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A REVIEW ON TRIBOLOGICAL BEHAVIOUR OF 3D PRINTED MECHANICAL COMPONENTS

BY

GHEORGHE MACOVEI and VIOREL PALEU*

"Gheorghe Asachi" Technical University of Iași, Faculty of Mechanical Engineering,
59A Prof. D. Mangeron Blvd., 700050, Iași, Romania

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Technologies such additive manufacturing are slowly becoming more and more present on the market, covering different areas of the industry due to its great potential. Even so, there are still many aspects which are unexplored or which can be improved. One of them being the study of the tribological proprieties for all these parts, which are produced through additive manufacturing methods, such as powder bed fusion, binder jetting, direct energy deposition, fused filament fabrication, material jetting, vat photopolymerization, and sheet lamination. The scope of this paper is to bring together the tribological proprieties for the 3D printed parts, and to have a critical analysis of these proprieties, in order to easily decide which printing method is suitable, depending of the working conditions of the printed component. In addition, this paper will describe the working principle for each technology, and the type of materials that are commonly used in the printing process. Depending of the printing method, the tribological proprieties vary greatly. For example, for the parts which are manufactured through powder bed fusion, it was found that the wear resistance is higher, and with a lower friction coefficient than for a part manufactured through traditional methods. In addition, for many printing

*Corresponding author; *e-mail*: viorel.paleu@academic.tuiasi.ro
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methods, the produced part might require an additional step of treatment. This is the case with binder jetting, where infiltration and sintering are often used because the 3D-printed part is porous and weak. Some researchers found that the average friction coefficient measured for a steel-based part, treated with bronze infiltration, is comparable with the friction coefficient measured on a part made of the same material, manufactured through the direct energy deposition method. Of course, due to the physical limitations of the 3D printing method, the system will allow only the usage of a specific type or class of materials. One of such method is fused filament fabrication, where only thermoplastics are used. Along with vat photopolymerization and material jetting, these methods present comparable tribological proprieties.

Keywords: additive manufacturing, tribology, polymerisation, laser, sintering.

1. Introduction

The industry is evolving, and so the functional requirements for many mechanical components. Meeting the design specification for all these components is often a truly challenging task, when they are manufactured through traditional technologies. Over the years, the additive manufacturing technology has started to conquer the field of the manufacturing technologies due to its advantages, such as: reduced cost (for manufacturing and for the infrastructure needed for manufacturing), reduced labour time, eliminate the investment of customized tooling, produce very complex components at low cost, possibility to modify the design during the product stage with minimal effort, remote locations manufacturing opportunity, and improved quality (Attaran, 2017).

However, the additive manufacturing technology still needs attention from the scientific community, because this technology has also disadvantages that needs to be reduced or, if possible, eradicated. One of such disadvantage is that the surface quality is very difficult to be precise controlled during the manufacturing process, since it is defined by the end of each layer (Barari *et al.*, 2016).

The surface quality is one of the most crucial parameter for the tribological proprieties, therefore the tribological study of such components are of great interest for applications where a contact is present with another component, which is in relative contact motion with respect to the 3D printed component.

In order to have a clear view over all methods of manufacturing from the additive manufacturing technology, it is necessary a review to bring them together, for an easier decision when choosing what type of technology should be used, when a 3D printed mechanical component is needed with specific tribological proprieties.

2. Description of the 3D printing methods

Many methods are available on market, the main difference being how the material is added and bonded together to form the final part. Some methos uses lasers to cure an UV sensitive resin (stereolithography – SLA), others uses lasers to melt or to partially melt a layer of powder or a wire (powder bed fusion – PBF, and direct energy deposition – DED), other methos uses a binder liquid to ensure the bonding between powder particles (binder jetting – BJ), other methods are based on the extrusion of the material through a nozzle (fused filament fabrication – FFF), and other methods uses sheets of paper, metal or other materials, which are bonded and cut in the desired shape (sheet lamination – SL). A better classification is to presented by (Bikas *et al.*, 2015).

