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Effect of Mechanical Tumbling Parameters on Surface Roughness and Edge Radius of Medical Grade Cobalt Chromium Alloy

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***Abstract*— Smoothly polished prosthesis surface is a crucial requirement in medical application and important feature that determine the proper response to corrosion and biocompatibility in the human body. Tumbling is one of the pre-polishing processes that can be conducted in order to improve the surface roughness of the machined prosthesis. However, the using of ceramic media for the tumbling process in medical application is not widely reported. This study was conducted to investigate the effect of mechanical tumbling parameters on the surface roughness of medical grade CoCr alloy by using alumina (Al2O3) based ceramic media. The experiment was performed with a different level of rotational speed (35, 55, and 75 rpm) and soaking time (4, 6 and 8 hours) of the tumbling process. The surface roughness of specimens before and after the process was measured using Mitutoyo Formtracer CS-5000 and the edge radius was measured using Olympus SZX9 microscope integrated with I-solution Lite software. It was figured that 6 hours tumbling time at 55 rpm showed the most significant reduction (32 %) in surface roughness (Ra) of the CoCr alloy specimen, while 8 hours tumbling time at 75 rpm showed the highest effect on the edge radius of the specimen at 63 % increment.**

***Keywords*— CoCr alloys; medical application; mechanical tumbling; surface finish.**

I. INTRODUCTION

Artificial bones, known as a prosthesis, is commonly made of polymer, composite ceramic and metal [1]. Surface roughness properties play an important role in the fabrication of prosthesis as the materials need excellent tolerate contact with the bones and tissues in the body [2]. The improper surface roughness of the prosthesis may find difficulties in joint with adjacent bones and other tissues, which will cause the loosening of the implant [3]. On the other hand, the rough surface also will contribute to high wear rate and corrosion, where the ion release from these processes may go to the surrounding tissue and cause allergic and problematic symptoms [4]. Thus, it is essential that these prostheses need to undergo the proper surface finishing process so that the desired surface finish can be achieved based on the clinical standard [5]. Key factors for the prosthesis or biomaterials is to have low wear, low friction, and smooth surface and perfect clearance [6]. Nowadays, cobalt chromium (CoCr) alloys were used in such applications as hip and knee prosthesis due to its excellent properties instead of biocompatibility material.

Numerous research has been done in some modification in implant surface to improve their incorporation in bone tissue [7]. Different parameters of surface roughness varies depend on several medical requirements including bio-tolerance and ability to perform a better combination for the artificial joints application [8].

Tumble finishing or other terms which known as tumbling or rumbling [9] is a method for smooth out and polishing a rough or irregular surface on relatively small work parts. In the metalworking field, burr and a sharp edge are common remaining by-product after machining operation [10]. Metal tumbling is widely used in industry to burnish, deburring, cleaning, radius adjustment, de-flash, descale, eliminating rust, polishing, brightening, surface hardening, prepare parts for further finishing, and separating die cast runners [11].

Tumbling operation consists of loading a charge composed by the components to be finished, media, water, and compound within a rotating barrel. A horizontal of a multi-dimensional barrel is occupied with the parts which are then rotated which represent the tumbling process. The rotation transmits to the granular material a shear force able to carry up the charge until a critical state is reached: at this stage, a portion of the material, previously involved in a solid motion, collapses in an avalanche flow namely active layer. This way some phenomena can occur. These phenomena depend upon several aspects such as the physical and geometrical properties of the granular elements, the shape and the typology of the barrel and the process parameters. Different granular flows can be observed when one of these aspects changes.

Tumbling media which have cutting ability can get rid of burrs and can smoother work part surfaces [11]. The impact force of the abrasive on the work part rises as the larger media pieces presence. Thus the effectiveness of the abrasive can improve the work part surface to be more shine. A very important function of the medium is to separate parts during the debarring, cutting, surface improving or burnishing operations. The media parts volume ratio is normally used to control the amount of part-on-part contact which will occur in a vibratory or tumble finishing operation. At low ratios, considerable part-on-part contact occurs, while at higher ratios part-on-part contact is limited. Media has the unique ability to scrub surfaces and physically assist compounds in their cleaning function [11]. Both abrasive and non-abrasive media are effective in this. They can remove organic soils, scale, and other inorganic residues. Fig. 1, 2, and 3 shows the type of media.


