INFLUENCE OF PROCESSING METHODS ON THE SURFACE QUALITY OF INJECTION MOLDED THERMOPLASTIC MATERIALS

Daniiel SERBAN[1], Ionelia VOICULESCU[2]

This paper presents the micro-texturing experiments of mold cavity surfaces made by subtractive manufacturing methods: milling, photochemical machining, electrical discharge, laser beam machining, and additive manufacturing methods (metal binder jetting). The microstructures of the metal surfaces and those replicated on polymer components obtained by injection molding were analyzed. The hardness and chemical composition were evaluated on the processed areas of the mold cavities. Based on the value of the replication rate of thermoplastic products obtained by injection molding, the performance limits were evaluated, and each processing technology's optimal field of application was established. The process parameters and surface quality correlations were observed and discussed.

Keywords: surface texturing, laser beam machining, additive manufacturing, injection molding.

1. Introduction

The quality of the mold cavity surfaces influences aesthetics, functionality, polymer flow, and extraction of injected parts after complete solidification. The unique finishing of the mold surfaces and the appropriate design of the chemical composition of the polymer composites can contribute to obtaining superior and predictable characteristics of the molded products. For example, micromachining high-accuracy patterns are used to manufacture microlens injection molded in cyclic olefin copolymers or texturing cavity surfaces to be replicated by injection molding in the automotive, medical, construction, and furniture industries.

The research and innovation strategies promoted by the European Union indicate the use of advanced technologies such as additive manufacturing (AM) [1] and laser technologies [2]. Research activities are directed to advanced technologies, such as electrochemical micro texturing (ECMtex), "*electrochemical spark*" micromachining (ECSMM as a hybrid ECM + EDM process) [3], "micro chiseling" (diamond machining of molds for optical components on a nickel substrate [4]), micro-EDM, micro-ECM, ultrasonic-

[1] PhD. Student, University POLITEHNICA of Bucharest, Romania, e-mail: serbandaniiel@gmail.ro
[2] Prof., Faculty of Engineering and Management of Technological Systems, University POLITEHNICA of Bucharest, 060042, Romania, e-mail:ioneliav@yahoo.co.uk

assisted EDM (EDM+US) [5], laser-assisted machining (LAM) [6], lithography, electroplating, and molding (LIGA, ger., Lithographie, Galvanoformung, Abformung), Fabrication of biomimetic surfaces (PDMS), and Embedded Elastomeric Stamping (PEES) [7].

Micro-fabrication refers to all processes (mechanical, physical, chemical, traditional or non-traditional, subtractive or additive) that allow obtaining products with high dimensional precision and complex details of micrometric dimensions. In this process (mainly mechanical, but not limited to), small chips are removed with great geometric precision [4], allowing users to obtain details or textured surfaces at the micron level, ensuring rigorous modeling of the shape and roughness of the mold surface. Brinksmeier and Preuss [4] demonstrated that the required precision could be achieved by micromachining in a single step, without multiple passes, using a "micro-chiseling" process in which hexagonal prisms were machined onto the die surfaces with diamond tools, applying a special machining strategy.

Sortino et al. [8] studied the performance of surfaces obtained using micromachined brass inserts fixed to a movable plate of a prototype mold. They carried out 228 tests using polymethyl methacrylate material, obtaining good replication and excellent performance. Three technologies for obtaining polymer products were compared: standard injection, injection combined with compression, and vacuum injection molding.

Experiments performed using an Nd: YAG laser (neodymium-doped yttrium aluminum garnet; $Nd{:}Y_3Al_5O_{12}$) to fabricate a microfluidic circuit mold demonstrated excellent structures below 20 μm can be reproduced [9]. The experiments with laser equipment and a 5-axis movement system demonstrated that flat surfaces in the micrometric range could be processed at good productivity and precision. The beam is directed quickly and precisely with a mirror system without changing the position of the workpiece. In contrast, although parabolic and spherical surfaces can be machined by deflecting the laser beam and changing the position of the workpiece in X, Y, Z, B, and C coordinates simultaneously, the machining accuracy is affected [9].

Piccolo et al. analyzed the replication of submicron details during injection molding of a product for which the mold cavity surfaces were laser textured (wavelength of 1030 nm, pulse duration of 310 fs, pulse energy of 2.51 μJ, the scan speed of 1500 mm/s and frequency of 250 kHz). After obtaining the texture parallel to the flow direction, a 10 nm Al_2O_3 deposition was applied [10].

The traditional methods used for texturing mold surfaces are polishing, sandblasting, electrical discharge machining, or photochemical etching. Nowadays, laser texturing has become a standard technology. The reference in this field is the standard VDI 3400 – 75 "Electrical Discharge Machining (EDM), Definitions, Production, Application," which indicates the degree of surface texture that can be obtained by the mold makers using different methods [11].

