Examination of surface roughness of holes of plastic parts drilled under cryogenic cooling conditions

To cite this article: G Varga et al 2018 IOP Conf. Ser.: Mater. Sci. Eng. 448 012065

View the article online for updates and enhancements.
Examination of surface roughness of holes of plastic parts drilled under cryogenic cooling conditions

G Varga¹, S Ravai-Nagy², F Szigeti³

¹ Institute of Manufacturing Science, University of Miskolc, Miskolc – Egyetemváros, Hungary
² Department of Engineering and Management of Technology, Faculty of Engineering, Technical University of Cluj-Napoca, Baia Mare, Dr. V. Babes 62/A, Romania
³ Institute of Engineering and Agricultural Sciences, University of Nyíregyháza, Nyíregyháza, Kótaji u. 9-11, Hungary

¹ gyula.varga@uni-miskolc.hu

Abstract. Machining performance can be improved by cooling with cryogenic assistance. This paper focuses on the influence of cryogenic cooling conditions using dry ice, solid carbon dioxide when drilling of PE-HD1000 plastic parts. The goal was to determine how the surface roughness of the drilled hole changes as a function of the cutting speed and the feed rate at room temperature and when cryogenic cooling is applied. The function relations were determined using Factorial Experiment Design. Improvement of the machinability of low temperature drilling results the improvement of roughness of the drilled hole.

1. Introduction

Industrial plastics are used in large quantities in different areas of industry for their various advantageous properties. Their dynamic development and the emergence of new materials is a continuous challenge for the industry, as the optimal cutting parameters vary considerably depending on the plastic material quality. Determining the optimal parameters for cutting industrial plastics is a continuous challenge for production engineering specialists. During machining, the realization of dimension accuracy and surface quality prescribed by the designers must be cost-effective.

During the processing of industrial plastics, it is known that the heating is the determining element of the machining due to the friction of the tool - chip, the work-piece - tool interface and the energy used to remove the chips. In the case of industrial plastics, due to warming, the machinability of material deteriorates, the plastics melts when machining, it stuck to the tool and the work-piece. One way of increasing the cutting parameters is the use of cooling and lubricating fluids, however, the coolants and lubricants have negative effects on the polymers, so the literature recommends dry machining and the use of cooling by compressed air. Industrial plastics cannot be machined over a certain temperature. To increase the cutting performance, heating of the work-piece must be limited. To keep the work-piece and the tool under a certain temperature, it is possible to use the cooling of the various parts of the machining system to reduce the heating of the work-piece, chip and tool.
Solution can be cryogenic cooling, which comprehensive examination has been carried out by Yildiz and Nalbant [1] in 2008 and Kaynak et al [2] in 2014. Benefits of application of cryogenic cooling: it can increase tool life and dimension accuracy during the cutting process; reduce the cutting temperature, surface roughness, and the energy used during the metal removal process, thereby improves the productivity. Jawahir et al summarized the most frequently applied liquids in cryogenic cooling [3]. During cutting processes, most of cryogenic cooling applications have been investigated mostly in turning operations [4-7], although other machining operations such as grinding [8-10], drilling [11-12] and milling [13-14] also occur.

The performance of cryogenic treated tools increased from 65% to 343%, depending on the cutting conditions [15]. In another experiment HSS twist drill for cryogenic treated twist drill was used for drilling stainless steel work-pieces. The results of the study showed a significant improvement in the lifetime of cryogenic treated drills [15]. Kim and Ramulu [16] used cryogenic treated carbide tools for drilling thermoplastic composites to inspect the machinability from the point of view the drilled hole quality and tool wear. Their results showed that while the cryogenic treated carbide tools produced better drill properties compared to conventional carbide tools, conventional carbide tools showed better wear resistance than cryogen-treated ones.

Based on an overview of the literature on processing in cryogenic environments, research can be divided into three main groups:

- Cooling tool (recommended for machining materials where overheating of tools causes premature wear, e.g. machining of carbidies) [17];
- Cooling the work-piece (when aim is changing the properties of the material to be machined) [18];
- Cooling of work-piece and tool (for high-precision machining when working on the work-piece and preventing thermal expansion of the tool) [19].

Our paper presents the results of experiments done by cryogenic drilling of the PE-HD1000 polyethylene work-piece. During the experiment we have studied the effect of cooling on the surface roughness of the bore and the chips separation properties.