Fig. 1 Aluminium Oxide Media


Fig. 2 Ceramic Media


Fig. 3 Silicon Carbide Media

One of the most important properties necessary in tumbling media is hardness [12]. The media must be harder than the material it is to grind, polish, or remove. From Table 1, the aluminum oxide-based ceramic media shows that the higher value of hardness properties compared to media of plastic. Based on the hardness properties, the selection of aluminum oxide-based ceramic media for the tumbling finishing process is rational for the surface roughness reduction of CoCrMo.

TABLE I
PROPERTIES COMPARISON BETWEEN PLASTIC MEDIA AND ALUMINIUM OXIDE BASED CERAMIC MEDIA

Mechanical Properties	Plastic Media	Aluminum Oxide based Ceramic Media
Density, gm/cc	2.6	3.89
Compressive Strength, Mpa	1200	2600
Hardness, Kg/mm^2	1019	1440
Maximum Use Temperature, ^{0}C	650	1750

In the tumbling process, bath solutions are also added to mass finishing processes to prevent scratched and black on sample surface from embedded abrasives. The solutions are usually broken up into four types which are deburring and finishing, burnishing, cleaning, and water is stabilizing [13]. Deburring and finishing compounds are mainly designed to suspend the small particles created when deburring and abrading parts. They are also designed to keep workpieces clean and inhibit corrosion. Burnishing compounds are designed to enhance brightness and to develop certain colors after mass finishing. Cleaning compounds are usually dilute acids or soaps designed to remove soil, grease, or oil from the incoming parts. They also provide corrosion resistance for ferrous and nonferrous parts. Water stabilizer is used in conjunction with water to maintain a consistent water hardness and level of metal ions. When combined with compounds, the water not only carries the abrasives and keeps the media clean, but also acts as a cushion to help protect the parts [14].

Tumbling finishing provide a deburring process which used to deburr, clean, radius, polish, brighten and prepare parts for further finishing. Burrs are undesired projections of material beyond the edges of the workpiece due to plastic deformation during machining. Burrs of excessive size often must be removed for the part to be handled safely, assembled, or function effectively. Besides that, the tumbling process deburrs an estimated 30-50% of all hand size and smaller metal piece parts [15]. The agitated tumbling barrel causes the solution to circulate and lubricate the media in a smooth tumbling action. Burrs are slowly abraded away. Usually, different shapes are used in the same load to reach into every geometry of the part [16].

The rotational speed of the barrel will produce a centrifugal force that acts on the components in the barrel which clinging them on the barrel's wall. At some point, the components bump and starting collide with each other. This movement will create a polishing process on the workpieces [17]. The changes in these variables produced a different value of surface roughness. Several investigations have been studied on the characterization of the rotating tumbling motions.

Henein et al. [18] developed a tool, called the bed behavior diagram, allowing navigating the map of the possible granular motions as a function of the filling percentage and the rotational speed. The bed behavior strictly depends upon the particular charge and the employed barrel. Boateng [19] attempted the identification of the kinematics: the change in velocity profiles deeply modifies flow behavior from pseudoplastic to Newtonian to dilatant types. Boschetto and Veniali [20] found the relationship between granular material density, responsible of the dilatancy, and the velocity gradient within the active region: in this work the rolling and the cascading regime are considered as the most suitable for tumble polishing. Mellmann [21] analyzed and modeled the transition behaviors in a simplified way highlighting that in correspondence of rolling–cascading transition no mathematical model is known. Some experimental investigations have been carried out to empirically observe the kinematics of the rotating cylinder adopting different measuring techniques. Pérez-Alonso and Delgadillo [22] used digital image processing to validate 2DDEM code: simulation of ideal spheres are very close to experimental values. Nakagawa [23] employed noninvasive nuclear magnetic resonance imaging to determine axial segregation of particles within rotating cylinders. Bbosa et al. [24] reconstructed the motion of mono-sized glass balls within a small tumbling mill: experiments were undertaken using the positron emission particle tracking. Domblesky et al. [25] and Hashimoto et al. [26] presented force-based models of workpiece-media contact to predict material removal rates. Potentially powerful Discrete Element Methods (DEM), which model media particles as discrete entities and tracks their interactions with the workpiece, are being pursued by Uhlmann et al. [27] and Spelt's research group [28]. While the DEM approach is computationally expensive and reliant on difficult to obtain material properties when fully realized, it has the potential to predict media-workpiece impact modes, forces, and frequencies, thus providing insights on material removal mechanisms and expected finishes.