2.1. Beam - based processes

This process is based on the principle in which a beam (often laser) is used to cure, melt, or solidify the material. When using lasers, the process can be divided in two categories depending on the effect induced by the laser beam (Bikas *et al.*, 2015). The first category can be considered laser melting (or laser sintering), in which the beam is used to melt (or partially melt) the raw material which is often powder but it can also be supplied as wire. The second category can be considered laser polymerization, in which the laser is used to change the phase of a photo-sensitive resin.

2.1.1. Laser melting

- **Selective laser sintering (SLS)** is a process in which a laser is used to heat a layer of powder only to the point that the particles fuse together. The powder can be metallic or non-metallic. When the layer is completed, the system adds a new layer of powder and the process repeats, with the difference that the area on which the laser acts might be different, depending of the data receive from computer.

- **Selective laser melting (SLS)**. The process is basically almost the same process as for SLS, with the difference that the laser beam has enough power to completely melt the powder particles.

- **Direct metal laser sintering (DMLS)**. As the name suggests, this process uses only metallic powder. The process is very similar with SLS/SLM, and it is developed and owned by EOS (Khaing *et al.*, 2001).

- **Laser engineered net shaping (LENS)**. Uses a high power laser and a special designed nozzle which focuses the powder (based on gravity or with an air jet)

on the laser spot. The laser is powerful enough to melt the substrate and the powder added in the process.

- **Direct metal deposition (DMD)**. In this process the material (supplied as powder) and the beam is focused on the same spot in the 3D space, with the scope to add melted material in that position. Aster the material is added, the system moves the nozzle in a new position, on a defined trajectory defined by the computer.

- **Laser powder deposition (LDP)**. This process is similar with LENS, in which the powder is injected directly into the focus point of the laser from substrate.

- **Selective laser cladding (SLC)**. This process uses a substrate on which a high power laser creates a melting pool on which the metal powder is added (Jeng *et al.,* 2000).

2.1.2. Laser polymerization

- **Stereolithography (SLA)**. Is the process in which an UV radiation solidifies a very thin layer of photosensitive monomer resin. After the layer is completed, the platform is submerged again into the resin, and a blade sweeps the surface to ensure the flatness of the next layer (Bikas *et al.,* 2015).

- **Solid ground curing (SGC)**. Is the process in which a mask is used to define the layer, and a high power UV source to cure the exposed photo-sensitive resin.

- **Liquid thermal polymerization (LTP)**. As the name suggests, the process is based on the principle in which a laser beam trigger the polymerisation of the resin through thermal energy. The system is similar with SLA, with the difference that the laser is a bit more powerful, and the resin is thermosetting.

- **Beam interference solidification (BIS)**. Is the principle in which two or more laser beams with different wavelength collide in the focal point. When two laser beams are used, one of them excite the liquid polymer to the reversible metastable state, and the second one is used for polymerisation (Hyuk Moon *et al.*, 2005, Bikas *et al.,* 2015)

- **Holographic interference solidification (HIS)**. Is the process in which a holographic image is projected in a vat filled with photosensitive resin. The solidification will take place on the entire exposed surface of the vat.

2.1.3. Electron beam

The process is nearly identical with the laser melting processes, the main difference is given by the energy source used to melt the powder, where the laser is replaced by an electron gun.

2.2. Extrusion based processes

- **Fused filament fabrication (FFF)**. Is the most know type of 3D printing process. The process consists in the extrusion of a thermoplastic material, which is heated with 1°C above the melting point of the material, to facilitate the solidification right after the material is extruded on a preheated platform. The newly added material fuses with the material added in the previous layer, or partially with the preheated platform.

- **Robocasting** is a freeform fabrication technique for dense ceramics and composites that is based on layer-wise deposition of highly loaded colloidal slurries. The process is essentially without binder with less than 1% organics, and parts can be fabricated dried, and completely sintered in less than 24 hours (Cesarano, 1998).

2.3. Material jetting based processes

- **Binder jetting (BJ).** Also known as three dimensional printing (3DP), is the process in which a binder is jetted over a powder layer with the purpose to bind together the powder particles. The position on of the jet is controlled by a computer.