2. Experimental conditions
During the experiment, Ø12mm diameter holes were made according to DIN 388 standard with HSS twist drill where the length of the hole was different: L/D = 1; L/D = 2.5 and L/D = 5. At the previous two drilling, a blind hole was made, while in the third case it was a through hole.

Further data:
- Machined material: PE-HD1000
- Cutting speed:
  - \( v_1 = 6.78 \text{ m/min} \) (revolution number of the spindle: \( n_1 = 180 \text{ rev/min} \));
  - \( v_2 = 18.85 \text{ m/min} \) (revolution number of the spindle: \( n_2 = 500 \text{ rev/min} \));
- Feed rates:
  - \( f_1 = 0.32 \text{ mm/rev}; \)
  - \( f_2 = 0.62 \text{ mm/rev}; \)
- Temperature of the work-piece:
  - \( T_1 = -35^\circ\text{C}; \)
  - \( T_2 = +20^\circ\text{C}; \)
- Cooling medium: solid carbon dioxide (dry ice, \( \text{SCO}_2 \)).

Elements of the technology system used for the drilling experiment:
- CNC controlled machine tool: Type NCT EmL510B;
- Thermometer, measuring range: -200\(^\circ\text{C}\) \( \pm 1200\text{C}^\circ\); K type probe, measuring accuracy: 0.1C\(^\circ\).

During the experiments, 8 experimental settings were performed using combinations of the above parameters. At each experimental setup 5 holes were made to meet the statistical requirements for the experiments. Variation of experimental data are listed in Table 1. Figure 1 shows the model of work-piece and the locations of holes machined during the experiments. Figure 2 shows the experimental setup at the different temperatures: \( T_1 = -35^\circ\text{C} \) and \( T_2 = +20^\circ\text{C} \).
Table 1. Variation of experimental data

| No. | Cutting speed \( v_c \), \( \frac{m}{min} \) | Feed rate \( f \), \( \frac{mm}{rev} \) | Temperature \( T \), \( ^\circ C \) |
|-----|---------------------------------|---------------------------------|-----------------|
| 1   | 6.78                            | 0.32                            | -35             |
| 2   | 18.85                           | 0.32                            | -35             |
| 3   | 6.78                            | 0.62                            | -35             |
| 4   | 18.85                           | 0.62                            | -35             |
| 5   | 6.78                            | 0.32                            | 20              |
| 6   | 18.85                           | 0.32                            | 20              |
| 7   | 6.78                            | 0.62                            | 20              |
| 8   | 18.85                           | 0.62                            | 20              |

Positioning holes for the work-piece fixing at the work holding system

**Figure 1.** 3D model of the work-piece before and after drilling

Machining in room temperature \( T_2 = +20^\circ C \)

**Figure 2.** Using different fixtures at machining of different temperatures

According to Szabo [20] the effectiveness of a machining process can be expressed among the others by the following parameters: accuracy, surface roughness, complex surface quality (integrity), material removal rate, costs and productivity of the process. In this paper the surface roughness, the Arithmetical mean deviation of the profile (\( R_a \)) is examined. After the experiment we analysed the surface roughness of the drilled holes. The surface roughness of the holes was measured by the TalySurf520 3D surface measurement system.
roughness measuring equipment (Fig. 3), we examined the 2D roughness parameters (Ra, Rz, Rt) when the measuring length was set to 12.5 mm.

The roughness was measured with a CL2 white light confocal chromatic displacement sensor (CCS) and a probe with a magnifying glass MG140. When using the AltiSurf 520, the measurement parameters are set in the Phenix V2 measuring software running on the computer. Here we selected the type of measurement (profile or surface), then we set the measurement parameters: measurement position, measured profile or surface dimensions, resolution, sensor selection and settings, data file name and other data. Our measurement was profile measurement.

![Image](image.jpg)

**Figure 3.** Measurement of surface roughness on AltiSurf 520 type measuring equipment

The holes having different lengths were measured times. Figure 4 shows the places of surface roughness measurements of the different holes.

| 01 | 01 | 01 |
|----|----|----|
| ![Image](image1.jpg) | ![Image](image2.jpg) | ![Image](image3.jpg) |

| L/D = 1 | L/D = 2.5 | L/D = 5 |
|---------|-----------|---------|
| 12.5    | 12.5      | 12.5    |
| 2       | 2         | 2       |

**Figure 4.** Measuring places of surface roughness of the different holes

After cutting the drilled work-pieces into two parts, the roughness was measured on both sides of the holes and the averaged was calculated. In addition, 2 holes were made with the same technological parameter variants and the average was calculated too.