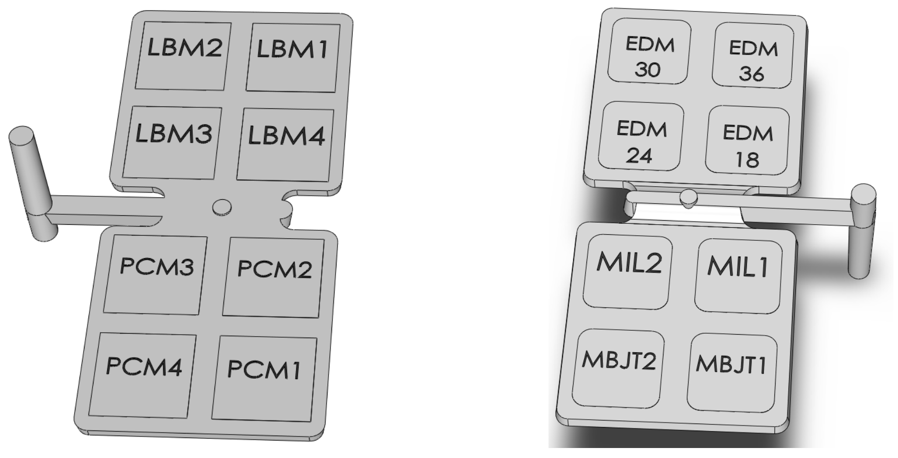
The Society of Plastics Industry specifies twelve finishing degrees for mold surfaces. A surface finish comparison chart shows that each finishing level is correlated with a *Ra* value [12].

This paper presents five technologies for processing the cavity surfaces of an injection mold, highlighting the texturing peculiarities and surface replication effects of thermoplastic composites obtained by injection molding. The processes studied are milling (MIL), photochemical machining (PCM), laser beam machining (LBM), electrical discharge machining (EDM), and metal binder jetting (MBJT). The novelty of the work consists of analyzing the correlations between the method and process parameters, the quality of the textured surfaces, and the replication rate of the injection molded samples to find out each processing technology's capabilities and optimal field of application.

2. Experiments

2.1 Model design

The product to be analyzed consisted of two plates with dimensions of 50 mm x 50 mm x 2.5 mm, on which four impressions of 20 mm x 20 mm were designed to be processed by photochemical machining, abbreviated PCM1, 2, 3, 4, and four by laser beam machining LBM1, 2, 3 and 4 (see Fig 1a). On the opposite faces, four impressions were designed to be textured by electrical discharge machining EDM18, 24, 30, 36, two by milling MIL1 and MIL2, and two by the BJT class metal additive technologies, abbreviated MBJT1 and MBJT2 as shown in Fig. 1b.



a *b*

Fig. 1 Product model and impressions to be textured

2.2 Materials and equipment

The dedicated mold was built using a standard mold base with active plates of DIN 1.2312 steel that have hardness values between 30-33 HRC. In the mold have been machined, the cavities and the pockets to fit the inserts. The inserts for evaluating subtractive methods were performed on hardened and tempered steel, up to 27 HRC. The inserts for analyzing the AM process were manufactured by the additive manufacturing method class binder jetting, BJT [13], made of stainless steel SS316L. The chemical compositions of the mold materials are presented in Table 1 and Table 2. The thermoplastic samples were obtained by injection molding of 100% recycled polypropylene–homopolymer flakes, Rompetrol J800 type. The injection molding experiments were performed using a Battenfeld Plus 350 machine, Austria (350 kN clamping force), equipped with an injection unit with a 30 mm diameter screw, 60 cm^3 capacity, at a maximum pressure of 110 MPa. The surface roughness was measured with a Vogel apparatus (Germany), and the microhardness was measured using a Shimadzu HMV 2T apparatus (Japan). The microstructure was evaluated using an Olympus GX51 optical microscope (Germany) and an SEM microscope (Quanta Inspect S, FEI, Holland) equipped with an Ametec Z2e EDS sensor for local micro-chemical analyzes. In this paper, all measurements are referred to the textured mold surfaces abbreviated PCMi, LBMi, MILi, EDMi, and MBJTi and to the replicated surfaces of molded sample no. 37, abbreviated IM37-PCMi, etc.

3. Results and discussions

3.1 Chemical composition

The microstructures of metallic or non-metallic surfaces were analyzed in the LAMET laboratory from UPB. Highlighting the specific microstructural aspects of the surfaces processed with different processes was pursued. Cross sections were taken for the samples processed by electrical discharge machining, and the hardened areas were evaluated. Energy Dispersive X-Ray Analysis (EDAX) method was used to evaluate the chemical composition of the mold cavity plates and BJT inserts, as presented in Table 1 and Table 2.

Table 1

Chemical composition of low alloy steel mold cavity plates (EDAX method)

Element	C	Si	Mn	Fe	Co
%wt	0.62	0.89	0.59	97.34	0.56

Table 2

Chemical composition of BJT inserts (DIN 1.4404)

