Analysis of the polymeric abrasive paste regeneration for abrasive flow machining

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Abstract: The influence of conditions and the sifting process efficiency of the worn-out polymeric abrasive paste containing silica (SiO_2) and polymer chips remaining after the surface treatment were investigated. The abrasive paste regeneration process consisted of sifting the used paste through sieves of a vibrating screen, on which abrasive grains and polymer chips were recovered. The diameter of the sieve holes determined the size of the recovered abrasive grains and polymer chips, on the size of which the efficiency of the process depended. The lowest efficiency of the sifting process was obtained using a sieve with the holes diameter equal to the diameter of the grain and the polymer chips of the given fraction. The highest efficiency of the sifting process was obtained for a sieve with a diameter of 0.032 mm. The regenerated polymeric abrasive paste can be reused in the process of abrasive flow machining.

Keywords: polymeric abrasive paste, abrasive flow machining, efficiency of sifting, processing of polymer surfaces.

Analiza regeneracji polimerowych past ściernych do obróbki przetłoczono--ściernej

Streszczenie: Zbadano wpływ warunków i wydajność procesu przesiewania zużytej polimerowej pasty ściernej zawierającej krzemionkę (SiO_2) i pozostałe po obróbce powierzchni wióry polimerowe. Proces regeneracji pasty ściernej polegał na przesianiu zużytej pasty przez sita przesiewacza wibracyjnego, na których odzyskiwano ziarna ścierne i wióry polimerowe. Średnica otworów sita determinowała wielkość odzyskanych ziaren ściernych i wiórów polimerowych, od których wielkości zależała wydajność procesu. Najmniejszą wydajność procesu przesiewania uzyskano stosując sito o średnicy otworów równej średnicy ziarna oraz wiórów polimerowych danej frakcji, a największą sito o średnicy 0,032 mm. Zregenerowaną polimerową pastę ścierną można ponownie wykorzystać w procesie obróbki przetłoczono – ściernej.

Słowa kluczowe: polimerowe pasty ścierne, obróbka przetłoczno-ścierna, wydajność przesiewania, obróbka powierzchni polimerowych.

Polymeric materials are widely used in various fields of technology. More and more often they replace traditional construction materials used in the production of machines and mechanisms elements or are used as functional materials for abrasive flow machining [1, 2]. Therefore, the authors developed an effective finishing technique that improves the surface roughness of polymer products [3-5].

Abrasive flow machining (AFM) is an advanced finishing process used for deburring, polishing, or radiusing of edges and interior surfaces of hard-to-reach workpiece geometries in which special viscoelastic abrasives are used [6]. One of the first studies of this advanced machining process was done by Rhoades [7, 8]. He explained the rules of the process in detail. Two opposing cylinders are used that clamp the workpiece between each other and seal the machining passage (Fig. 1). Hydraulically operated pistons inside the cylinders repeatedly press the abrasive medium back and forth through or across the workpiece to finish (see Fig. 1). One up and down piston movement corresponds to the duty cycle [9–11].

Wang *et al.* [12, 13] generally described the process as well as the abrasive paste used in it. The semi-solid abrasive paste consists of abrasive particles up to a content of 5–60 vol. %. and a polymeric carrier [10–13]. The viscosity of the abrasive paste is adjusted by adding oil and other additives. An alternative to the average paste with a high market price are polymeric materials that can provide the viscoelastic properties of the paste [5, 12].

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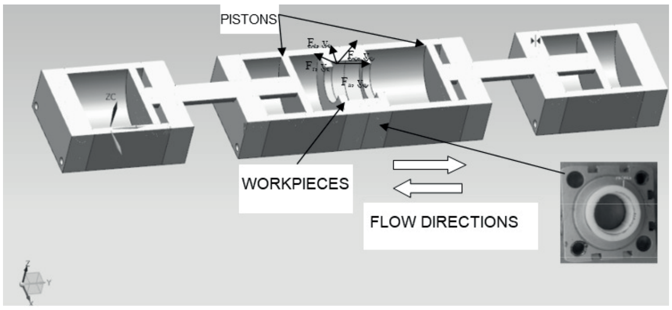

Fig. 1. The essence of abrasive flow machining consisting in forcing the abrasive paste through the workpiece; F_a – the force with which the paste moves through the piston, F_r – the axial force from the viscoelastic paste, F_t – the perpendicular force from the viscoelastic paste F_c – the total force of the abrasive grain interaction on the treated surface [3]