### 3. Results of experiments of conventional and cryogenic drilling technology

#### 3.1. Examination of the surface roughness

After creating measuring the surface roughness of the holes on different places according to Figure 4 the evaluation could be done. To make it properly the measured data are organised into Table 2. It contains the technological parameters (cutting speed, feed rate, temperature) applied when executing the experiments. Featuring characteristics of the Table 2 are the measuring places (can be 1, 2 or 3) and the type of the hole (L/D = 1, L/D = 2.5, and L/D = 5). When the hole was short (L/D = 1) than there are 2 zeros in the table, because there was surface roughness measurement only one place. This can be seen on the other places as well.
### Table 2. Measured values of the Ra

| No. | Cutting speed \(v_c\) \([\text{m}/\text{min}]\) | Feed rate \(f\) \([\text{mm}/\text{rev}]\) | Temp. \(T\) \([\degree\text{C}]\) | Measuring place | \(L/D = 1\) | \(L/D = 2.5\) | \(L/D = 5\) |
|-----|-----------------|-----------------|-----------------|-----------------|--------|--------|--------|
| 1   | 6.78            | 0.32            | -35             | 01              | 5.1178 | 3.6075 | 3.3110 |
|     |                 |                 |                 | 02              | 0      | 3.1690 | 3.0285 |
|     |                 |                 |                 | 03              | 0      | 0      | 3.0272 |
| 2   | 18.85           | 0.32            | -35             | 01              | 4.7049 | 3.2111 | 4.0046 |
|     |                 |                 |                 | 02              | 0      | 2.9395 | 3.6853 |
|     |                 |                 |                 | 03              | 0      | 0      | 3.7515 |
| 3   | 6.78            | 0.62            | -35             | 01              | 3.0559 | 4.6259 | 4.9782 |
|     |                 |                 |                 | 02              | 0      | 5.2961 | 4.6710 |
|     |                 |                 |                 | 03              | 0      | 0      | 4.4323 |
| 4   | 18.85           | 0.62            | -35             | 01              | 3.9561 | 3.7175 | 4.5925 |
|     |                 |                 |                 | 02              | 0      | 3.9801 | 4.6896 |
|     |                 |                 |                 | 03              | 0      | 0      | 4.6177 |
| 5   | 6.78            | 0.32            | 20              | 01              | 6.4884 | 7.1530 | 5.7206 |
|     |                 |                 |                 | 02              | 0      | 6.9983 | 4.4424 |
|     |                 |                 |                 | 03              | 0      | 0      | 4.2652 |
| 6   | 18.85           | 0.32            | 20              | 01              | 8.1934 | 7.8114 | 4.8942 |
|     |                 |                 |                 | 02              | 0      | 7.4200 | 3.9610 |
|     |                 |                 |                 | 03              | 0      | 0      | 3.9929 |
| 7   | 6.78            | 0.62            | 20              | 01              | 5.5749 | 4.4706 | 6.3571 |
|     |                 |                 |                 | 02              | 0      | 3.8248 | 5.8988 |
|     |                 |                 |                 | 03              | 0      | 0      | 5.9632 |
| 8   | 18.85           | 0.62            | 20              | 01              | 4.9095 | 5.3008 | 6.9399 |
|     |                 |                 |                 | 02              | 0      | 4.4423 | 6.5988 |
|     |                 |                 |                 | 03              | 0      | 0      | 5.5185 |

Featuring profiles can be seen in Figure 5 for the case of short holes, that is when \(\frac{L}{D} = 1\). In Figure 5 it the differences can be compared in between drilling with \(T_1= -35\degree\text{C}\) and \(T_2= +20\degree\text{C}\). The amplitudes are greater at drilling in room temperatures.

#### 3.2. Evaluation of the measured values

The measured values of Table 2 can be demonstrated in stereoscopic square column diagrams. Figure 6 shows the differences of drilling in different temperatures. Figure 6 contains the measuring results belonging to the different \(L/D\) ratios, on the different measuring places (1, 2 or 3) on the base of the different technological parameter variation (Table 2). When the temperature is cooler \((T_1=-35\degree\text{C})\) the values of Ra roughness parameter is lower, so better. To give more precious values, it is suggested to calculate the average values of the Ra roughness parameters along the axis of the holes. These average values can be found in Table 3 where the transformed values of the technological parameters are shown as well. They are used when the application of Factorial Experimental Design \([21-22]\).
Machining temperature $T_1=-35^\circ C$  
Machining temperature $T_2=+20^\circ C$