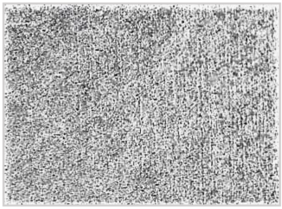
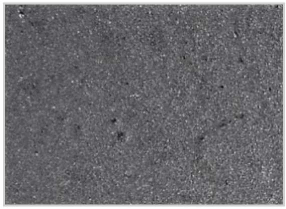
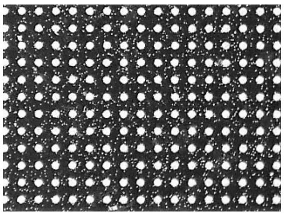
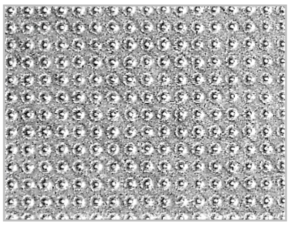
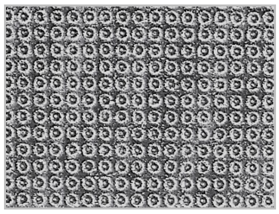
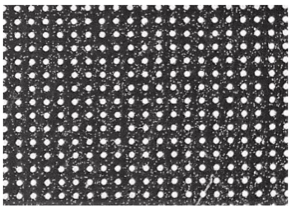
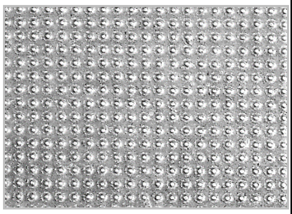
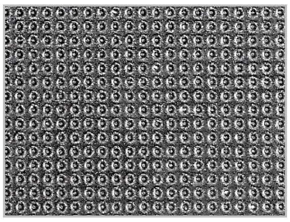
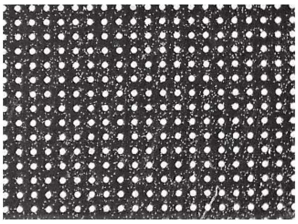
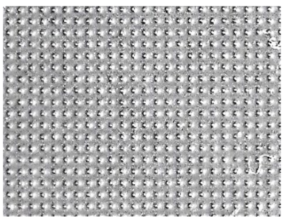
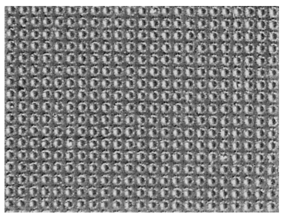
Element	Al	Si	Mo	Cr	Mn	Fe	Ni
%wt	4.66	1.19	1.60	18.05	1.43	63.07	10.01

3.2 Photochemical machining method

Photochemical texturing involves the chemical etching of selectively protected surfaces using a patterned mask. The optical images of the masks used for the photochemical process are shown in Table 3.

Table 3

Images of IM37 sample surfaces: replication rate, optical images of mask, PCM textured

Sample	Mask	Chemical etched surface	Injection molded surface, sample IM37
PCM1 rRa= 59.57% ΔRa= 0.1727 µm	 No raster	 Ra_{PCM1}=0.4272 µm	 $Ra_{IM37-PCM1}$=0.2545µm
PCM2 rRa= 83.22% ΔRa= 0.7681 µm	 Raster 80 lines/cm	 Ra_{PCM2}=4.5785 µm	 $Ra_{IM37-PCM2}$=3.81µm
PCM3 rRa= 94.95% ΔRa= 0.2314 µm	 Raster 100 lines/cm	 Ra_{PCM3}=4.585 µm	 $Ra_{IM37-PCM3}$=4.3536µm
PCM4 rRa= 94.38% ΔRa= 0.1668 µm	 Raster 120 lines/cm	 Ra_{PCM4}=2.9684 µm	 $Ra_{IM37-PCM4}$=2.802µm

The textured mold surfaces and the replicated surfaces on the molded product have been processed on a 2 x 1.5 square millimeter surface, and optical images were performed at magnification 20:1. Four models were chosen: without raster (PCM1), with a raster of 80 lines/cm (PCM2), 100 lines/cm (PCM3), and 120 lines/cm (PCM4).

The roughness *Ra* is indicated as Ra_{PCMi}, for mold surfaces, respectively $Ra_{IM37\text{-}PCMi}$, for the polymeric replicated surface. For all processes, the replication rate, *rRa,* was evaluated as a ratio of *Ra* measured on the injection molded sample no. 37, IM37, and the corresponding *Ra* of the mold cavity surface, with formula (1) and, respectively, the difference ΔRa, estimated using formula (2). The *Ra* value represents the arithmetic mean of five measurements in one direction, respectively, and five in a perpendicular direction for each analyzed surface.

$$rRa = Ra_{IM37}/Ra_{mold} \text{ [\%]} \tag{1}$$

$$\Delta Ra = Ra_{mold} - Ra_{IM37} \text{ [µm]} \tag{2}$$

Reasonable replication rates resulted for samples PCM3 (*rRa*=94.95%) and PCM4 (*rRa*=94.38%), while a poor replication rate was obtained for sample PCM1 (*rRa*=59.57%). At the same time, the processing accuracy of the photochemical machining method is higher for the depth of 0.03 mm compared to that carried out at a depth of 0.1 mm due to the lower erosion effect on the side walls during dissolving in a chemical solution.

3.3 Laser texturing method

In the paper, the laser processing was performed on the plates made of the same steel used for the photochemical processing, using a 20W power fiber laser equipment (Q-Switch fiber laser, wavelength 1064 nm, pulse duration 120÷150ns, and 0.66 mJ the maximum pulse energy). Four different sets of parameters were chosen, abbreviated LBM1..4. The laser texturing parameters' values, the representative images of the laser-textured surfaces, and the replicated injection molding ones, as shown in Table 4. The model has been drawn as a 20 mm x 20 mm square and double hatched with a step of 20µm. The laser beam scanned the surfaces following the hatch traces on the four impressions surfaces with LBM1 to LBM4 parameters controlled by the EZCAD2 application. The roughness of the laser beam machined surface was abbreviated $Ra_{LBMi,}$ and of the replicated injection molded surface of sample nr. 37 $Ra_{IM37\text{-}LBMi}$, respectively.