It is proved that tumbling can improve the surface finish of the product significantly [29]. However, these processes have not received the same level of scientific scrutiny as other material removal processes and thus remain in need of comprehensive, predictive, and systematic modeling investigations. In this paper, the effect of mechanical tumbling on the surface roughness of CoCr alloy were reported.

II. Material and Method

For research is used an ASTM F75 CoCr alloy solid cut into the rectangular with the tapered angle. Table 2 summarizes the composition of CoCr alloy.

TABLE II
The Composition of Coco Alloy in Weight Percent

Ni	N	Co	Cr	Ti	Mo
< 0.5	< 0.25	57.4 - 65.0	27.0 - 30.0	< 0.1	5.0 -7.0
Al	**Fe**	**Mn**	**W**	**C**	**Si**
< 0.1	< 0.75	< 1.0	< 0.2	< 0.35	< 1.0

The machining process that involved in this study was tumbling machining which provides polishing, cleaning, burnishing and deburring toward the surface of medical grade CoCr alloy. CoCr alloy specimens were cut by using Wire Electrical Discharge Machining (EDM Wire Cut). These specimens were ground by using Bainpol-VTD grinder in order to remove the oxidation layer from the specimen. Then the specimens were cleaned before undergo tumbling process. The dimension of the CoCr alloy specimen is shown in Fig. 4.

Fig. 4 The dimension of CoCr alloy specimen

The manipulated variables in this experiment were speed and time taken for the tumbling process, which was determined based on the literature. The tumbling barrel was filled with CoCr alloy specimens, Al_2O_3 based ceramic media, and sodium hydroxide solution. The rotational speed of the tumbler machine was controlled at 35 rpm, 55 rpm and 75 rpm which gives the three-speed variation for this experiment. The speed was adjusted by the connected inverter that can variate the motor speed of the tumbling machine. Running time were set at three variations; 4 hours, 6 hours, and 8 hours.

Aluminum based ceramic media was used for this tumbling process, and it is fixed for every run of the experiment. These media were filled for half full of the 3-litre barrel volume. There were two different cutting type of ceramic media used, which are angle cut and straight cut as shown in Fig. 5 and Fig. 6 respectively. The 100ml of sodium hydroxide solution was measured and filled in the tumbling barrel as it is necessary for the CoCr alloy specimens to experience the same effect in every run of the tumbling process.

Fig. 5 Angle cut ceramic media

Fig. 6 Straight cut ceramic media

In overall, there are nine runs of the experiment were conducted with difference parameter setup. The measurement of surface roughness and edge radius was taken before and after the tumbling process. The steps involved for the tumbling process on CoCr alloy are as follows:

- The tumbling barrel is half full filled with the six pieces of CoCr alloy specimen and the Aluminum Oxide based ceramic media.
- The tumbling barrel is filled with sodium hydroxide solution, and the barrel's cover is tighten.
- The speed of 35 rpm ran tumbler machine for about 4 hours.
- The work pieces and media is rinsed with fresh water.
- All of the steps above were repeated but with different time taken off 6 hours and 8 hours.
- All of the steps above were repeated with different rotational speed of 55 rpm and 75 rpm.

Mitutoyo Formtracer CS-5000 had been used to measure the roughness of specimen surface as shown in Fig. 7. The average Ra values were taken as an indicator of the surface roughness of the specimen. On the other hand, the edge radius was measured by using Olympus SZX9 Microscope integrated with Resolution Lite software as shown in Fig. 8. The changes of edge radius are related to the significant burr removal.

Fig. 7 Mitutoyo Formtracer CS-5000

Fig. 8 Olympus SZX9 Microscope

III. Results and Discussion

The results of the effect of rotational speed and tumbling time on the changes in surface roughness and edge radius were presented and discussed in this section.