**Figure 5.** Comparing of 2D profile of the work-piece when (L/D=1)

Machining temperature $T_1=-35^\circ C$  
Machining temperature $T_2=+20^\circ C$

**Figure 6.** Comparing of Arithmetical mean deviation (Ra) of the profiles drilled in different temperatures
Table 3. Averages of the measured values of Ra

| No. | X₁ | X₂ | X₃ | \( \frac{L}{D} = 1 \) | \( \frac{L}{D} = 2.5 \) | \( \frac{L}{D} = 5 \) |
|-----|----|----|----|-----------------|-----------------|-----------------|
| 1   | -1 | -1 | -1 | 5.1178          | 3.3759          | 3.1447          |
| 2   | +1 | -1 | -1 | 3.0559          | 4.9610          | 4.6243          |
| 3   | -1 | +1 | -1 | 4.7049          | 3.0753          | 3.9404          |
| 4   | +1 | +1 | -1 | 3.9650          | 3.8488          | 4.4531          |
| 5   | -1 | -1 | +1 | 6.4884          | 7.0750          | 4.8090          |
| 6   | +1 | -1 | +1 | 5.5749          | 4.1477          | 5.0200          |
| 7   | -1 | +1 | +1 | 8.1934          | 7.6158          | 4.2800          |
| 8   | +1 | +1 | +1 | 4.9095          | 4.8715          | 6.3500          |

Using the method of Factorial Experiment Design and the software written in „Mathcad 15.0” empirical formulas (1)-(3) were determined from the average values can be seen in Table 3.

\[
Ra_{L=1} = 5.1247 - 0.019v_c + 5.041f - 0.068T - 0.284v_c \cdot f + 7.663 \cdot 10^{-3} \cdot v_c \cdot T + 0.254f \cdot T - 0.019v_c \cdot f \cdot T \tag{1}
\]

\[
Ra_{L=2.5} = 6.0949 - 0.091v_c + 1.117f + 0.108T - 0.049v_c \cdot f - 8.396 \cdot 10^{-3} \cdot v_c \cdot T + 0.017f \cdot T + 4.994 \cdot 10^{-3} \cdot v_c \cdot f \cdot T \tag{2}
\]

\[
Ra_{L=5} = 4.3747 - 0.018v_c - 1.714f + 0.17f + 0.23v_c \cdot f - 6.452 \cdot 10^{-3} \cdot v_c \cdot T - 0.176f \cdot T + 0.014v_c \cdot f \cdot T \tag{3}
\]

Substituting the values of the factors into formulas (1)-(3) surfaces can be determined and axonometric figures can be drawn. When using formula (1) the result regarding to L/D=1 can be get and its axonometric figure is shown in Figure 7.

![Figure 7. Changing the Arithmetical mean deviation (Ra) of the profile when L/D=1](image-url)
After substitution into formula (2) Figure 8 relates to $L/D=2.5$ and Figure 9 belongs to formula (3) when $L/D=5$.

![Figure 8](image_url)

**Figure 8.** Changing the Arithmetical mean deviation (Ra) of the profile when $L/D=2.5$

![Figure 9](image_url)

**Figure 9.** Changing the Arithmetical mean deviation (Ra) of the profile when $L/D=5$

### 4. Summary

Based on the analysis of the results of surface roughness tests, it can be stated:

- In case of cryogenic cooling, when $L/D=1$ and $L/D=5$, the values of the Arithmetical mean deviations of the profile (Ra) were lower for each cutting speed and feed rate variations.

- When the hole belonging to $L/D=1$ ratio was drilled, the best parameter combinations were: $v_c=18.85$ m/min; $f=0.32$ mm/rev; and $T_i=-35^\circ C$. In case of $L/D=2.5$ the best parameter combinations are: $v_c=6.78$ m/min; $f=0.62$ mm/rev; and $T_i=-35^\circ C$, and for $L/D=5$ these parameter combinations: $v_c=6.78$ m/min; $f=0.32$ mm/rev; and $T_i=-35^\circ C$. 


Although in the case of L/D=2.5 also the hole drilled on cryogenic way served the best surface roughness, but it is interesting to note that, when using high cutting speed (v_c=18.85 m/min) and low feed rates (f_l=0.32 mm/rev) is used, almost identical surface roughness was obtained for both temperatures. It requires further investigation to determine its reason.

In case of applying cryogenic cooling the Arithmetical mean deviation (Ra) of the profile is increasing when increasing the L/D ratio. This trend can be noticed drilling in room temperature as well.