The influence of processing parameters on the surface roughness was evaluated with Taguchi analysis on an orthogonal matrix L4 with three factors: power, beam speed, frequency, and two levels with a larger-the-better strategy. (A rougher surface correlated with better productivity). Mean square deviation (*MSD*) was calculated with the formula (3) and the Signal-to-Noise (*SN* Ratio) with formula (4):

$$MSD = n^{-1} \sum_1^n \frac{1}{y_i^2} \quad \text{(for larger the better strategy)} \tag{3}$$

$$S/N = -10 \log (MSD) \tag{4}$$

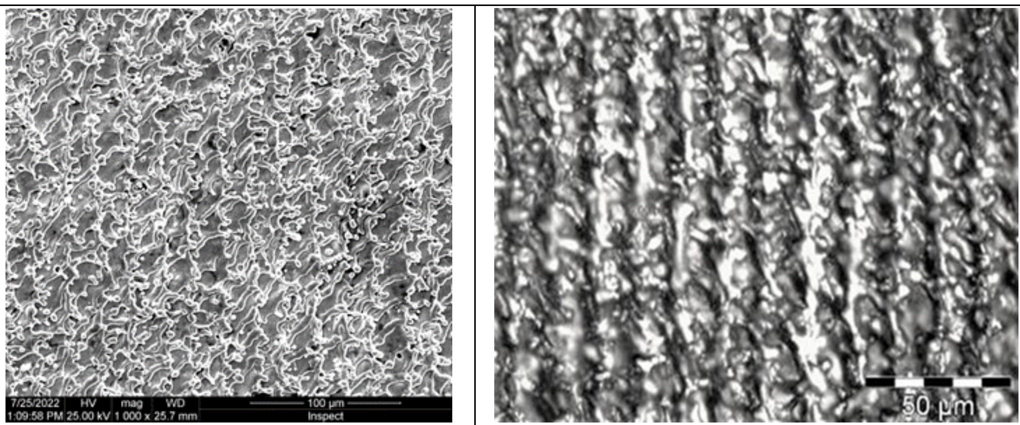
Table 4

Taguchi analysis *larger-the-better* on injection molded sample IM37, LBM textured surfaces

No	Power [%]	Speed [mm/s]	Frecuency [kHz]	$(y_i) = (Ra_{D1} + Ra_{D2})_i/2$ [µm]					*MSD*	*S/N* Ratio
				1	2	3	4	5		
1	60	500	20	1.0875	1.0125	1.038	1.089	1.062	0.895	0.478
2	60	800	30	0.8155	0.8925	0.876	0.948	0.847	1.313	-1.183
3	90	500	30	1.159	1.138	1.124	1.128	1.160	0.767	1.151
4	90	800	20	0.904	1.0065	0.993	0.987	0.992	1.053	-0.225

Taguchi (Table 4) analysis revealed the dominant effect of beam scanning speed and beam power on roughness *Ra*. Also, the best results regarding replication rate were obtained for minimum values of laser beam power, scan speed, and frequency.

The results reported by Piccolo et al., although the mold heating temperatures, Tm, were located far outside the range recommended for PP (30÷50 °C), respectively Tm 90 °C and Tm 120 °C [10]. In our experiments, the replication rate obtained for the PP/Tm 90 °C is close to those recorded for sample IM37-LBM1 for Tm 45 °C, and a similar visual aspect can be observed (Fig. 2).



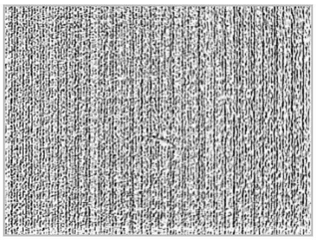
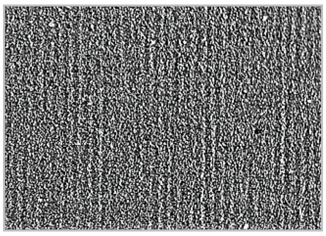
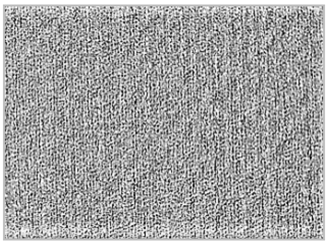
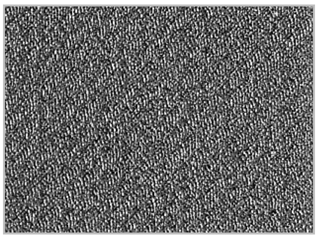
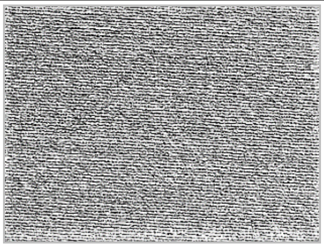
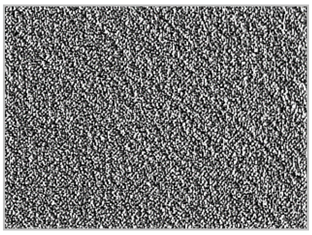
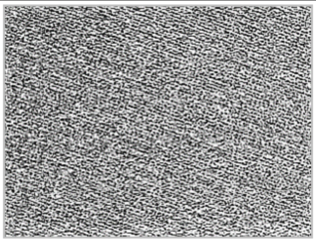
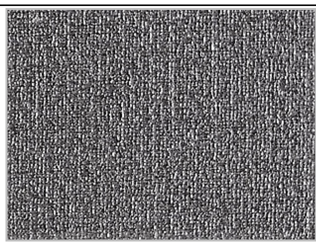
a *b*

Fig. 2 a) SEM image of laser LBM1 surface; b) Optical image of laser LBM1 surface

Table 5 shows the optical images and roughness values of the laser-textured mold surfaces Ra_{LBM} and for the injection molded sample nr. 37 replicated ones $Ra_{IM37\text{-}LBM}$. It was observed that the replication rate is higher for rougher surfaces (sample LBM1 with Ra_{LBM1} 1.089µm and *rRa*=77.2%) and lower for glossier surfaces (sample LBM4 with Ra_{LBM4} 0.517 µm and *rRa*=52.96%).

