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Increasing the injection moulding productivity through EDM surface modulation

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Abstract

The productivity of the injection moulding process is considerably deteriorated due to the demoulding issues as a result of increasing part and polymer complexity. An effective method to overcome some of the issues is the application of coatings on mould surface to reduce adhesion and friction during the moulded part ejection. In such solutions, the mould is coated after the machining by methods such as milling and EDM. In fact, die-sinking EDM is widely used to machine moulds with high accuracy, surface quality and aspect ratios. In this research, a novel method is analysed where the texture of the EDM surface is modulated to achieve desirable surface functionality, leading to reduction of part sticking during ejection in injection moulding. The effect of primary parameters of EDM process on the resulting surface is analysed. It is seen that while the surface amplitude parameters such as Ra and Rz remain similar to the standard eroded surface, the spacing parameter RSm and slope measure RΔq can be modulated. The effect of the surface texture during injection moulding is evaluated by measuring the forces during the ejection stage to characterise part sticking. Similar or considerably reduced ejection forces are observed for the modulated EDM texture compared to the polished surfaces, depending on the polymer type and part geometry. The ejection force observations are correlated to the static and dynamic friction coefficient of surface textures against different polymers. The reduction of ejection forces comparable to the coated surfaces places surface texturing as an effective alternative or a supplement to reduce the demoulding issues and thus increasing the injection moulding productivity and part quality.

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Keywords: Electrical discharge machining (EDM); Surface texturing; Injection moulding; Demoulding

1. Introduction

Injection moulding is a widely used mass manufacturing process, and to some estimates, at least one third of all plastic parts are manufactured using injection moulding process, where depending on the part complexity, accuracy and dimensions, die-sinking EDM is employed to machine complete or partial features of a complex mould. In fact, a large portion of die-sinking EDM applications involve machining of moulds used for injection moulding. Since injection moulding is a mass replication manufacturing process, productivity is of utmost importance to keep the costs down and to reduce wastage for environmental concerns. Based on the mould complexity among others, cooling phase in injection moulding cycle is the longest, thus considerably affecting the overall process productivity. However, the cooling phase is essential for ejection of the moulded part from the mould cavity, both to preserve the quality of the part and mould surface, such as warping of the part or adhesion of the polymer residue on the mould surface. Various demoulding issues and some solutions have been well summarised in [1], where the deformation components of friction (mechanical interlocking, hysteresis, ploughing) and adhesion component of friction (thermodynamic / chemical, electrostatic, capillary attraction) are considered as primary mechanisms during demoulding.

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In terms of manufacturing of mould, optimising surface wettability or surface energies and optimising surface topography are considered common approaches to reduce demoulding issues.

Surface wettability or surface energy optimisation often involve coating of the mould surface, where the choice of coating material and method also needs to consider the mould geometry and polymer to be replicated. Since the coatings may reduce the adhesion of replicated part to the mould surface, it may allow reduction in cooling time, reduce the sticking of polymer residues on the polymer surface and increase the mould life-time.

Surface topography optimisation in injection moulds mainly refer to polishing, deburring and choosing optimal roughness of the mould surface. While polishing can significantly increase the total mould cost and is often performed manually affecting the final part accuracy, it is rarely done for the appearance alone as it is believed to facilitate ejection of the part from the mould [2]. Both deburring and polishing may be used to affect the final surface roughness of the mould after machining operations using milling and EDM, where the required optimal roughness is often polymer dependent.

If the demoulding issues in injection moulding can be reduced or eliminated, considerable reduction in the cooling phase cycle time and part wastage due to warping can be realised. However, current solutions from the mould manufacturing perspective involve costly and time consuming methods of polishing and coating. In this paper, the research focuses on an alternative technique to solve demoulding issues through surface topology optimisation using EDM. The presented results are mainly divided into the method of generating modulated EDM texture and performance evaluation of such surfaces in injection moulding.