A. Analysis of Surface Roughness

The surface roughness measurement were taken before and after the tumbling process as it is necessary to determine the difference in response values that being affected by the selected parameters. The average surface roughness different and percentage of surface roughness reduction of the specimens is calculated for every run of the experiment. The experiment result is summarized in Table 3.

TABLE III
EXPERIMENT RESULT OF SURFACE ROUGHNESS, RA DIFFERENCE AND PERCENTAGE OF SURFACE ROUGHNESS REDUCTION

Run	Time Taken, (hour)	Speed, (rpm)	Surface Roughness, Ra difference, (µm)	Percentage of Surface roughness reduction, (%)
1	4	35	0.0375	5.439
2	4	55	0.0680	16.408
3	4	75	0.0025	11.380
4	6	35	0.0950	30.370
5	6	55	0.1565	32.328
6	6	75	0.0930	26.488
7	8	35	0.0140	5.417
8	8	55	0.0655	18.545
9	8	75	0.0080	1.887

The result is illustrated in Fig. 9 that represents the graph of average surface roughness difference versus rotational speed. The three lines that represents the selective time shows the same graph trend which the average difference of surface roughness is increasing initially from 35 rpm to 55 rpm and then become drop when proceeding to higher speed which is 75 rpm. This means that all of the surface roughness value, Ra of CoCr alloy specimens has decreased but the reduction of the Ra value is different for every run of the tumbling process. The highest average Ra difference value is obtained when the speed parameters is set at 55 rpm.

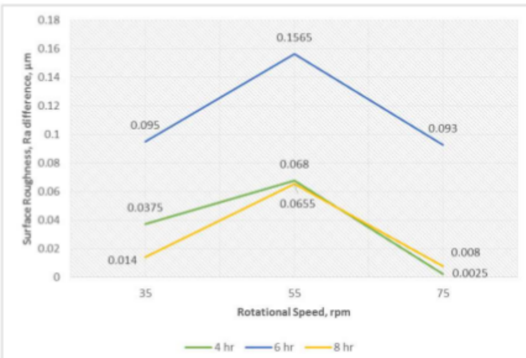

Fig. 9 Graph of surface roughness difference against rotational speed

The component in the tumbling barrel begin to move in a regular and orderly manner from 35 rpm to 55 rpm. This action provided an effective cutting deburring and polishing on the CoCr alloy specimens which caused the value of the average Ra difference become increase. There is relative movement of media against parts within the bulk of the load or in the regions adjacent to the walls of the barrel. This means the reduction of the Ra values is become higher due to this tumbling condition as the specimen and media were colliding effectively for the polishing and deburring purpose.

When going for the further rotational speed which is up to 75 rpm, it showed that the average difference in Ra value become drop which means the reduction of Ra value become lower. This happen is due to component movement behavior in the tumbling barrel which being swept upwards only to fall back against the parts below. The CoCr alloy specimens were not polished well by the media at this such speed. This condition is not effective due to their behavior that being severely damaged by colliding with one another and the media seems to be more wear as they experience a vigorous collision between themselves and the barrel's wall. In other words, this phenomenon is known as impingement where the colliding motion occur in the non-effective slide zone in the tumbling barrel [30]. The higher rotational speed caused the component in the barrel experience more centrifugal force that made them to be cling at the barrel's wall. Thus this make the component to be sliding and bumping on the narrow slide zone of the movement behavior in the barrel that contribute to the slow cutting rate.

Time taken of the tumbling process would give effect towards the surface roughness of CoCr alloy specimens where the variation of this parameter was made by three levels which is 4, 6 and 8 hours of tumbling process. Initially, the average Ra difference value becomes increasing as the cutting rate become high when the time is set from 4 hours to 6 hours of tumbling process. The increment in cutting rate is due to the frequent collision between the abrasive media and the specimens that occur in the tumbling barrel [31]. The media obviously has their ability to make the cutting and polishing action towards CoCr alloy specimens in the beginning duration of tumbling process which 4 to 6 hour.

A tumbling process extended until 8 hours, the average Ra difference value turned out to decrease which means the less reduction of surface roughness value. This happened is because of the repetitive colliding motion of the component in the barrel that effects the abrasive media to experience more wear. The component happened to be more frequent to collide with themselves and the barrel's wall for a long time taken of the tumbling process. Thus the cutting and polishing rate becomes less that results in the less reduction of the surface roughness value.