- **Multi jet printing (MJP).** Is the process in which a UV curable liquid plastic is printed onto a flat platform. An wax support material is also used to fill voids and other non-freestanding features. During the printing process an UV lap flashes to solidify the material, creating a fully cured plastic part.

2.4. Sheet lamination

- **Laminated object manufacturing (LOM).** The process is based on the principle in which a stack of sheets of paper, are coated with a thermal activated adhesive on one side. The adhesive is activated by applying pressure and heat on the stack. The unwanted material is sliced with a laser beam and removed. (Park *et al.*, 2000).
- **Ultrasonic consolidation (UC)** is the process which uses a high frequency ultrasonic energy source to induce combined static and oscillating shear forces

within meta foils to produce solid-state bonds and build up a near-net shape part, which is then machined to the final dimensions (Janaki Ram *et al.*, 2007).

3. Tribological proprieties

For the review of the tribological proprieties, this article will present results obtained by different researchers from tests performed on different type of materials. The order of the reviews will depend on the type of the manufacturing process, and on how often that process is used in the industry.

3.1. Tribological behaviour of the components produced by beam - based processes

-Powder bed fusion (Laser melting)

Mohd Yusuf *et al.*, (2021) has studied the tribological behaviour of 316L sample of stainless stell, additively manufactured by laser powder bed fusion and processed via high-pressure torsion. The study was performed on a TE 77 tribometer in pin-on-disk mode, under dry sliding conditions. The fixed part was the sample, the counterpart was an alumina ball with a diameter of 6 mm, and a hardness of 1160HV.

The surface of the sample was grinded with 800 – 4000 grits SiC papers, then polished with 3µ and 1µ diamond suspension. The load was 5 N, and the sliding oscillating frequency of the contact was 1 Hz for a 2 mm stroke, at 21°C at a humidity of 30.3%. A total of 8 separated tests were performed for this study. The results are presented in Fig. 1a for the coefficient of friction, and Fig. 1b for the wear behaviour.

It can be observed in Fig.1a that the friction coefficient presents a significant decrease which starts from approximately 0.6 down to 0.5 during one slide, followed by a stabilisation phase to approximatively 0.45 for the rest of the cycles. He concluded that the low coefficient of friction can be explained by the larger yield stress required to produce plastic deformation (due to the treatment) , as the hardness increases due to the extreme submicron/nano-scale grain refinement, which increase the resistance to sliding and reduces friction between sample and alumina ball (Mohd Yusuf *et al.*, 2021).

Fig. 1b presents the wear depth measured from different locations along the wear track. The original plane surface is shown by the ash line.

He concluded that the treatment enhanced the tribological proprieties of the 316L steel, having as reference for comparation other tribological studies.

Qin *et al.*, (2020) has reviewed the literature for the dry wear performance of metal components manufactured by powder bed fusion and concluded that the wear performance of such components is better in comparation with the parts manufactured through traditional technologies. His study also presented that the PBF materials which are completely densified due

to the small and densely arranged grains, presents higher resistance to deformation, compared to material obtained by traditional processes.

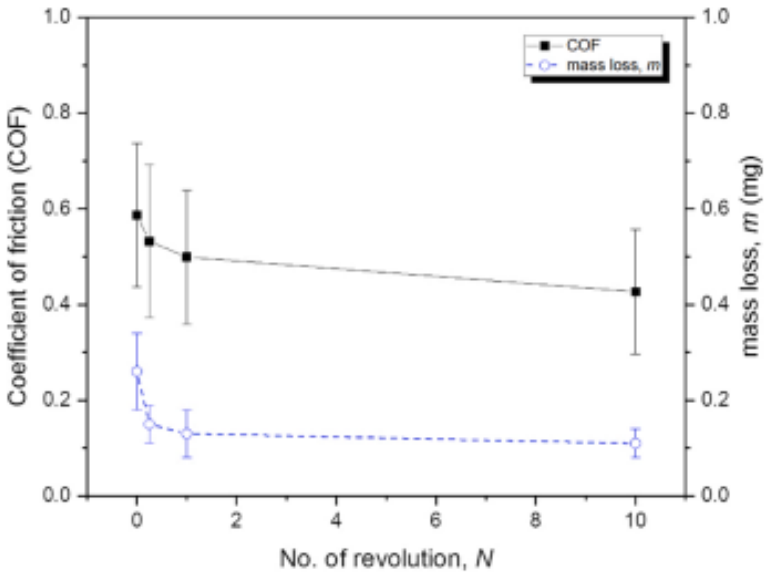


Fig. 1a – Variation of the friction coefficient with the number of strokes (Mohd Yusuf *et al.*, 2021).

