, the cost of the model should decrease and approach the price of the wax model.

To determine the linear shrinkage, flat specimens with 100x20x5 mm dimensions were used. The measurements were taken with a caliper at ambient temperature, and the shrinkage calculated. The mean value of 6 determinations made for each tested pattern material was adopted as the result of the linear shrinkage of the material.

Relative elongation, coefficient of thermal linear expansion and softening temperature of plastics used for patterns were determined with a 402 C dilatometer from Netzsch based on the E228-11 standard [13]. Cylindrical samples with ø 6 x 20 mm dimensions were heated at a speed of 3 K / min in an inert gas (helium) environment. The test was repeated on 3 samples of each material.

The value of relative elongation was determined from formula (1):

$$\frac{\Delta L}{L_0} \times 100\ \% = \frac{L - L_0}{L_0} \times 100\ \% \tag{1}$$

where:
L_0 - initial length of the sample,
L - sample length at temperature T.

The value of mean coefficient of thermal linear expansion was determined from formula (2):

$$\alpha(T_1,T_{ref})=\frac{\frac{dL}{L_0}(T_1)-\frac{dL}{L_0}(T_{ref})}{T_1-T_{ref}} \quad (2)$$

where:
T_1 and T_{ref} – boundary temperatures of the range,

Softening temperature of plastics was determined from the relative elongation derivative as a function of temperature at the point of local extremes. Due to the large difference in the relative elongation of the wax compared to the standard sample (corundum), the value of the coefficient of thermal linear expansion for the corundum standard was taken as zero.

Bending tests of materials for foundry patterns were carried out on flat samples with 100x20x5 mm dimensions [14]. Three-point bending was performed on the INSTRON 5932 machine, using a head with a pressure force of up to 500 N at ambient temperature, with a support spacing of 80 mm. Traverse speed was 2mm / min. The test was repeated on 6 samples of each material.
The values of the bending strength of individual materials were determined from formula (3):

$$6_{fm}=\frac{\frac{Fl_r}{4}}{\frac{bh^2}{6}}=\frac{3Fl_r}{2bh^2} \quad (3)$$

where:
σ_{fm} - bending strength (the highest bending stress carried by the sample),
F - the largest value of force recorded during sample loading,
l_r - support spacing,
b - sample width
h - sample height.

Tests of the surface roughness of patterns were carried out with a Diavite COMPACT II/VH profilometer from DIAVITE AG on samples with 50x50x7 mm dimensions according to ISO & DIN [15], using a 1.5 mm measuring section and 0.25 mm elementary sections at ambient temperature. The test was repeated on 3 samples of each material.

A visual assessment of the interior of ceramic moulds (after cutting the moulds through) was also carried out to determine the degree of contamination of the cavity with residues of the melted out plastic patterns and to determine the possibility of their removal at this stage. An observation was made at ambient temperature (at ambient temperature) by assessing three samples from the melting of each material. The process of melting out plastics from the cavities of ceramic moulds was carried out in an autoclave, using supersaturated steam at a temperature of about 180°C and a pressure of 7 atm applied for 10 minutes.

Ash residue analysis after burning out of plastics was carried out on samples weighing 20 g. The test consisted in placing the appropriate amount of plastic in a quartz tube and then heating in a furnace at 700 °C for 30 minutes in an air atmosphere. After removal and cooling down, the tube was weighed on a Radwag model PS 4500.R2.M precision balance with an accuracy of 0.01 g at ambient temperature. The test was repeated on 3 samples of each material. The ash content was calculated.

3. Results

Table 1 presents the results of measurements of the average shrinkage of patterns made from casting waxes by conventional method and from plastics by 3D printing technique. The softening temperatures of materials used for patterns are shown in Table 2.

Table 1.
Average shrinkage of foundry patterns

Material designation	M	TWN	TWZ	DS	DL
Type of material	casting waxes			3D printing plastics	
Average shrinkage [%]	1.20 ± 0.11	0.51 ± 0.09	0.83 ± 0.16	0.28 ± 0.10	0.10 ± 0.08
The mean increase in size [%]	-	-	-	0.40 ± 0.12	0.53 ± 0.10

Table 2.
Softening temperature of materials used for foundry patterns

Material designation	M	TWN	TWZ	DS	DL
Type of material	casting waxes			3D printing plastics	
Softening temperature [°C]	36.2	43.8	44.4	52.8	53.7

In Figure 1 and 2 show the thermal expansion characteristics of materials used for foundry patterns. In the group of patterns made from casting waxes, differences in thermal expansion were observed, corresponding to the maximum expansion among these materials. The casting wax designated as TWN had the lowest expansion. In contrast, patterns made of plastics by 3D printing technology had significantly lower values of relative elongation, determined for a larger temperature range (25 - 70°C), compared to patterns made of casting waxes (in Figure 1). Among these materials, plastic designated as DL had the lowest expansion.
Over the entire test temperature range (25 - 70°C), the average coefficient of thermal linear expansion is much lower for patterns made from plastics than for patterns made from casting waxes. In the studied temperature range, patterns made from plastics are characterized by a stable dependence of the average coefficient of thermal linear expansion on temperature (in Figure 2).