Table 5

Replication rate, parameters; optical images of LBM textured surfaces and IM37

Sample	Parameters	Laser beam textured surface	Injection molded surface IM37
LBM1 *rRa=77.2%* *Δ=0.241 µm*	Power 60% Speed 500mm/s Frequency 20kHz	 Ra_{LBM1}=1.058 µm	 $Ra_{IM37\text{-}LBM1}$=0.817µm
LBM2 *rRa=66.8%* *ΔRa= 0.291 µm*	Power 60% Speed 800mm/s Frequency 30kHz	 Ra_{LBM2}=0.876 µm	 $RaI_{M37\text{-}LBM2}$=0.586µm
LBM3 *rRa= 65.7%* *ΔRa= 0.392 µm*	Power 90% Speed 500mm/s Frequency 30kHz	 Ra_{LBM3}=1.142 µm	 $Ra_{IM37\text{-}LBM3}$=0.750µm
LBM4 *rRa= 52.96%* *ΔRa= 0.459 µm*	Power 90% Speed 800mm/s Frequency 20kHz	 Ra_{LBM4}=0.977 µm	 $Ra_{IM37\text{-}LBM4}$=0.517µm

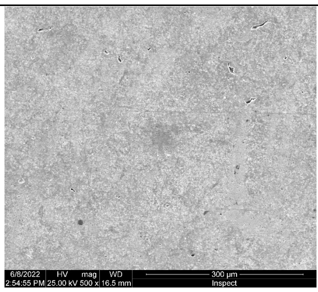
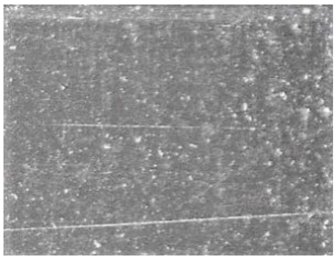
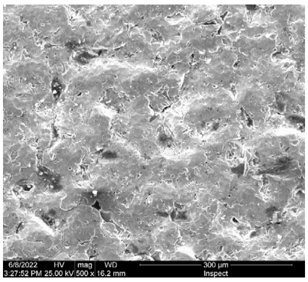
3.4 *BJT* additive method

The two inserts used to analyze the additive methods were made with metal binder jetting class according to ISO 52900 [13] and abbreviated MBJT. The additive process consisted of depositing a layer of SS316L stainless steel powder, leveling, and "printing" by selectively jetting the binder and then a thermal consolidation process. The deposition procedure continued layer by layer until the insert (as a plate) was obtained. Then the excess powder was removed, and the "printed" product was consolidated by sintering in special furnaces at temperatures corresponding to the base material. Additive methods use stereolithography native extension-type files (*STL)*, which describe only the surface geometry of a three-dimensional object (exported from CAD applications).

As can be seen from the data presented in Table 6, the polished finish surface texture MBJT1 has the lowest roughness both for the insert (Ra_{MBJT1} 0.1704 µm) and the injection molded sample 37 ($Ra_{IM37\text{-}MBJT1}$ 0.15 µm).

Table 6

SEM and optical aspect of insert and replicated surface of sample IM 37

Sample	Finishing stage	Metal BJT insert surface	Injection-molded surface IM37
MBJT1 *rRa= 86.16%* *ΔRa= 0.0241 µm*	Polished	 $Ra_{M\text{-}BJT1}=0.1704\ \mu m$	 $Ra_{IM37\text{-}MBJT1}=0.15\mu m$
MBJT2 *rRa= 91.57%* *ΔRa= 0.381 µm*	Standard	 $Ra_{M\text{-}BJT2}=4.530\ \mu m$	 $Ra_{IM37\text{-}MBJT2}=4.148\mu m$

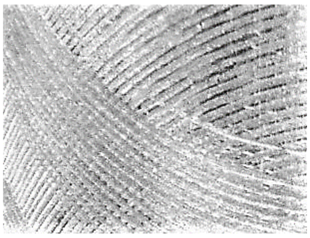
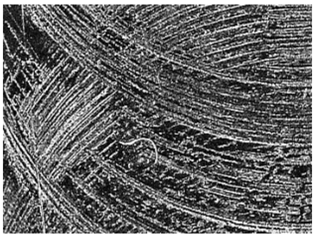
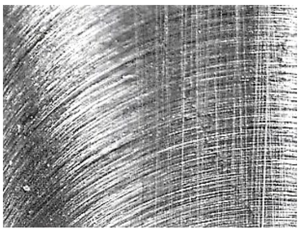
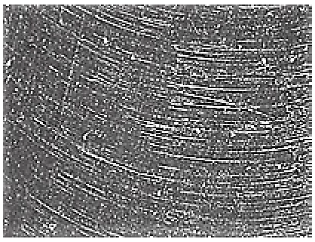
In contrast, the standard MBJT2 roughness surface has roughness values over 25 times higher for both the BJT insert (Ra_{MBJT2} 4.530 µm) and the injection molded correspondent surface ($Ra_{IM37\text{-}MBJT2}$ 4.148 µm). The replication ratio in the case of the standard finish (*rRa*=91.57%) was higher than the polished finish (*rRa*=86.16%) due to the contraction effect that occurs when the injected polymer product solidifies.