2. Experimental setup and measurement methods

2.1. EDM

Die-sinking EDM machine Form 2000 with 3DS option from GF Machining Solutions is used for the generation of mould insert surfaces. Dielectric oil IME110 from Oelheld GmbH is used and copper tool electrodes are used for all the experiments. For experimental analysis, Böhler W300 (1.2343), Böhler STAVAX ESR (1.2083), Böhler M303 (1.2316) and ASP 23 (1.3344/1.3395) are used. Böhler M390 is used for mould inserts. Some thermal properties of these materials are shown in table 1.

Table 1. Thermal properties of the used workpiece materials from datasheets.

Steel properties @200°C	Thermal conductivity (W/mK)	Specific heat (J/kgK)	Density (kg/m^3)
1.2343 (W300)	27.7	550	7.64
1.2083 (Stavax)	20	460	7.75
1.2316 (M303)	24.8	529	7.7
1.3344 (ASP23)	27	510	7.78
M390	16.5	-na-	7.54

2.2. Injection moulding and ejection force measurement

The effect of mould texturing is analysed by performing successive injection tests with polished and EDM textured mould inserts. For this purpose, an Arburg 320S 500-150 Injection press is used. The test mould is equipped with a Kistler 9204B-SP2 force detector (10 kN max) in a position able to detect the force during injection and ejection cycle.

The mould temperature is set to 80°C and the ejection speed to 10 mm/s. To determine the ejection force, measured force over time is used to determine the peak force and the impulse, which is integral of the force over ejection time as shown in fig. 1 (bottom). For the coated cores, Balinit® A which is PVD TiN coating and Vickers® which is chromium based electrolytic coating are used.

2.3. Tribology measurements

Tribological pin-on-disk tests are carried on thermally treated (59 HRC) polished and EDM textured surfaces with 40 mm diameter in steel M390 by measuring the static and dynamic friction between half-spherical plastic bodies and textured flat plates. Half-spherical pins with 5 mm radius out of Zytel® 101L (PA) and Zytel® HTN FE8200 NC010 (PPA) are injected and served as counter-bodies. For the friction test, two pins are in contact with the metallic flat plates applying a contact force of 12.5 N and 80°C contact temperature. Applying an initial relative speed of 10 mm/s the peak separation force (static friction) is tested and evaluated with ten tests. The dynamic friction is analysed during 600 s at 10 mm/s keeping 12.5N contact force.

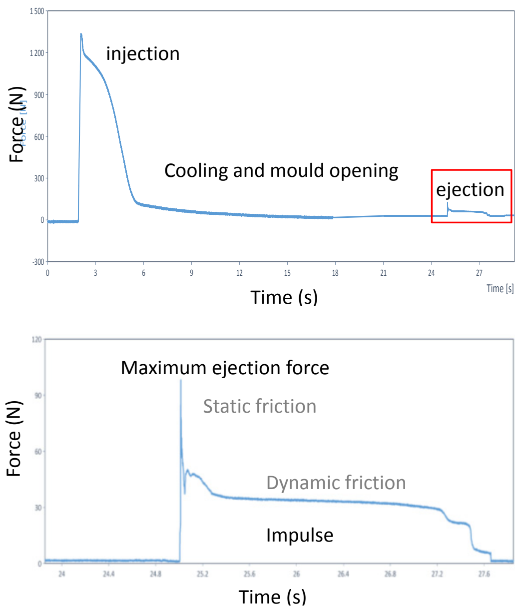

Fig. 1. Top: an example of a typical force profile of a complete injection moulding cycle for Zytel® HTN FE8200 (PPA). Bottom: Detailed ejection force profile shown by red window in top image. Initial sticking force from static friction and dynamic friction force components can be observed.

2.4. Surface roughness and dimensional metrology

Tactile measurements using Talysurf from Taylor Hobson is used to measure surface roughness parameters and Alicona Infinitefocus is used for optical analysis of the eroded surfaces along with dimensional metrology. The analysed surface roughness parameters are Ra, Rz, RSm and RΔq, with cut-off length λ_c of 0.8 mm and sample length higher than 6 mm.