Acknowledgments
“Project no. NKFI-125117 has been implemented with the support provided from the National Research, Development and Innovation Fund of Hungary, financed under the K_17 funding scheme.”

“The described study was carried out as part of the EFOP-3.6.1-16-00011 “Younger and Renewing University – Innovative Knowledge City – institutional development of the University of Miskolc aiming at intelligent specialisation” project implemented in the framework of the Széchenyi 2020 program. The realization of this project is supported by the European Union, co-financed by the European Social Fund.”

References
[1] Yildiz Y, Nalbant M 2008 A review of cryogenic cooling in machining processes, vol 48 (3) International Journal of Machine Tools & Manufacture pp 947-964
[2] Kaynak Y, Lu T, Jawahir I S 2014 Cryogenic machining-induced surface integrity: a review and comparison with dry, MQL, and flood-cooled machining Vol. 18 (2) Machining Science and Technology pp. 149–98.
[3] Jawahir I S, Attia H, Biermann D, Duflo J, Klocke F, Meyer D, et al. 2016 Cryogenic manufacturing processes vol 65 (2) CIRP Annals - Manufacturing Technology pp 713–736.
[4] Evans C 1991 Cryogenic diamond turning of stainless steel vol 40 (1) CIRP Annals pp 571-575
[5] Bagherzadeh A, Budak E 2018 Investigation of machinability in turning of difficult-to-cut materials using a new cryogenic cooling approach Vol 119 Tribology International pp 510–520
[6] Jerold B D, Kumar M P 2012 Experimental comparison of carbon-dioxide and liquid nitrogen cryogenic coolants in turning of AISI 1045 steel Vol 52 (10) Cryogenics pp 569–574
[7] Wang Z Y, Rajurkar K P 2000 Cryogenic machining of hard-to-cut materials Vol 239 (2) Wear pp 168–175.
[8] Paul S, Chattopadhyay A B 2006 Environmentally conscious machining and grinding with cryogenic with cryogenic cooling Vol 10 Machining Science and Technology pp 87-131
[9] Chattopadhyay A B, Bose A, Chattopadhyay A K 1985 Improvements in grinding steels by cryogenic cooling Vol 7 (2) Precision Engineering pp 93–98.
[10] Paul S, Chattopadhyay A B 1996 The effect of cryogenic cooling on grinding forces Vol 36 (1) International Journal of Machine Tools and Manufacture pp 63–72
[11] Ahmed L S, Kumar M P 2016 Cryogenic Drilling of Ti–6Al–4V Alloy Under Liquid Nitrogen Cooling Materials and Manufacturing Processes vol 31 pp 951–959
[12] Liska J, Kodacsy J 2012 Drilling of glass fibre reinforced plastic vol 472-475 Advanced Materials Research pp 958-961.
[13] Yu S, Ning H, Liang L, Xinlong L, Wei Z 2006 Effects of cryogenic nitrogen gas jet on machinability of Ti-alloy in high speed milling vol 17 (11) China Mechanical Engineering pp 1183-1187
[14] Fillipi A D, Ippolite R 1971 Facing milling at -180°C vol 19 (1) Annals of CIRP pp 399–406
[15] Chatterjee S 1992 Performance characteristics of cryogenically treated high speed steel drills vol 30 (4) International Journal of Production Research pp 773-786
[16] Kim D, Ramulu M 2004 Cryogenically treated carbide tool performance in drilling thermoplastic composites vol 32 Transactions of the North American Manufacturing Research Institute pp 79-85
[17] Pušavec F, Kopač J 2011 Sustainability Assessment: Cryogenic Machining of Inconel 718 vol 57 (9) Journal of Mechanical Engineering pp 637-647
[18] Aldwella B, O’Mahonyb J, O’Donnellag E 2014 The effect of workpiece cooling on the machining of biomedical grade polymers vol 33 Procedia CIRP pp 305-310
[19] Akinuma Y, Kidani S, Aoyama T 2012 Ultra-precision cryogenic machining of viscoelastic polymers Vol 61 (1) CIRP Annals - Manufacturing Technology pp 79-82
[20] Szabó O 2014 Goodness indicator and technological optimization of honing, Key Engineering Materials, vol 581 pp 261-265
[21] Taguchi G 1987 System of experiment design (New York) UNIPUB Kraus International Publications
[22] Fridrik L 1987 Chosen chapters from the topics of experimental design of production engineering (Budapest) Műszaki Könyvkiadó (in Hungarian)