3.5 Milling method

The optical aspect of milled surfaces and replicated sample IM -37 for an area of 2 mm x 1.5 mm is presented in Table 7. The surface of sample MIL1 was milled using a 5mm diameter carbide tool coated with TiAlN, with a machining speed of 7200 min^{-1}, cutting depth of 0.01 mm, and a feed of 500 mm/min. The surface of sample MIL2 was milled with the same tool, using a speed value of 10,000 min^{-1} and feed of 200 mm/min. The roughness results confirmed a more advanced degree of finishing for the machined surface using a higher speed and a lower feed (MIL2).

Table 7

Roughness, replication values, and optical images of milled surfaces for sample IM37

Sample	Parameters	Milled surfaces	Injection molded surfaces IM-37
MIL1 *rRa*= 96.4% *ΔRa*= 0.0413 *μm*	Speed 7200 min^{-1} Feed 500 mm/min	 Ra_{MIL1}=1.1479 *μm*	 $Ra_{IM37\text{-}MIL1}$=1.1066 *μm*
MIL2 *rRa*= 78.72% *ΔRa*= 0.0644 *μm*	Speed 10000 min^{-1} Feed 200 mm/min	 Ra_{MIL2}=0.3027 *μm*	 $Ra_{IM37\text{-}MIL2}$=0.2383 *μm*

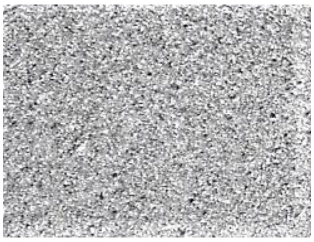
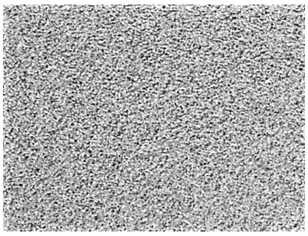
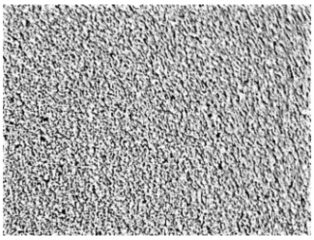
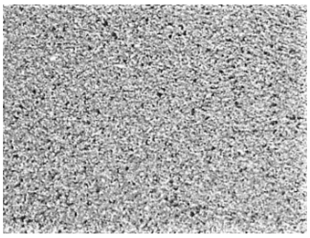
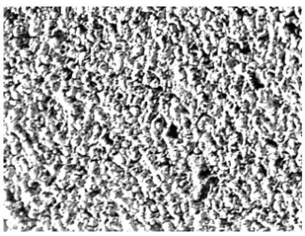
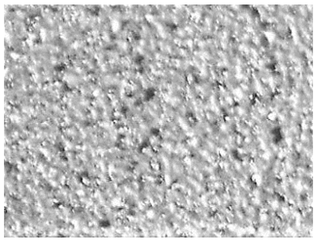
The shrinkage effect in polymeric composite material (as results from the texture detail topography) and the complex (plastic and elastic) deformation of the apparatus measuring tip can explain the results of replication rate, respectively *rRa*=78.72% for MIL2 compared to *rRa*=96.4% for MIL1. Once again, it is confirmed that a very low roughness does not ensure a higher replication rate for products made by injection molding thermoplastic materials.

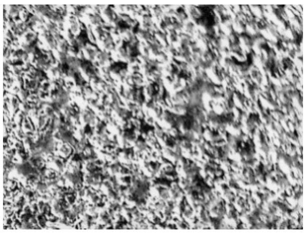
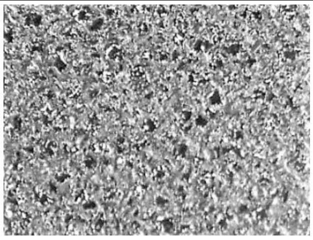
3.6 Electrical discharge machining method

Four impressions were electrical discharge machined - EDM, on an area of about 19 mm x 19 mm, using "predefined" parameters that theoretically predicted values for the roughness of *Ra* 4.5, *Ra* 3.15, *Ra* 1.6, and *Ra* 0.8. The roughness values of the surfaces processed with the EDM method predicted and measured are presented in Table 8. Abbreviations used in Table 8 were: the roughness *Ra* is indicated as Ra_{EDMi}, for mold surfaces, respectively $Ra_{IM37\text{-}EDMi}$, for the polymeric replicated surfaces of sample nr. 37.

Table 8

***Ra*, process parameters, optical images of EDM textured and replicated surfaces**

Sample	Parameters	EDM textured surface	Injection molded surfaces IM37
EDM18 *rRa=* *60.78%* *ΔRa=* *0.2446 µm*	Voltage -200 V Current *I* 1 A A*=3.2 µs Predicted *Ra* 0.8 µm	 $Ra_{EDM18}=0.6772\ \mu m$	 $Ra_{IM37\text{-}EDM18}=0.4116\mu m$
EDM24 *rRa=* *80.38%* *ΔRa=* *0.2932 µm*	Voltage +200 V Current *I* 4 A A*=3.2 µs Predicted *Ra* 1.6 µm	 $Ra_{EDM24}=1.4432\ \mu m$	 $Ra_{IM37\text{-}EDM24}=1.16\ \mu m$
EDM30 *rRa=* *96.6%* *ΔRa=* *0.1043 µm*	Voltage +200 V Current *I* 6 A A*=50 µs Predicted *Ra* 3.2 µm	 $Ra_{EDM30}=3.0735\ \mu m$	 $Ra_{IM37\text{-}EDM30}=2.969\mu m$