3. EDM surface modulation

3.1. Comparison of the 3DS texture with standard texture

The surface texture modulation in EDM is a recent development and marketed under various commercial names by different EDM machine tool manufacturers. The analysis of such texture in terms of surface characterization is recently presented by [3]. In current work, such texture is generated by the used machine tool, named 3DS. A comparison of the standard EDM texture and the 3DS surface for similar resulting surface roughness Ra is shown in fig. 2. It is seen that the crater geometry varies considerably between the two textures, resulting from the adaptation of EDM process parameters. In fact, the modulated surface texture has craters with larger diameter compared to the craters for standard texture. Table 2 presents a comparison of different surface roughness parameters for standard EDM texture and 3DS texture, where large differences in RSm and RΔq are evident.

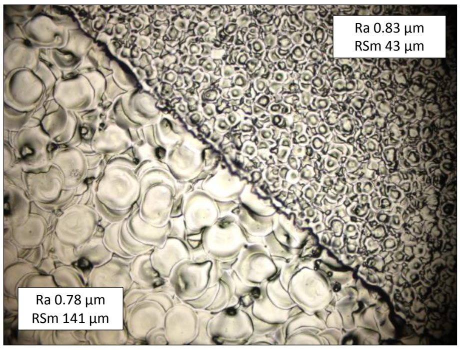

Fig. 2. The standard EDM texture (upper right) is compared with the modulated EDM texture (3DS) for similar surface roughness Ra.

Table 2. Surface roughness parameter comparison for standard and 3DS texture generated on W300 in the 25 mm x 25 mm area.

Core	Ra (µm)	Rz (µm)	RΔq (°)	RSm (µm)
EDM 3DS-1	1.95	12.33	8.15	223
EDM VDI26	1.99	12.43	14.33	109
EDM 3DS-2	1.59	9.20	6.89	204
EDM VDI24	1.69	10.63	14.3	88
EDM 3DS-3	0.93	5.75	4.95	160
EDM VDI20	1.03	6.51	11.67	65
EDM 3DS-4	0.39	2.59	2.58	148
EDM VDI12	0.40	2.69	8.5	38

3.2. Effect of EDM process parameters

A preliminary comparison between the pulse parameters used to generate these two different textures is presented in [3], however the effect of the parameters on the surface roughness is not analysed. In this work, a mixed level factorial design has been used to analyse the effect of pulse parameters on the surface roughness. A copper electrode with 25 mm x 25mm surface area is used to erode 0.3 mm deep cavities in steel 1.2343 (W300). The electrode polarity is chosen as negative. Main input parameters are peak current I_p (30, 50 /A), discharge current I_d (3, 6 /A), pulse duration T_{on} (5, 10, 30, 70 /µs) and peak duration T_p (1.1, 1.8 / µs). Main effect of the parameters on surface roughness parameters Ra and RSm are shown in fig. 3 and fig. 4 respectively. It is seen that within the chosen value ranges for the pulse parameters, Ra is strongly influenced by the peak current and RSm is strongly affected by the discharge current. The effect of pulse duration becomes more significant for longer durations, whereas up to 30 µs, the effect is negligible compared to the discharge current. It must be noted that the peak current and peak duration are strongly correlated. In fact, upon further investigation it is found that the surface modulation to affect crater geometry can be undertaken in a number of ways, one of which is application of high peak current followed by a current tail. In yet another method, such textures can be also generated without the initial current peak.

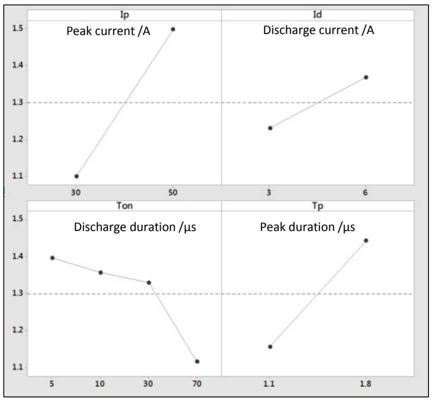

Fig. 3. Effect of main process parameters on surface roughness Ra (µm).