The most commonly used abrasives are silicon carbide, aluminum oxide or boron carbide [4, 13, 14]. Roughness or burrs are removed by alternating movement of the abrasive suspension along the surface and edge of the workpiece [15, 16]. Abrasive paste wears when used in finishing processes where polymers do not assist in material removal. However, the used paste can be recovered in the sifting process [17, 18]. After recovering, the carrier abrasive transfers pressure from the pistons to the abrasive particles [19–21]. The previously reworked abrasive absorbs the abraded material of the workpiece and transports it away from the place of its removal [22–24]. Consistent process efficiency and quality are ensured by invariable input parameters. However, the properties of the abrasive medium change under the influence of wear in the machining process [25]. In current studies, these changes in abrasive properties have not been systematically investigated or documented, except in our previous research [3].

This article presents an original method of selecting appropriate conditions for the sifting for worn-out abrasive polymer used for abrasive flow machining. The effectiveness of the abrasive grain sifting process of the applied abrasives (for 480 h) for different sieve sizes was characterized and compared. The characteristics that generally affect the efficiency of the abrasive grain sifting process, such as the behavior, size and composition of the abrasive particles, were also quantified. Moreover, the efficiency of the sifting process and individual sieves (w_0), depending on the grain diameter as well as the sifting efficiency of grain and chips through the holes of these sieves (W_i), were calculated. The entire process of sifting abrasives was tested under the same conditions on workpieces with the same initial surface quality.

EXPERIMENTAL PART

Materials

A commercially available diamond was used (NOTA Ltd. with 15 wt %) and SiO_2 (Góradże Ltd. with 15 wt %) as an abrasive a mixture of polymethylhydroborosiloxane (SiO_2) (85% by weight) with chips of the processed work- pieces material according to our own developed procedure. Abrasive grains were added in small portions to the polymer and then kneaded to obtain an even distribution of the abrasive grains in the paste. The abrasive grain was determined due to mesh scope (Tab. 1).

Complex geometries such as fluted inner surfaces have been processed for the purpose to study the mechanism of material removal and surface formation on polymeric materials.

The workpieces were made of acrylonitrile butadiene styrene copolymer (ABS), trade name ABS Extrafill Traffic White, producer 3D Jake. The number of workpieces (M) was determined so that the radius of the grain tip rounding differed between the diamond and the SiO_2 abrasive. The tip radius depended on the grain tip angle. The smaller the angle (γ), the greater the amount of workpieces material. The abrasive grain radius is smaller in diamond than in SiO_2 [19, 27]. Diamond grain (M_d) < SiO_2 grain (M_s).

T a b l e 1. Characteristics of abrasive grain scope

Abrasive grain material	Mesh scope	Average grain diameter, μm
Diamond	280	25–32
SiO_2	220	32–53
SiO_2	150	53–106
Diamond/SiO_2	70	106–212
Diamond/SiO_2	40	212–425
Diamond/SiO_2	24	425–850
Diamond	16	850–1400

Sifting process description

The process was carried out using vibrating screen. The screen structure is column-shaped. The type of drive used allows the vertical vibrations elimination of the screen, when correctly set. On the metal base of the screen, a column of 400 mm diameter circular screens sieves supported on springs was mounted. The column assembles from segments between which sieves and devices for cleaning them are placed. The chutes discharge the material from the screens to the discharge nozzles and then to the fraction collectors. On the base rests the first lower segment with a conical funnel. The column is covered with a flat cover with nozzles for feeding grain and removing dust. The station of the sifter is shown in Fig. 2. Circular screens, embedded in profiled frames, were used to test the sifting efficiency of the abrasive paste successive fractions (polymer + abrasive grain + processed material filings) through the holes in the sieve. The characteristics of the sheet metal sieves are presented in Table 2. The grains were divided according to their diameter into individual fractions: 0.025–0.035; 0.035–0.053; 0.053–0.106; 0.106–0.212; 0.212–0.425; 0.425–0.850 mm.