EDM36 *rRa*= *89.12%* *ΔRa*= *0.4623 μm*	Voltage +160 V Current *I* 16 A A*=50 μs Predicted *Ra* 4.5 μm	 Ra_{EDM36}=4.192μm	 $Ra_{IM37-EDM36}$=3.7359μm

(*) A- discharge pulse [μs]

The Charmilles Roboform 100 equipment used for this processing method includes special functions for selecting EDM parameters in the form of technological tables adapted to the combination of materials (workpiece - electrode), tool, and desired roughness, according to VDI 3400.[11] Charmilles recommends a tolerance of two *CH* units. CH No is evaluated as follows [14]:

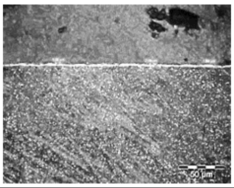
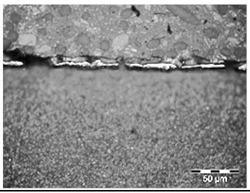
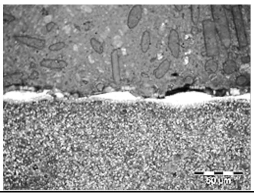
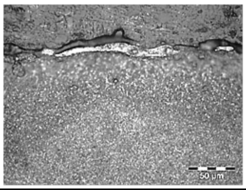
$$CH\ No = 20\log(10\ Ra) \tag{5}$$

CH No has a correspondent N class roughness according to ISO 21920-2021 (e.g., CH 30 – N8, CH 36 – N9) [15]. All the measured values are lower than those predicted in the technological tables proposed by the machine manufacturer, explained by the finer granulation of the graphite used in our experiments. The obtained results showed an excellent replication rate obtained for EDM30 (*rRa*=96.60%) and EDM 36 (*rRa*=89.12%), while EDM18 (*rRa*=60.78%) and EDM24 (*rRa*=80.38%) indicated lower replication rates and behavior influenced by the detail of texturing. This behavior is similar to that of the other previously analyzed processing methods. The EDM experiments confirm the results of previous research, namely the significant discharge current (*I*) influence on productivity and the degree of surface finish [16]. It is also observed that roughness increases as a function of discharge current (*I*) and frequency of discharges, an evolution highlighted by the optical images of the surfaces.

Microhardness was measured with a Shimadzu HMV 2T apparatus in LAMET Laboratory (UPB) using an indentation force of 980.7 mN and a test time of 10 seconds (ambient temperature of 28°C and 40% humidity). The maximum hardness value was obtained for sample EDM24 (347 HV0.1) and the minimum for sample EDM18 (272 HV0.1). In the images presented in Table 9, the "white layer" is visible as a discontinuous line bordering the EDM-processed surface of the samples in the cross-section. Samples EDM30 and EDM36 show a large dispersion of hardness results, and the aspect of the white melted layer is discontinuous and inhomogeneous.

Table 9

Microhardness HV0.1 and cross-sections images of EDM white layers

EDM18	*EDM24*	*EDM30*	*EDM36*
272 	*347* 	*300* 	*293* 

The hardness was measured on the areas located in the white layer's immediate vicinity resulting from the mold metal's rapid melting and solidification. The hardness value depends on the molten metal volume and the cooling rate provided by the temperature and the nature of the working environment. In principle, the hardness value increases when the volume of metal is smaller due to the faster cooling of a reduced volume of material. It is known that the melted material pressure and temperature values inside the cavity can vary during the filling and packing phases, depending on the flow distance. In this study, for the replication rate, *rRa,* of the pairs of similarly positioned impressions, LBM1 - EDM30, LBM4 - EDM24, PCM1 - MBJT1, and LBM2 - EDM36, such an influence was not confirmed. Increasing the roughness of the mold cavity surfaces leads to an improved replication rate. Thus, better replication rates were obtained for rougher surfaces for the same temperature and pressure values in the mold cavity.

The results indicate a clear correlation between the size of the topographic details of the mold surface and its replication. The replication rates agree with this observation for samples MIL2 and MIL1, EDM18, EDM30, and EDM36. The measurement method can influence the results by the degree of uncertainty. In the case of roughness measuring equipment, the tip radius of the probe and the pressing force on the micro-irregularities of the surfaces can produce both their plastic and elastic deformations, the extent of the phenomenon being greater in the case of polymer materials that have high plasticity.

Examples of industrial integration of engraving by milling, LBM in 2 ½ dimensions, and EDM micromachining or texturing have been performed by the authors during the doctoral studies, which can validate and confirm the application domain for each proposed technology [16].

3.7 Application domain

Photochemical machining is suitable for manufacturing precision details with limited depth, but it is still a successful method for mold texturing. The technology is not restricted to two dimensions of surfaces and size, and the chemical removal rate and skill of personnel influence productivity. An advantage of laser and photochemical texturing methods is that models are usually indicated as image-type files (JPEG, BMP), allowing great shapes and details flexibility. Professional photochemical texturing costs range from 10 euros/cm^2, and a precision of +/-0.01 mm can be obtained. Automotive and electrotechnical industries often require products with aesthetic surfaces made by **PCM**.