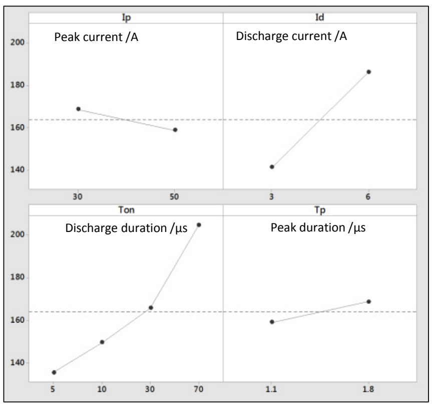

Fig. 4. Effect of main process parameters on surface roughness RSm (µm).

3.3. Effect of workpiece material

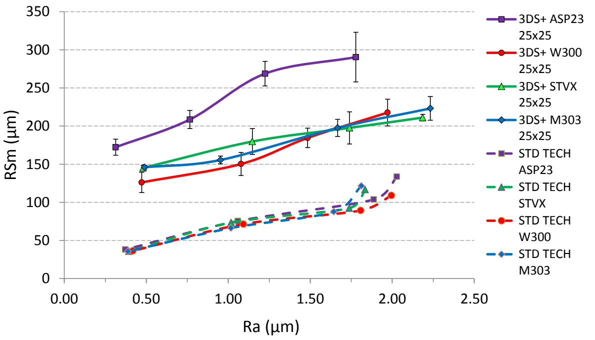

Fig. 5. Comparison of the effect of steel type on standard EDM texture and modulated 3DS texture in terms of surface roughness under same erosion conditions and parameters. Large differences in RSm between the 3DS texture and standard EDM texture is evident for different Ra.

The influence of workpiece material on the resulting standard EDM texture and 3DS texture has been analysed for different surface roughness. Same erosion parameters and conditions have been used for the comparison, where the erosion surface is 25 mm x 25 mm and the depth of erosion is 0.3 mm. Figure 5 shows the comparison of resulting surface roughness for different materials and textures. It is observed that for the standard EDM texture, the resulting surface roughness Ra and RSm values are similar irrespective of the workpiece material. However, for the 3DS texture, a large variation in these values is observed depending on the workpiece material. In fact, depending on the used same erosion parameters, difference in Ra from 0.2 µm to as high as 0.5 µm is observed within the chosen range for ASP23 and M303. While on one hand this signifies the effect of the workpiece material for the parameters used to generate 3DS texture, on the other hand it necessitates a model to ensure similar resulting Ra irrespective of the used steel. While comparing the significant thermal properties of the materials shown in table 1 and the behaviour of resulting roughness shown in fig. 5, no clear correlation could be established.

In order to predict the resulting surface roughness, linear regression is performed based on pulse parameters and resulting Ra for each specific material. However, this approach requires experimentation for all the needed workpiece materials. In order to predict Ra for different materials, another approach named multivariate regression from machine learning techniques has been used, where apart from the erosion parameters, all the known thermal properties and chemical composition of the materials has been used to create a prediction model, the results are shown in table 3.

Table 3. Comparison of the measured and predicted surface roughness Ra

WP Material	Measured Ra (µm)	Predicted linear regression		Predicted multivariate regression	
		Ra (µm)	Error (%)	Ra (µm)	Error (%)
ASP23	2.01	2	0.5	2.10	5
ASP23	0.54	0.5	8	0.44	18
M303	1.44	1.4	2.8	1.39	4
M303	0.81	0.79	2.5	0.82	2

4. EDM texture performance in injection moulding

4.1. Comparison of EDM texture and coatings

In order to evaluate the performance of EDM surface compared to several coatings used for injection moulding, ejection force measurements have been performed using different polymers. The details of the used polymers and the core insert surfaces are shown in table 4 and table 5 respectively. Here, cylindrical core insert with 28 mm diameter and 58 mm length from steel 1.6773 is used for injection moulding. The resultant polymer part wall thickness is 2.5 mm. The core contains cavities at the end to avoid vacuum effect. Same process parameters are used for injection tests for different polymers and the measured ejection force is averaged over 56 tests, measured once the stable conditions during injection process are reached. Figure 6 shows the results of the ejection force measurements for different core surfaces and polymers. It is seen that the polished surface results in high ejection forces compared to the coated and textured surfaces. Also, it is seen that the ejection force resulting from standard EDM texture is slightly higher than the modulated EDM texture (3DS) for different polymers, despite of similar surface roughness Ra.