T a b l e 2. Characteristics of sieves with circular holes

Sieve hole diameter mm	Mesh scope	Sieve holes area mm^2	Sieve clearance %	Sieve quantity pcs
0.025	498	38447	26	48289432
0.032	403	25195	27	31644920
0.053	299	13841	35	17384296
0.106	156	3764	38	4727584
0.212	79	977	39	1227112
0.425	39	237	38	297672
0.850	22	76	48	95456
1.400	15	33	57	41448

Fig. 2. Multi-level screen for abrasive grain with side vibrators station

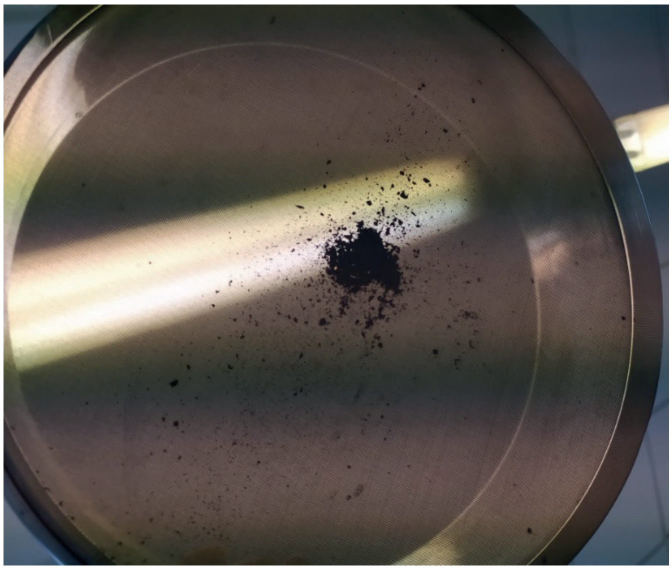

Fig. 3. View of the abrasive grain on a sieve with holes diameter of 0.212 mm

The sifting process was carried out as follows. 1 kg of used abrasive paste was loaded into the screen, which contained diamond grains and polymer chips with the fraction of 280–24 Mesh (sieve-diamond) or SiO_2 grains and polymer chips with the fraction of 220-24 Mesh (sieve-SiO_2), and after time τ the apparatus was stopped and the individual fractions passed through the sieve were weighed. The view of the abrasive grain on a sieve with a hole diameter of 0.212 mm is presented in Fig. 3.

RESULTS AND DISCUSSION

The number of grains that pass through the sieve, for the given time was measured. The sifting efficiency for the individual sieves was calculated as follows (Eqs. 1–6):

Sifting efficiency:

$$W_i = \frac{m_n}{\tau_p} \quad (1)$$

Calibrator surface:

$$F = \frac{\pi \cdot D^2}{4} \quad (2)$$

Mesh sieve:

$$F_{i,o} = p_i \cdot \frac{\pi \cdot D^2}{4} \quad (3)$$

Efficiency of sieving through the individual mesh sieve:

$$w_{i,o} = W_i \cdot p_i \quad (4)$$

Mass flow velocity:

$$G_i = \frac{w_i}{F} \quad (5)$$

Mass flow velocity through the mesh sieve

$$g_{i,o} = G_i \cdot p_i \quad (6)$$

The discharge of granular material through the mesh sieve from the tank is described by the relationship (Eq. 7):

$$W_i = f_i \cdot u = n \cdot \frac{\pi \cdot d_o^2}{4} \varphi \sqrt{a \cdot g \cdot d_o} = A \cdot d_o^{2.5} \quad (7)$$

and it is analogous to the equations obtained as a result of the research, describing the passage of the spent paste through the mesh sieve [28-32].

Where:

W_i – sifting efficiency, kg/h

w_0 – individual mesh sifting efficiency, kg/h

m_n – the mass of grains passed through the next sieve, kg

$m_n = M_{p(d\_s)} - m_m$

M_p – mass of abrasive paste, kg

m_n – mass of abrasive grain and polymer chips, kg

τ_p – time needed for the grains to pass through the sieve, h

D – calibrator diameter, m

p – mesh sieve clearance, %

f_i – surface discharge, m²

$u = \varphi\sqrt{a \cdot g \cdot d_o}$ – mesh linear velocity for the discharge of the granular material from the hopper, m/s

n – quantity of mesh sieves, $n = 1,2,3,\ldots$

A, a – constant,

φ – coefficient discharge,

g – coefficient gravity, m/s²

The equations describing the passage of polymer grains and chips through the sieves depending on the fraction diameter are presented in Tables 3 and 4. As shown in Fig. 4, the apparent sifting efficiency increased as the grain size decreased. The maximum efficiency (319 kg/h) was achieved for a sieve with a mesh sieve of 0.85 μm and a grain size of 32 μm, with the greatest grain size reduction from 1400 to 10 μm.