A 100 mm x 100 mm working area 2D Q-Switch fiber laser of 20W power is available for 5.000 euros and can be used for marking, engraving, or texturing at low costs and labor. **LBM** further experiments demonstrated excellent results on two dimensions of texturing injection mold surfaces made in steel DIN 1.2311, engraving, drilling vacuum access holes of 0.5 mm diameter, and "milling" groves of 0.6 mm x 0.5 mm x 20 mm for vacuum-forming mold made in aluminum alloy EN 7075. The low investment and easy work recommend a nanosecond Q-Switch fiber laser as a favorite solution for manufacturing metal surfaces of 100 mm x 100 mm and depths up to 0.5 mm or for cleaning at a fair precision +/-0.05 mm.

EDM and **milling** equipment are a must in mold-making shops. Electrical discharge machining and high-speed milling methods are usually used for surface finishing, often in the mold and die-making industry at high productivity and micron precision. EDM and milling are usually available at hourly rate costs ranging from 25 euros, depending on the complexity of the part and mold maker's provenience. A high-gloss mold cavity surface, the equivalent of a very low *Ra*, is obtained by **milling** or **EDM** at good productivity and low costs (during the night shift, for example). **LBM** and **photochemical** machining can obtain low *Ra* surfaces at lower productivity and limited depth. **EDM** and **LBM** can manufacture rough surfaces too.

Additive manufacturing methods are becoming popular in prototyping and the cost-effective manufacturing of mold components. **AM** is used, for example, in mold-making for manufacturing steel inserts with conformal cooling channels, allowing better cycle times and surface quality of injection molding high complexity shape products in automotive or electro technics industries. Although additional machining is necessary, **AM** can produce parts from 25 euros/cm^3, with configurations impossible to achieve by subtractive processing.

4. Conclusions

The experiments presented in this paper were directed to the most used subtractive technologies for mold surface finishing: photochemical machining, milling, electrical discharge machining, and the recent laser beam machining, and to the additive manufacturing method BJT, evaluated the replication ratio at injection molding of recycled polypropylene and observed and analyzed the influence of process parameters on the quality of the surface.

The size of the topographical details, which depends on the texturing method and the process parameters, can influence the replication of the injection-molded product. Better replication ratios were observed for rougher surfaces and higher injection molding temperatures.

Laser texturing of injection mold cavity surfaces is an accessible, economical method that offers new product design and fabrication possibilities. Meantime further experimental works are needed to observe and develop parameter templates fitted to the metal materials to be processed.

AM technologies offer new perspectives in designing mold steel components of high complexity.

REFERENCES

[1]. *** https://cordis.europa.eu/project/id/734342 accessed 20221229

[2]. ***https://www.poc.research.gov.ro/uploads/2021-2027/conditie-favorizanta/sncisi_19-iulie.pdf accessed 20221229

[3]. *V.K. Jain, D.S. Patel, J. Ramkumar, et al.* Micro-machining: An overview (Part II). Journal of Micromanufacturing. 2022 May; vol. **5**(1). pp.46-73.

[4]. *E. Brinksmeier, W. Preuss*, Micromachining, Phil. Trans. R. Soc. A**,** 2012, vol. **370**, pp.3973–3992

[5]. *NI. Marinescu, D. Ghiculescu, G. Jitianu.* Solutions for technological performances increasing at ultrasonic aided electrodischarge machining. International Journal of Material Forming. **2009** Aug; vol. **2**(1), pp. 681-684.

[6]. *Wan-Sik Woo, Choon-Man Lee*, A study of the machining characteristics of AISI 1045 steel and Inconel, 718 with a cylindrical shape in laser-assisted milling, Applied Thermal Engineering **91** (2015), pp.33-42

[7]. *ZZ. Dhokia, V.G. Nassehi*, A review of hybrid manufacturing processes - state of the art and future perspectives, International Journal of Computer Integrated Manufacturing, 2013, vol. **26**, no. 7, pp. 596-615.

[8]. *M. Sortino, G. Totis, E. Kuljanic*, Comparison of Injection Moulding Technologies for the Production of Micro-Optical Devices, Procedia Engineering, 2014, vol. **69**, pp.1296-1305

[9]. *A. D'Amico, C. Di Natale, F. Lo Castro, S. Iarossi, A. Catini*, Volatile Compounds Detection by IR Acousto-optic Detectors, Chapter in NATO Science for Peace and Security Series B: Physics and Biophysics · December **2008**, pp.21-59

[10]. *L. Piccolo, K. Puleo, M. Sorgato, G. Lucchetta, D. Masato*. Modeling the replication of submicron-structured surfaces by micro injection molding. Materials & Design. 2021 Jan 15, vol. **198**, 109272

[11]. VDI 3400 – 75 Electrical Discharge Machining (EDM), Definitions, Production, Application, (ger. Elektroerosive Bearbeitung; Begriffe, Verfahren, Anwendung)

[12]. *** https://www.moldmakingtechnology.com/articles/surface-finish-understanding-mold-surface-lingo accessed **2022**1229

[13]. ISO – the International Organization for Standardization, SR EN ISO/ASTM 52900:2022 Additive manufacturing — General principles — Fundamentals and vocabulary

[14]. ***Operating manual Roboform 100, document 490 599, 1989

[15]. ISO – the International Organization for Standardization, SR EN ISO 21920-2:2021 Geometrical product specifications (GPS) — Surface texture: Profile — Part 2: Terms, definitions and surface texture parameters

[16]. *D. Serban, C.G. Opran*. Researches regarding injection moulding of polymeric products in moulds with micro-profiled surfaces. In IOP Conference Series: Materials Science and Engineering 2018 August,Vol. **400**, No. 3, pp. 032009.