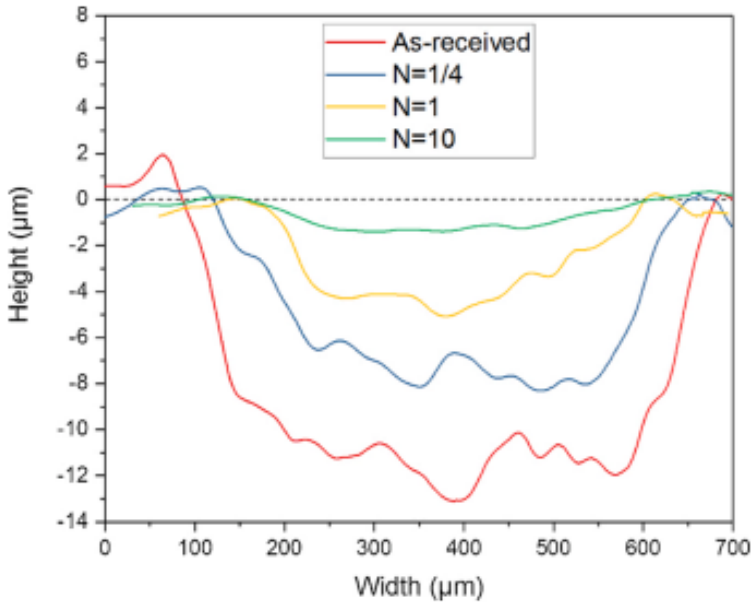


Fig. 1b – The wear depth in multiple sections (Mohd Yusuf *et al.*, 2021).

- Digital light processing (Laser polymerization)

Muammel *et al.*, (2022) has studied the tribological behaviour of 3D printed sample made of a photocurable polyurethane-based resin mixed with graphene nanoplatelets with 99.9% purity. The resin had a composition of 30% polyurethane acrylate, 30% monomer, 5% photo initiators and 5% colour pigment, with an overall density of 1.07-1.13 g/cubic centimetre, and a viscosity of 200-300 mPa·s at 25°C. The concentration of graphene was 0.5, 1, and 2% of the weight of the resin. The specimens were also introduced trough a post processing step, in which they were heated at 60°C for 30 minutes, and exposed to a 405 nm UV light.

The test was performed test on a cylinder-on-plate tribometer, with a stroke of 50 mm, a normal load of 150 N and a frequency of 30 Hz, in which the counterpart was a mobile steel plate. He found that the friction coefficient is very low at the beginning of the sliding path, followed by a sharp increase, which is then stabilised (Fig. 2).

The conclusion was that this effect is caused by the fact that the sample material begins to adhere to the steel plate, inducing a friction between parts with the same material (as the sample) which is generally higher. Due to this behaviour, the study concluded that the wear slows down after the running in stage. The graphene/resin composites showed a better wear behaviour due particles acting as sliding surfaces.