It is clear from Fig. 5 that the efficiency of performance increased with a reduction in the size of the sieves holes. Moreover, for a given sieve holes diameter, the sifting efficiency of the grains, grains and polymer chips fractions through a single sieve is bigger than that of the entire process.

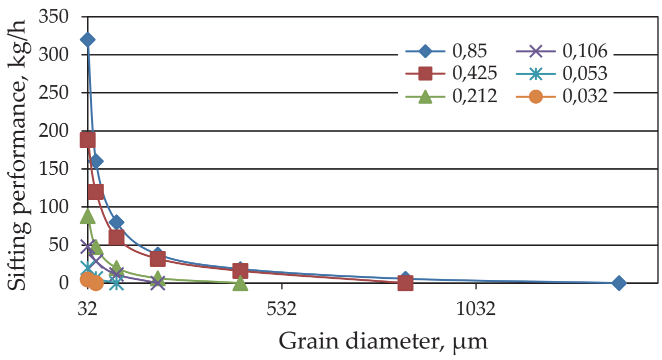

Fig. 4. Sifting efficiency of grain through individual sieve depending on the average diameter of abrasive grain

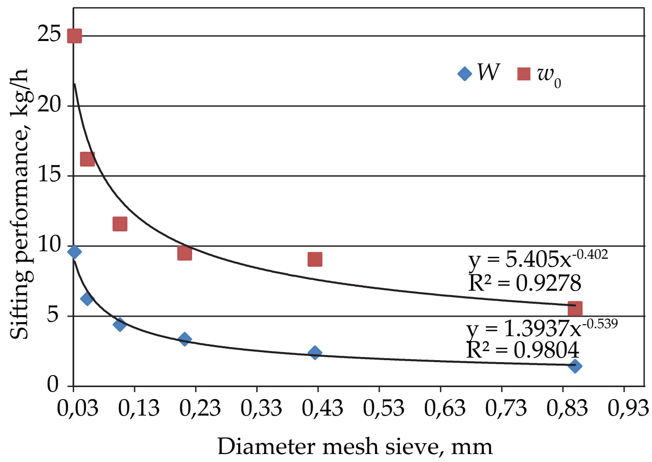

Fig. 5. Sifting efficiency of grain through the smallest sieve for the given fraction depending on the diameter of sieve holes

Table 3. Regression equations of sifting efficiency for individual sieves, depending on the diameter of the fraction of grains for the angle of setting of sieve position angle amounting to 42.5°

Mesh sieve diameter, mm	Regression equations	Coefficient of correlation
0.850	$y = 13.743x^2 - 157.46x + 443{,}77$	0.9764
0.425	$y = 7.7857x^2 - 91.071x + 270$	0.9956
0.212	$y = 5.8857x^2 - 56.994x + 138.56$	0.9991
0.106	$y = 2x^2 - 26.16x + 72.4$	0.9993
0.053	$y = 3.6x^2 - 24.4x + 40.8$	0.9995
0.032	$y = -4.8x + 9.6$	0.9999

Table 4. Sifting efficiency of grain through the smallest sieve for the given fraction

M_d, mm	p, %	F, m²	F_0, m²	W, kg/h	w_0, kg/h	G, kg/m²h	g_0, kg/m²h
0.85	25.9	0.126	0.033	1.44	5.56	11.46	44.27
0.425	26.5	0.126	0.033	2.40	9.06	19.11	72.11
0.212	35.4	0.126	0.044	3.36	9.49	26.75	75.57
0.106	38.0	0.126	0.048	4.40	11.58	35.03	92.19
0.053	38.5	0.126	0.048	6.24	16.21	49.68	129.04
0.032	38.4	0.126	0.048	9.60	25.00	76.43	199.04

CONCLUSION

It has been shown that spent polymeric abrasive paste can be successfully regenerated by sifting through vibrating screens using specific process parameters and reused in the abrasive flow machining. The sifting efficiency of individual sieves depends on the size of abrasive grains and polymer chips as well as the characteristics of the sieve used, which is described by the regression presented in Table 3. The lowest efficiency of the sifting process was obtained using a sieve with the diameter of the holes equal to the diameter of the grain and the polymer chips of the given fraction.

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