Table 4. Some properties of the used polymers

Polymer	Commercial name	Tensile Modulus (MPa)	Shrinkage (%)
Polyacetal (POM)	Derlin® 500P	3100	2
Elastomer (TPC-ET)	Hytrel® 7246	525	1.6
Polyester (PTT)	Sorona® 3301	2400	1.3
Polyester (PBT)	Crastin® S600F20	2500	1.9
Polyamide (PA66)	Zytel® 101L	3100	1.4

Table 5. Properties of the core insert surfaces

Core	Ra (µm)	RSm (µm)
Polished surface	0.11	42.75
TiN (PVD Bainit A)	0.07	53.47
Vickersil® Standard	0.22	50.21
Vickersil® Matt	0.28	59.16
EDM Standard (EDM1)	0.86	60
EDM 3DS	0.95	102.74

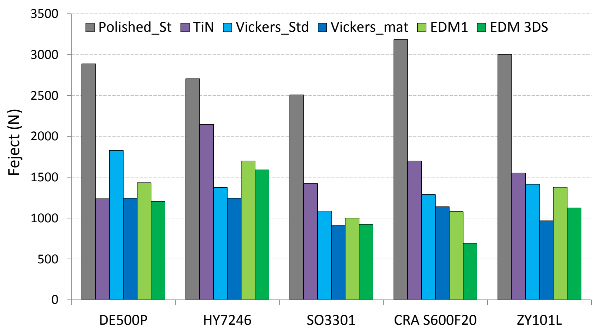

Fig. 6. Comparison of measured ejection force for different polymers and core insert surfaces with polished, coated and EDM textures.

4.2. Tribology analysis of the eroded surfaces

In order to reduce the characterisation effort of surface texture in terms of its demoulding performance, tribological analysis of the surfaces is performed. A possible correlation between the friction coefficient and demoulding forces during the injection moulding process can considerably reduce the texture characterisation effort. In this work, tribological analysis of the surfaces is carried out to determine static and dynamic coefficient using the method described before. Surface textures using EDM (3DS) and polishing or grinding are prepared with different surface roughness Ra on 40 mm diameter M390 steel plate. The measurement friction components, namely force of detachment to measure static friction and dynamic friction are presented in fig. 7 and fig. 8 respectively. The details of the surface textures for the presented friction measurements are shown in table 6. It is seen that for the textures generated with both methods, the friction force reduces with the surface roughness. Also, for similar surface roughness, the polished surfaces exhibit higher force of detachment for different polymers compared to the 3DS texture, whereas the dynamic friction coefficient is similar to a particular surface roughness irrespective of the preparation method. The variation in the measured dynamic friction for ground surfaces is thought to be originating from inhomogeneity resulting from the machining direction, whereas the EDM surfaces have random surface features.

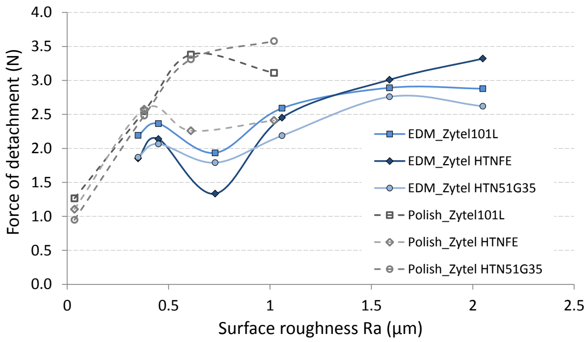

Fig. 7. Comparison of measured force of detachment (static friction) for different surface roughness, polymers and surface preparation method.