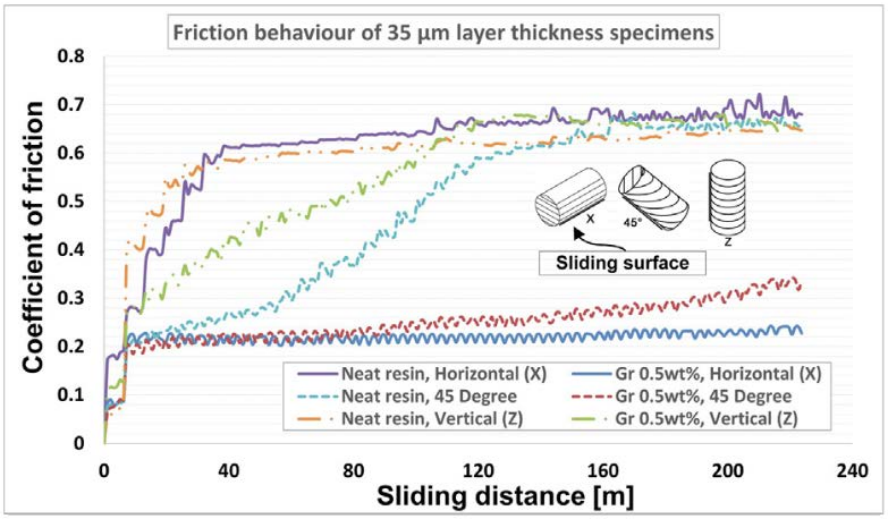


Fig. 2 – Variation of the friction coefficient with the sliding distance (Muammel *et al*., 2022).

In other study, Hanon M. *et al*., (2020) found that the post processed (cured with UV light) components presented a smaller wear depth and a greater

coefficient of friction. However, the curing process makes the components more brittle. One important fact is that both articles presented that the sliding tests are accompanied by a stick-slip behaviour.

3.2. Tribological behaviour of the components produced by extrusion – based processes

- Fused filament fabrication

Kaur *et al*., (2021) found that the tribological proprieties of the parts manufactured through this technology are greatly influenced by the printing parameters such as: printing speed, layer thickness, orientation extrusion temperature, raster angle, orientation, fill pattern and fill density.

Norani *et al*., (2020) has investigated the corelation between tribo-mechanical proprieties of 3D printed ABS and the internal structure of the component. The test was performed on a pin-on-disc tribometer, at a normal force of 58,68N and a sliding speed of 600 rpm for a sliding distance of 1000 m.

The counterpart was a carbon chromium steel disc. It was also mentioned that the tests were performed at 27°C. The article presented that the coefficient of friction is relatively dependant on the elastic modulus. Also, it was found that the triangular flip structure presented the shortest run-in stage with high wear resistance (Fig. 3). The predominant wear mechanisms are abrasive wear and delamination.

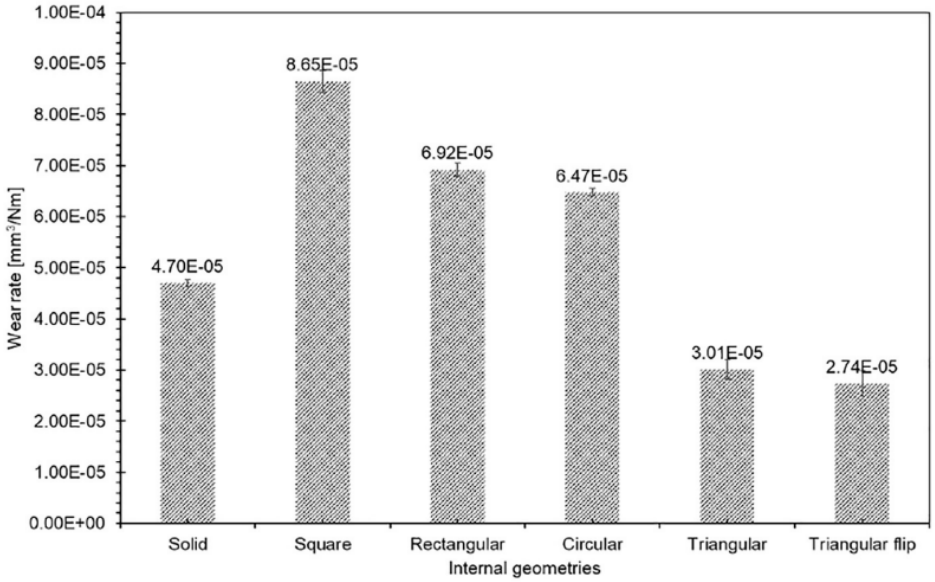


Fig. 3 – The influence of the internal structure on the wear rate (Norani *et al*., 2020).