B. Analysis of Edge Radius

The selective tumbling parameters give significant effect towards the final edge radius values to be much higher compared with initial edge radius values which means burr removal occur onto the CoCr alloy specimens. The result is summarized in Table 4 and illustrated in Fig. Ten that represents the graph of average edge radius difference against speed with the time taken as constant. While Fig. 11 shows the difference of edge radius before and after tumbling process.

TABLE IV
EXPERIMENT RESULT OF EDGE RADIUS DIFFERENCE AND PERCENTAGE OF EDGE RADIUS INCREMENT

Run	Time Taken, (hour)	Speed, (rpm)	Average Edge Radius the difference, (mm)	Percentage of Edge Radius increment, (%)
1	4	35	0.0045	1.622
2	4	55	0.0355	4.354
3	4	75	0.0970	13.550
4	6	35	0.0145	19.088
5	6	55	0.0595	31.776
6	6	75	0.1065	38.517
7	8	35	0.0250	29.353
8	8	55	0.0680	36.535
9	8	75	0.1640	63.077

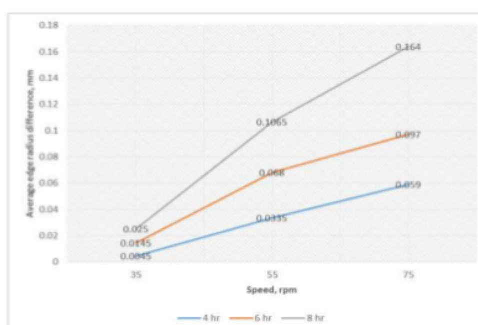

Fig. 10 Graph of average edge radius difference versus speed

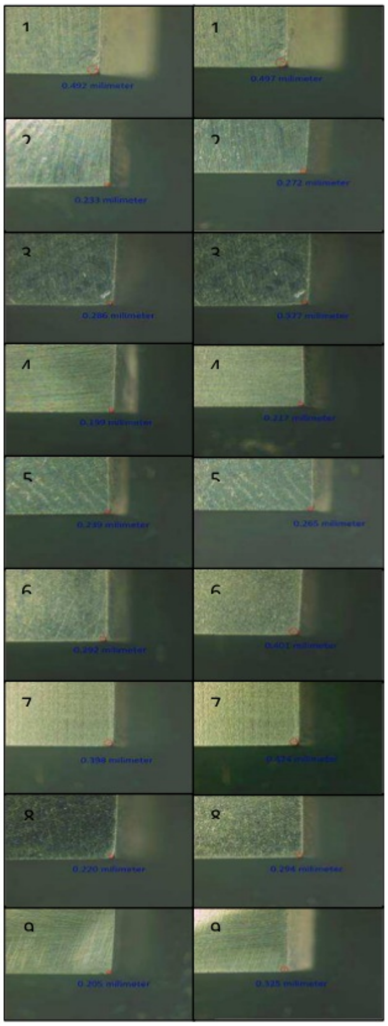

Fig. 11 Edge radius of the sample before and after the tumbling process for Run 1 – Run 9

The tribological behavior of the interactions between the media and specimen is complex. In this study, repetitive collision contact is developed and used to investigate the interface behavior of the tumbling process. The increasing of speed caused the specimen and media in the tumbling barrel to collide more vigorously within themselves. This situation provides slow but significant burr removal — the longer time is taken for the tumbling process, the more removing burr to increase [32]. When going for the further speed up to 75 rpm, the average edge radius difference becomes increasing steadily which means that significant burr removal is less gaining momentum compare to the previous speed that varies from 35 rpm to 55 rpm. This happened is because of the cutting action becoming less due to the motion of the component in the non-effective slide zone and the abrasive media also going to experience more wear as the speed increase [33]. The agitated tumbling barrel causes the solution to circulate and lubricate the media in a smooth tumbling action which caused burrs are abraded away. Further treatment at higher rotational speed would be linear edge smoothening [34].