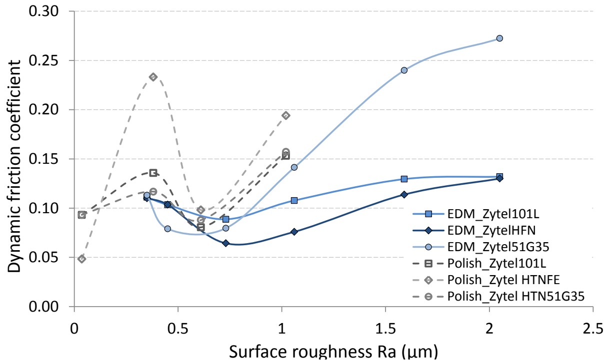

Fig. 8. Comparison of dynamic coefficient of friction for different surface roughness, polymers and surface preparation method.

Table 6. Surface roughness of the steel (M390) samples for tribology analysis

Core	Ra (µm)	RSm (µm)
Polished surface	0.036	-
Ground surface	0.38	-
Ground surface	0.61	-
Ground surface	1.02	-
EDM surface1	0.35	106
EDM surface 2	0.45	96
EDM surface 3	0.73	132
EDM surface 4	1.06	174
EDM surface 5	1.59	247
EDM surface 6	2.05	221

4.3. Effect of surface roughness on ejection forces

The effect of surface roughness characterised by tribological performance is further correlated by injection moulding tests. Here, a gear geometry is used with outer diameter 14 mm and inside diameter 9 mm, thickness of the wheel is 10 mm. The gear teeth surfaces have been machined with EDM 3DS texture with different surface roughness. Figure 9 shows the measured maximum ejection forces during injection moulding process for different polymers and surface roughness. It is seen that the ejection force reduces with the surface roughness, whereas it is also evident that the ejection force varies considerably with the polymer. Interestingly the trend observed from the force of detachment in fig. 7 for both polymers over different surface roughness for EDM textured surfaces matches with the measured ejection force during the injection moulding process.

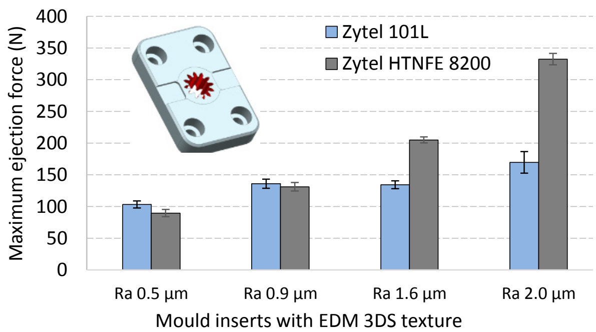

Fig. 9. Comparison of the maximum ejection force measurements for different surface roughness and polymers for a gear geometry as depicted in picture. The highlighted teeth surface in red have been EDM textured (3DS).

4.4. Effect of texture on part and mould surface

The demoulding process may affect the part and mould surface as mentioned before. In order to analyse the effect of surface texture regarding these aspects, a sample polymer part as shown in fig. 10 is replicated using a cavity machined using EDM with standard texture and a cavity with the modulated (3DS) texture. The polymer used is Grilon® BG50S (PA6 GF50) with 50% glass fibre. It is found that while performing injection moulding with standard EDM texture, the replicated part shows surface defects in form of burns (see fig. 10 insert), thought to be resulting from the diesel effect. On the other hand, the parts replicated using the modulated surface texture show no such surface defects for the similar surface roughness Ra of the mould cavity. The use of glass fibre reinforced polymers often results in high residues on the mould surface requiring periodic cleaning of the mould cavity. In the presented example, the mould cleaning interval was determined to be 4.5 hours for the standard EDM texture and about 10 hours for the 3DS texture.