Similar to the tribological proprieties described previously (for other processes), the coefficient of friction presents a running in stage followed by a stabilisation phase, this behaviour being presented in Fig. 4.

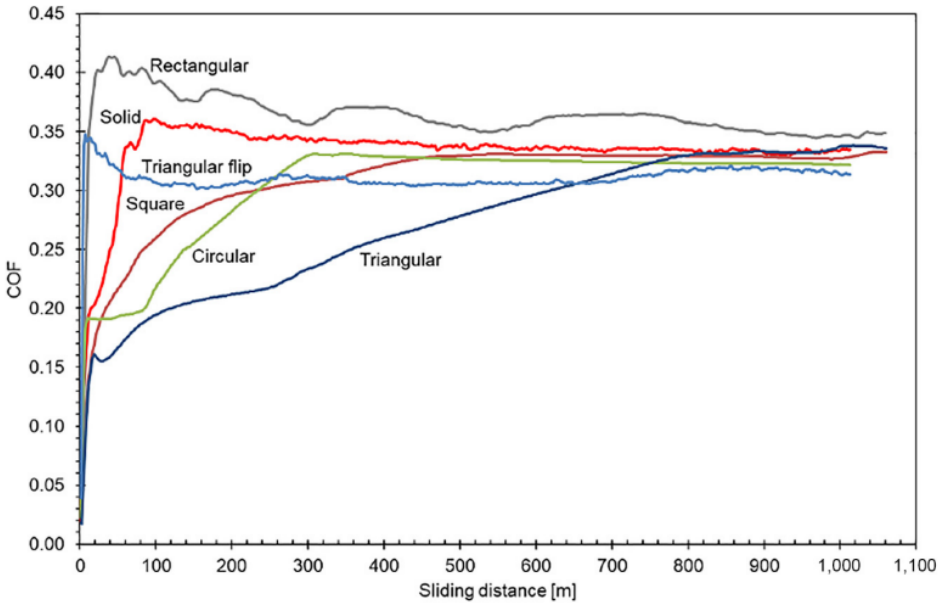


Fig. 4 – The variation of the coefficient of friction (COF) with the sliding distance (Norani *et al.*, 2020).

3.3. Tribological behaviour of the components produced by material jetting - based processes

- Binder jetting

Cui *et al.*, (2021) has investigated the tribological proprieties of a stainless steel and tungsten carbide samples infiltrated with bronze (BPJ316, BPJ420 and BPJWC). The samples were supposed to heat treatment at 180°C for 5 hours, and infiltrate with bronze at 1120°C for 5 hours inside a vacuum furnace. The test was carried out on a ball-on-disk tribometer in dry conditions at room temperature. The counterpart was a GCr15 ball with the diameter of 6.35 mm and a hardness of 596HV. The sample stroke was 10.5 mm at a frequency of 5 Hz, with normal loads of 5, 10 and 30 N.

The article presented that the wear is mainly caused by the pores which increases the adhesive or abrasive wear. It was also found that the bronze infiltrant acts as solid lubricant to some degree, reducing the wear intensity. The study also presented that the BJP420 and BJPWC were mainly degraded by abrasive and fracture wearing. It was also found that the friction coefficient

presented two stages: a running-in stage and a steady-state stage (Fig. 5); and it showed that the friction coefficient decreases with the load.