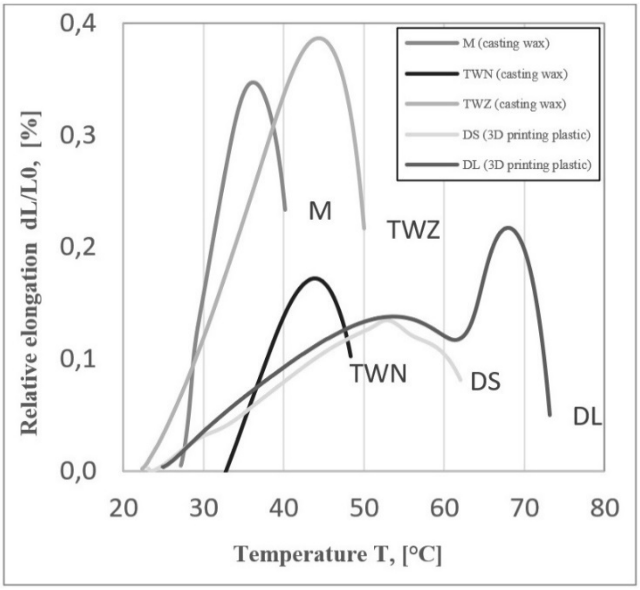

Fig. 1. Changes in relative elongation of foundry pattern materials as a function of temperature

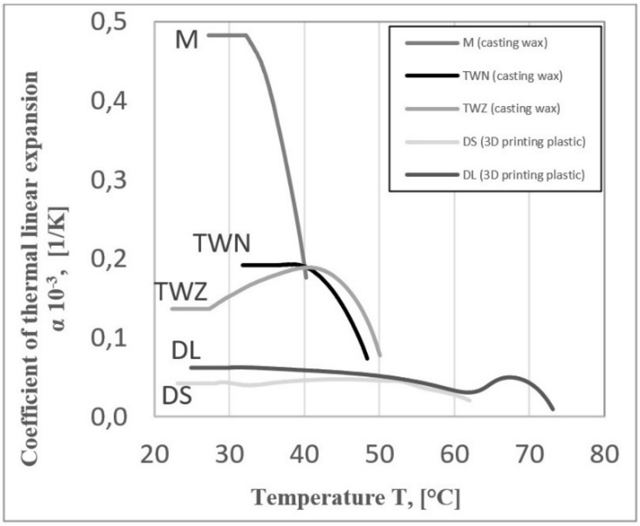

Fig. 2. Changes in the coefficient of thermal linear expansion of foundry pattern materials as a function of temperature

In Figure 3 shows a randomly selected comparison of the results of bending test carried out on the foundry pattern samples (made of waxes and plastics) in a bending stress - deflection value relationship. The average values of maximum bending stress for M, TWN and TWZ waxes are 1.75 ± 0.11, 7.8 ± 0.22 and 5.82 ± 0.37 MPa, respectively. The values of maximum bending stress for plastics designated as DS and DL are 5.1 ± 0.27 MPa and 12.85 ± 1.07 MPa, respectively.