IV. Conclusion

In this study, pre-polishing of the machined CoCr alloys have been carried out using the tumbling process. The rotational speed and tumbling time had been set at certain values in order to investigate their effects on the surface roughness and edge radius. This research found that it is important to know how the parameters of rotational speed and time took determines the motion behavior of elements in the tumbling barrel to supply the collision for the desired purpose of tumbling machining. Relating to the mix of the parameters, it is concluded that the high reduction in surface roughness, Ra of up to 32%, can be achieved at the intermediate level of rotational speed which is 55 rpm in 6 hours of tumbling process. Prolonging the time cycle and speed beyond this point lead progressively to a small difference to the value of surface roughness and degradation of the finish. Much burr removal can be achieved by the higher speed and longer time taken for tumbling process which is 75 rpm within 8 hours. There is a substantial need to reduce, prevent and eliminate burrs so that the part is more likely to be handled safely, assembled, or function effectively.

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References

[1] Abdul Ajiz, Gunawarman and Jon Affi (2015). The Effects of Short-Time Solution Treatment and Short-Time Aging on Mechanical Properties of Ti-6Al-4V for Orthopaedic Applications. International Journal on Advance Science Engineering Information Technology, 5 (4): 329-334.

[2] Jaspreet Singh, Rupinder Singh and Harwinder Singh (2017). Dimensional accuracy and surface finish of biomedical implant fabricated as rapid investment casting for small to medium quantity production. Journal of Manufacturing Processes, 25: 201–211.

[3] K. Sadiq, M. M. Stack and R. A. Black (2015). Wear mapping of CoCrMo alloy in simulated bio-tribocorrosion conditions of a hip prosthesis bearing in calf serum solution. Materials Science and Engineering C, 49: 452–462.

[4] S. Cottrino, D. Fabre`gue, A. P. Cowie, J-L Besse, S. Tadier, L. Gremillard and D. J. Hartmann (2016). Wear study of Total Ankle Replacement explants by microstructural analysis. Journal of The Mechanical Behavior of Biomedical Materials, 61: 1-11.

[5] Andy Nieto, Jing Ming Zhao, Young-Hwan Han, Kyu Hong Hwang and Julie M. Schoenung (2016). Microscale tribological behavior and in vitro biocompatibility of graphene nanoplatelet reinforced alumina. Journal of The Mechanical Behavior of Biomedical Materials, 61: 122-134.