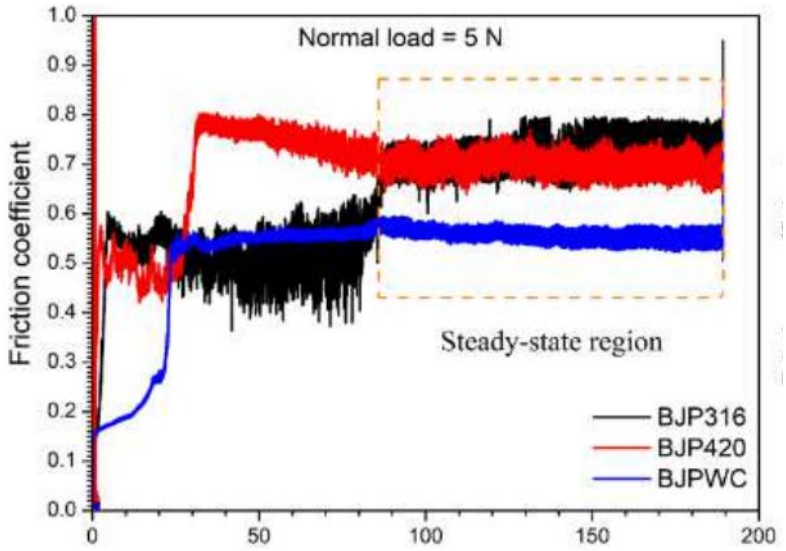


Fig. 5 – The running-in stage and the steady-state stage of the friction coefficient.

Wang *et al*., (2020) suggested that the smeared bronze across the wear track acted as solid lubricant, while the formed passive oxide film acted as tribofilm that inhibited the abrasive wear under high loads.

3.4. Tribological behaviour of the components produced by sheet lamination - based processes

Zhang *et al*., (2013) has studied the tribological behaviour of a laminated composite made of silicon steel sheets and a mix of MoS2 and graphite. The test was performed on a ball-on-disk tribometer according to ASTM: G133-05. The counterpart as a 440C ball with a diameter of 9.5 mm and hardness of 62HRC. The applied load was 4-10 N. The sliding was linear with a frequency of 4-10 Hz, and a stroke of 6 mm, the test being carried out for 30 minutes at a temperature of 20±3°C and a humidity of 20±5%. The test was performed on multiple samples with different filling coefficient of lubricant mixture.

Fig. 6 presents the curves of the friction coefficient as a function of sliding time in dry conditions, for samples with different filling ratio, at a normal force of 6 N and a fervency of 4 Hz. As the curves suggests, the lubricant has to be in the right amount for an optimal friction coefficient, which for this study has the smallest mean value of 0.16 for a filing ratio of 40%.

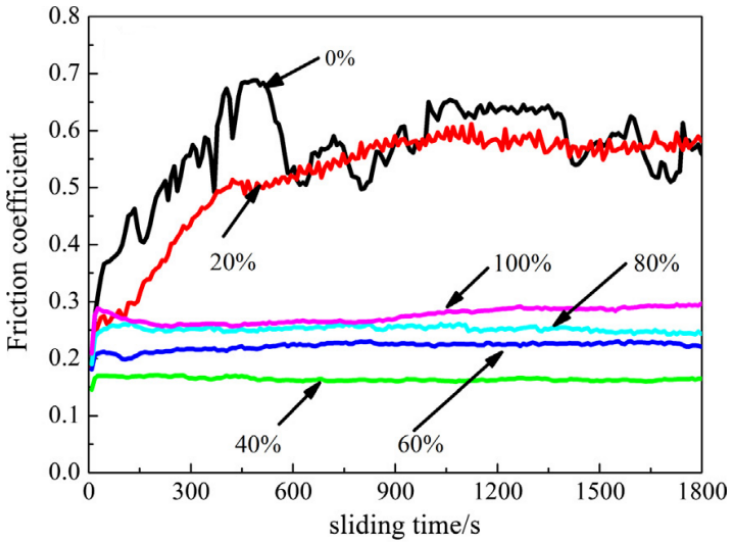


Fig. 6 – The variation of friction coefficient for different filling ratio (Zhang *et al.*, 2013).