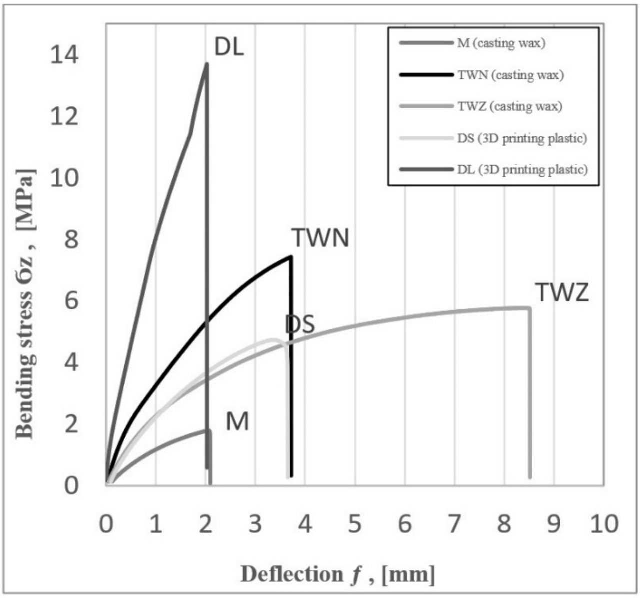

Fig. 3. Bending stress-deflection curves recorded for foundry pattern materials

In the systems tested, the bending curves are of a parabolic character, where the nature of the stress - strain diagram for plastics designated as DL indicates the failure mechanism typical for brittle materials, while for casting waxes designated as M, TWN and TWZ this mechanism is typical for plastic materials. The casting wax designated as TWZ has a very long range of deflection path during which the stress gently rises and then falls. The value of the deflection which is followed by a decrease in stress leading to sample failure is approx. 2 and 3.6 mm for DL and DS plastics, respectively, and 2, 3.7 and 8.5 mm for M, TWN and TWZ casting waxes, respectively.

The results of the surface roughness analysis of foundry patterns made from casting wax and plastics are presented in Table 3. These are the average values of the surface roughness profile parameters of material a given from three measurements. The lowest surface roughness has the pattern made from plastics designated as DL (Ra 0.50 ± 0.11 µm) and pattern made from the casting wax designated as M (Ra 0.68 ± 0.09 µm). The highest value of the surface roughness parameters has the pattern made from plastics designated as DS (Ra 1.16 ± 0.07 µm).

After melting out in an autoclave, visual analysis of the cut through cavities of ceramic moulds (FC) made from materials prepared in two configurations, i.e. based on binder thickened with flour and backfills: (i) quartz, and (ii) zirconium/molochite, allowed the assessment of impurities left in these moulds as residues from the process of melting out pattern materials from the cavities. The contamination of the facing (pattern-adjacent) layer cavity with residues of foundry pattern materials is insignificant for most tested molds. After melting out the plastic pattern designated as DL, in ceramic molds (FC) based on both quartz and zirconium / molochite, no defects and contaminations were disclosed (only slight traces of residue of dye). It was confirmed in the next stage that all residual materials and traces of dye were removed in the process of burning the moulds.

Ceramic moulds with the first layer based on zirconium give a greater possibility of smelting cavities compared to ceramic moulds with the first layer based on quartz. With the use of plastics, ceramic molds (especially with based on zirconum) with high purity of cavities can be produced, which should allow to obtain precision castings without surface defects (non-metallic inclusions).

Table 3.
Surface roughness profile parameters of foundry patterns made of wax and plastics

Material designation	M	TWN	TWZ	DS	DL
Type of material	casting waxes			3D printing plastics	
Ra - arithmetic mean deviation of the roughness profile [µm]	0.68 ± 0.09	1.09 ± 0.12	1.03 ± 0.25	1.16 ± 0.07	0.50 ± 0.11
Rz - maximum height of the roughness profile [µm]	2.54 ± 0.31	4.91 ± 0.51	4.97 ± 1.18	5.59 ± 0.71	2.84 ± 0.53
Rt - total height of roughness profile [µm]	3.73 ± 0.75	9.48 ± 2.39	9.17 ± 3.48	12.15 ± 3.22	4.41 ± 1.18

Table 4 presents the results of average ash content analysis after burning out materials used for foundry patterns. Plastics and waxes leave a very low ash content (0.05 – 0.1 %) after burning out. The exception is casting wax designated as TWZ, for which the ash content is much higher and amounts to 0.35%.

Table 4.
Ash residues in ceramic mould cavities after burning out of foundry patterns

Material designation	M	TWN	TWZ	DS	DL
Type of material	casting waxes			3D printing plastics	
Average ash residue [%]	0.05 ± 0.02	0.10 ± 0.02	0.35 ± 0.06	0.05 ± 0.01	0.05 ± 0.01

4. Conclusion

Plastics for foundry patterns manufactured by 3D printing technology show very high quality characteristics:

- low linear shrinkage. The shrinkage of plastics is nearly two times lower than the shrinkage of casting waxes, which allows obtaining the final detail with the highest dimensional accuracy,
- low thermal expansion, which guarantees the production of dimensionally repeatable and shape- stable foundry patterns,
- high bending strength and higher softening temperature in comparison to casting waxes which can provide patterns with very high mechanical durability during all production stages,
- the value of the surface roughness parameter of the foundry patterns depends on the type of material used and technology of pattern production. The lowest surface roughness is characteristic of the patterns which, using plastics designated as DL, are made by Smooth Curvature Printing technique ensuring the highest precision in the surface finish of patterns.
- On the other hand, patterns made by the Binder Jetting technique from plastics designated as DS have the highest surface roughness which may indicate difficulties in obtaining the required smoothness of the final detail,
- very low ash content after melting out of foundry patterns. Only patterns made from the casting wax designated as TWZ leave much higher ash content after burning out. In addition, the tested model materials do not cause negative effects in relation to mould, which would result in damage to the structure of the samples during firing of the foundry patterns,
- use of ceramic moulds with the first, pattern-adjacent layer based on a binder thickened with flour and zirconium sand backfill for the process of melting out patterns made from plastics (designated as DS and DL) and casting wax (designated as M) should give the possibility of obtaining high-quality precision castings due to using the appropriate plastics and ceramic mould with high quality surface after smelting process and low ash content after burning the plastic residues.

Plastics are materials of a particular quality (relatively low softening temperature and at the same time very hard, have low linear shrinkage, high resistance to destruction, adequate smoothness, wetting ability and very low ash content) in relation to casting waxes. For 3D printing techniques the production of wax models and then final products in the process of precise casting, it is very useful in the making of small parts and miniaturized assemblies. Plastic that has optimal properties and allows prototype patterns to be produced using 3D printing for use in unit and serial production in the method of precise casting is marked as DS.

Acknowledgements

The research was carried out as part of task completion in the Implementation Doctorate "Precision casting of high-quality details in ceramic moulds based on patterns and cores made by 3D printing technology" conducted at the Faculty of Non-Ferrous Metals of the AGH University of Science and Technology in Krakow for The Specodlew Enterprise of Foundry Innovation Ltd. in Skawina.

References

[1] Jones, S., Yuan, C. (2003). Advances in shell moulding for investment casting. *Journal of Materials Processing Technology*. 135(2-3), 258-265. DOI: 10.1016/S0924-0136(02)00907-x.

[2] Bonilla, W., Masood, S.H. & Iovenitti, P. (2001). An investigation of wax patterns for accurancy improvement in investment cast parts. *International Journal of Advanced Manufacturing Technology*. 18(5), 348-356. DOI: 10.1007/s001700170058.

[3] Bemblage, O., Karunakar D.B. (2011). A Study on the Blended Wax Patterns in Investment Casting Process. In the World Congress on Engineering, 6-8 July 2011 (vol. I). London, United Kingdom: Imperial College London.

[4] Keshav Kamboj, Er. (2017). Optimization of Process Parameters of Wax Pattern in the Investment Casting Process by using Different Form of Waxes. *International Journal for Innovative Research in Science & Technology*. 3(8), ISSN (online): 2349-6010.

[5] Wawulska-Marek, P., Matysiak, H. & Kurzydłowski, K.J. (2014) Technological properties of model waxes used in precision casting technology. *Materials Engineering*. 35(1), 45-46. YADDA: 752fae89-10b8-4748-999c-90041bba210d. (in Polish).

[6] Marszałek, G. & Majczak, R. (2012). Polyethylene wax - preparation, modification and application. *Polymers.* 9, 640-645. DOI: 10.14314/polimery.2012.640. (in Polish).

[7] Beniak, J., Krizan, P. & Matus, M. (2019). Mechanical properties of biodegradable plastic parts produced by 3d printing. *MM Science Journal*. 3, 2746-2750. DOI: 10.17973/MMSJ.2019_03_201806.

[8] Syrek, H. (2013). Application of 3D printers for the production of wax models in the lost wax casting process. *Nafta-Gaz*. 69(12), 929-935. YADDA: 4ecaa592-fc6c-4716-bd08-1eb3c4e0a51b. (in Polish).

[9] Polwax S.A. (2019, October). *Technical conditions of FORMOWAX*. Retrieved February 10, 2020, from https://www.polwax.pl/oferta/masy-modelowe/formowax-/58.

[10] Romonta (2019, July). *Investment casting waxes*. Retrieved February 10, 2020, from https://www.wachs-und-mehr.de/index.php/en/produkte/feinguss

[11] Voxeljet (2019). *Investment casting applications*. Retrieved February 10, 2020, from www.voxeljet.com/applications/investment-casting/.

[12] Lemondim (2019). *Solidscape*. Retrieved February 10, 2020, from https://lemondim.pl/solidscape/.

[13] ASTM E228 – 17. Standard Test Method for Linear Thermal Expansion of Solid Materials With a Push-Rod Dilatometer.

[14] PN- EN ISO 178: 1998 Plastics. Determination of properties during bending (in Polish).

[15] ISO 4287:1997/Cor.1:1998/Cor.2/2005. Geometrical Product Specifications (GPS) – Surface texture: Profile method – Terms, definitions and surface texture parameters.