[6] J. L. Zakrzewski, M. R. M. van den Brink, and J. A. Hubbell (2014). Overcoming immunological barriers in regenerative medicine. Nat Biotech, vol. 32: 786–794.
[7] Ali Alallak (2010). Deburring of components: A survey of current and future deburring processes. Master Thesis in Production Engineering. Uppsala University.
[8] A. Boschetto, L. Bottini and F. Veniali (2018). Surface roughness and radiusing of Ti6Al4V selective laser melting-manufactured parts conditioned by barrel finishing. International Journal of Advance Manufacturing Technology, 94: 2773–2790.
[9] A. Boschetto and L. Bottini (2015). Roughness prediction in coupled operations of fused depositionmodeling and barrel finishing. Journal of Materials Processing Technology, 219: 181–192.
[10] Safian Sharif, Ibrahim Ogu Sadiq, Noordin Mohd Yusof, Amrifan Saladin Mohruni (2017). A Review of Minimum Quantity Lubrication Technique with Nanofluids Application in Metal Cutting Operations. International Journal on Advance Science Engineering Information Technology, 7 (2): 587-593.
[11] Hinde, A.L. & Kalala, J.T. (2009). The application of a simplified approach to modelling tumbling mills, stirred media mills and HPGR's. Minerals Engineering, 22(7-8):633–641.
[12] Ryu, J.J. & Shrotriya, P., (2013). Influence of roughness on surface instability of medical grade cobalt-chromium alloy (CoCrMo) during contact corrosionfatigue. Applied Surface Science, 273, pp.536–541.
[13] Pradyot Patnaik (2002). Handbook of Inorganic Chemicals. McGraw-Hill, New York.
[14] B. Mullany, H. Shahinian, J. Navare, F. Azimi, E. Fleischhauer, P. Tkacik and R. Keanini (2017). The application of computational fluid dynamics to vibratory finishing processes. CIRP Annals - Manufacturing Technology, 66: 309–312.
[15] Wenhui Li, Li Zhang, Xiuhong Li, Shengqiang Yang and Fengfeng Wu (2017). Theoretical and simulation analysis of abrasive particles in centrifugal barrel finishing: Kinematics mechanism and distribution characteristics. Powder Technology, 318: 518–527.
[16] Wenhui Li, Li Zhang, Xiuhong Li and Shengqiang Yang (2016). Discrete Element Simulation of Particle Behavior in Mass Finishing Process: A Parametric Study. Journal of The Balkan Tribological Association, 22 (3): 2380-2399.
[17] Rupinder Singh, Alok Trivedi and Sunpreet Singh (2017). Experimental investigation on shore hardness of barrel-finished FDM. Sadhana, 42 (9): 1579–1584.
[18] Henein, H., Brimacombe, J.K., Watkinson, A.P., 1983. Experimental study of trans-verse bed motion in rotary kilns. Metall. Trans. B 14B, 191–205.
[19] Boateng, A.A., 1998. Boundary layer modeling of granular flow in the transverseplane of a partially filled rotating cylinder. Int. J. Multiph. Flow 24 (3), 499–521.
[20] Boschetto, A., Veniali, F., 2009. Workpiece and media tracking in barrel finishing. Int.J. Mach. Mach. Mater. 6 (3–4), 305–321.
[21] Mellmann, J., 2001. The transverse motion of solids in rotating cylinders – forms ofmotion and transition behaviour. Powder Technol. 118, 251–270.
[22] Pérez-Alonso, C., Delgadillo, J.A., 2012. Experimental validation of 2D DEM code bydigital image analysis in tumbling mills. Miner. Eng. 25 (1), 20–27.
[23] Nakagawa, M., 1997. NMRI study: axial migration of radially segregated core ofgranular mixtures in a horizontal rotating cylinder. Chem. Eng. Sci. 52 (23), 4423–4428.
[24] Bbosa, L.S., Govender, I., Mainza, A.N., Powell, M.S., 2011. Power draw estimationsin experimental tumbling mills using PEPT. Miner. Eng. 24 (3-4), 319–324.
[25] Domblesky J, Evans R, Cariapa V (2004) Material Removal Model for Vibratory Finishing. International Journal of Production Research 42(5):1029–1041.
[26] Hashimoto F, Johnson SP, Chaudhari RG (2016) Modeling of Material Removal Mechanism in Vibratory Finishing Process. Annals of the CIRP 65(1):325–328.
[27] Uhlmann E, Eulitz A, Dethlefs A (2015) Discrete Element Modelling of Drag Finishing. Procedia CIRP 31:369–374.
[28] Naeini SE, Spelt JK (2011) Development of Single-cell Bulk Circulation in Granular Media in a Vibrating Bed. Powder Technology 211:176–186.
[29] Alena Prudnikava, Yegor Tamashevich, Kazimir Yanushkevich, Heshmat Noei, Dieter Lott, Andreas Stierle and Brian Foster (2018). Toward Optimization of Centrifugal Barrel Polishing Procedure for Treatment of Niobium Cavities. IEEE Transactions on Applied Superconductivity, 28 (4): 1-5.
[30] V. Vijayaraghavana and S. Castagne (2018). Measurement of surface characteristics of Ti6Al4V aerospace engineering components in mass finishing process. Measurement, 115: 279–287.
[31] H. Chen, Y.G. Xiao, Y.L. Liu and Y.S. Shi (2017). Effect of Young'smodulus on DEMresults regarding transversemixing of particles within a rotating drum. Powder Technology, 318: 507–517.
[32] Fukuo Hashimoto, Hitomi Yamaguchi, Peter Krajnik, Konrad Wegener, Rahul Chaudhari, Hans-Werner Hoffmeister and Friedrich Kuster (2016). Abrasive fine-finishing technology. CIRP Annals - Manufacturing Technology, 65: 597–620.
[33] Singh, R., Walia, R.S. & Suri, N.M. (2012). Study of Parametric Effect on Surface Roughness Improvement for Hibrid Centrifugal Force Assisted Abrasive Flow Machining Process, International journal of Latest Research in Science and Technology, 1(3):198–201.
[34] Bańkowski Damian, Krajcarz Daniel, Młynarczyk Piotr (2017). Deburring and smoothing the edges using vibro-abrasive machining. Procedia Engineering 192: 28 – 33.

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