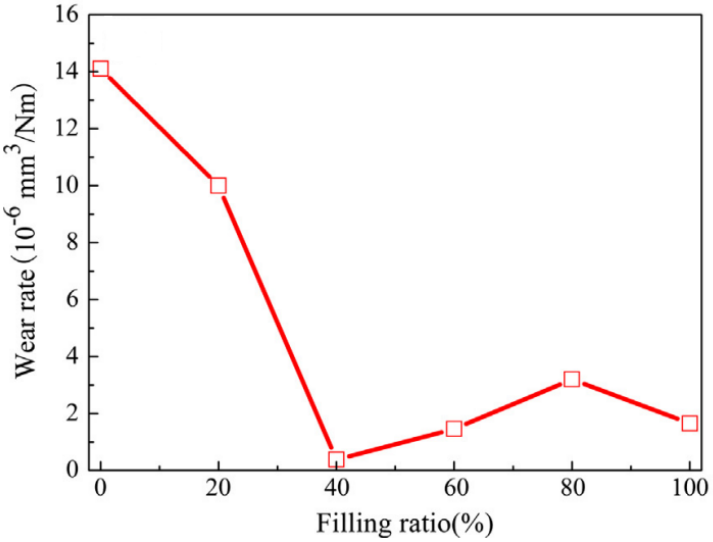


Fig. 7 – The variation of wear rate for different filling ratio (Zhang *et al.*, 2013).

Fig. 7 shows the influence of the filling ration on the wear rate. Zhang *et al.*, (2013) suggested that the low wear rate is caused by the adhesion of the transfer film of MoS2 on the contact region, since the transfer film is much more difficult to be destroyed.

4. Conclusions

All 3D-printed specimens have a running-in phase during friction tests in which the coefficient of friction varies greatly, followed by an equilibrium phase in which the coefficient of friction stabilises at a certain value.

Many additive manufacturing methods require an additional post-processing step to improve the tribo-mechanical properties of the manufactured samples.

In addition to the nature of the material used in the printing process, the deposition parameters of additively manufactured machine parts are the main factors affecting their tribological properties.

Additive manufacturing can produce self-lubricating components with very good tribological performance, but further studies are needed to optimise the desired tribological parameters.

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O SINTEZĂ A COMPORTAMENTELOR TRIBOLOGICE AL COMPONENTELOR IMPRIMATE 3D

(Rezumat)

Tehnologii precum fabricarea aditivă devin tot mai prezente pe piață, acoperind diferite domenii ale industriei. Chiar și așa, există încă multe aspecte neexplorate sau care pot fi îmbunătățite. Un exemplu concret îl reprezintă studiul proprietăților tribologice pentru piesele produse prin metode de fabricație aditivă, cum ar fi: fuziunea în pat de pulbere, pulverizare cu liant, depunerea energetică directă, fabricarea cu

filament fuzionat, material pulverizat, fotopolimerizarea în cuvă şi laminarea foilor. Scopul acestei lucrări este de a reuni proprietățile tribologice pentru piesele imprimate 3D şi de a realiza o analiză critică între aceste proprietăți, pentru a decide cu uşurință ce metodă de imprimare este potrivită, în funcție de condițiile de lucru ale componentei imprimate. În plus, această lucrare va descrie principiul de lucru pentru fiecare tehnologie şi tipul de materiale care sunt utilizate în mod obişnuit în procesul de imprimare. În funcție de metoda de imprimare, proprietățile tribologice variază foarte mult. De exemplu, pentru piesele care sunt fabricate prin fuziune în pat de pulbere, s-a constatat că rezistența la uzură este mai mare şi cu un coeficient de frecare mai mic decât pentru o piesă fabricată prin metode tradiționale. De asemenea, în cazul multor metode de imprimare, este posibil ca piesa produsă să necesite o etapă suplimentară de tratare. Acesta este cazul metodei cu jet de liant, utilizându-se adesea infiltrarea şi sinterizarea, deoarece piesa imprimată 3D este poroasă şi cu rezistență mecanică scăzută. Unii cercetători au constatat că valoarea coeficientul de frecare măsurat pentru o piesă din oțel şi tratată prin infiltrare cu bronz, este comparabilă ca ordin de mărime cu coeficientul de frecare măsurat pentru o piesă din acelaşi material, însă fabricată prin metoda depunerii directe de energie. Desigur, din cauza limitărilor fizice ale metodei de imprimare 3D, sistemul va permite doar utilizarea unui anumit tip sau a unei anumite clase de materiale. Una dintre aceste metode este fabricarea cu filament fuzionat, pentru care se utilizează numai materiale termoplastice. Împreună cu fotopolimerizarea în cuvă şi depunerea în jet de material, aceste metode prezintă proprietăți tribologice comparabile.