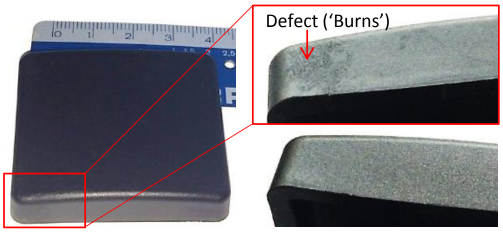

Fig. 10. Image of a sample replicated part from PA6 GF50, where the insert picture (highlighted by box) shows surface defects in form of burn marks resulted while using standard EDM texture and absence of such defects while using modulated (3DS) surface texture as shown in bottom right.

4.5. Discussion

EDM surface texture can be modulated using the primary pulse parameters and polarity without additional requirements, such as special electrode or dielectric. The presented 3DS surface texture results in larger diameter craters with lower depth, mainly through melting effect and avoiding the evaporation of the anode material. The resulting roughness from such parameters is highly affected by the workpiece material, mainly from thermal properties and chemical composition due to the involved melting effect.

Tribological analysis of the 3DS surface reveal lower friction against polymers, since the erosion craters are more flat, as evidenced from average profile gradient RΔq parameter. Interestingly the friction behaviour correlated well with the ejection forces measured during the injection moulding tests, which indicates higher friction components during ejection compared to the adhesion for selected roughness and material pairs. Since the craters are more flat, re-solidified polymer undergoes less mechanical deformation during ejection which may explain the lower ejection forces. The more flat texture also facilitates effective evacuation of the gas from the mould cavity, preventing the burning or the 'diesel-effect' as evidenced for the glass fibre reinforced polymers. Compared to the standard EDM texture, the more flat craters in 3DS reduces the polymers residues left in the mould surface, reducing the mould cleaning requirement.

While the more flat erosion craters explain the glossy appearance of the mould surface, the lower friction, lower ejection forces and improved part and mould surface quality, the difference in forces for different polymers depend on the shrinkage and other properties which has not been evaluated in depth. Also, it is observed that the effect of texture also varies on the part geometry, where wall thickness and therefore the effect of polymer shrinkage, contact surface between the part and mould on the ejection path significantly affect the ejection forces.

5. Conclusions

Based on the presented analysis of modulated EDM surface texture and its performance in injection moulding, following conclusions can be drawn:

- EDM surface texture can be modulated using the main parameters pulse duration, current and polarity.
- Compared to the standard texture, modulated 3DS texture craters show much larger diameter, thus altering roughness parameters RSm and RΔq, while keeping similar Ra and Rz.
- Tribology analysis of the 3DS texture reveals lower friction with lower surface roughness, however compared to the polished surface, similar friction behaviour is analysed for Ra 0.4-0.6 µm.
- Ejection forces have been found to be dependent on the polymer type and surface roughness, where good agreement between the static friction and maximum ejection force; and between dynamic friction and ejection impulse is observed.
- Modulated texture 3DS is found to reduce the burn or 'diesel-effect' like surface defects on the replicated part and debris accumulation on the mould surface.
- Texture generated by flat craters evident from lower $R_{\Delta q}$ can be attributed to reduction in ejection forces, and lower friction through mechanical deformation.
- In future, systematic investigation is required to gain deeper insight into the part ejection mechanism. On the practical side, clustering or similar machine learning technique can be used for classification and understanding of the optimal surface roughness and surface texture based on geometry and polymer type.
- Texturing methods further need to be analysed by comparing EDM 3DS and similar texture generated using Laser beam machining.

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References

[1] Delaney, K.D., G. Bissacco, and D. Kennedy, *A Structured Review and Classification of Demolding Issues and Proven Solutions.* International Polymer Processing, 2012. 27(1): p. 77-90.
[2] Rosato, D.V. and Rosato, M.G., *Injection molding handbook.* Springer Science & Business Media, 2012.
[3] Klink, A., Holsten, M., and Hensgen, L., *Crater morphology evaluation of contemporary advanced EDM generator technology.* CIRP Annals - Manufacturing Technology, 2017. 66(1): p. 197-200.