Fundamental Process Design and Characterization of Additively Manufactured Polymer-Metal Joints

Francis N. Njihia, James Mutua, Samuel K. Kabini, and James Wamai

Abstract— Automotive, aerospace, electronics, and medical device manufacturers are leveraging the potential of combining polymer and metals to produce highly efficient components. The motivation is the lightweight and compact nature of parts produced with fewer assembling components. Despite the growing need, the different chemical and physical properties constantly challenge polymer bonding to metals. The well-known techniques of bonding polymers to metals include adhesive bonding, mechanical fastening methods, and weld-based techniques such as friction spot joining ultrasonic bonding. However, these joining methods have limitations related to geometrical design, joint configuration, safety, and reliability of complex components. The choice of an appropriate joining method is of great significance for increased functional integration in the assembly of parts and improved efficiency and safety.

Additive manufacturing is the newest technological innovation that has been proposed to enable the combination of polymers and metals. The 3D printing method provides enhanced creation of intricate designs, offers process flexibility, and superior manufacturing control compared to other bonding techniques such as laser joining, ultrasonic joining, and friction spot joining. In light of these developments, the main aim of this paper is to present the fundamentals of designing, testing, and characterizing polymer-metal joints. In this preliminary work, the use of Acrylonitrile butadiene styrene (ABS) and En AW 6060 aluminium alloy in the process will be justified, the international standards for designing and testing polymer-metal joints will be established, and the effect of the metal surface modification on the joint strength will be determined. It is expected then that the deductions made from the aforementioned objectives will form a foundation of ongoing research work, whose results will be documented in future publications.

Keywords—Additive Manufacturing, Joining, Metals, Polymers

I. INTRODUCTION

Lightweight, compact, and high resilience are increasingly dominating features required in manufacturing efficient and high-performance components. These requirements have led to developing customized materials and seeking ways to leverage the potential of using dissimilar multifunctional materials. Engineered polymers have emerged as alternative materials for most industrial applications. However, these polymers may not fully substitute the conventional metals, thus requiring combining polymer and metals to create polymer-metal hybrid parts. This has enabled the development of products with structural and non-structural requirements in a single customized solution. These manufacturing trends have occasioned the continuous exploration of appropriate and reliable joining techniques for these physically and chemically dissimilar materials. Metals possess desirable properties such as high strength, toughness, and heat resistance, whereas polymers have higher corrosion resistance, excellent deformability properties, and lightweight characteristics.

Polymer-metal hybrids can be made through several manufacturing techniques. They include thermoplastic-based fiber metal lamination (T-FML), polymer-metal joining, and polymer-metal composites. Fibre–metal laminates (FMLs) are lightweight structural materials consisting of alternating thin layers of metal and fiber–polymer composite. The manufacturing process of FMLs involves a long process to cure the polymeric matrices, and their industrial application is limited due to concerns related to the growth of fatigue cracks. The crack growth is often associated with delamination, a potential problem with fiber–metal laminates, and can occur when a partially delaminated panel is subjected to a compressive force [1].

Hybrid polymer-metal parts can also be made through the fabrication of a composite. In the process, combining polymers with metal particles results in polymer-metal blend parts with interesting optical and mechanical properties. The mechanical properties of such parts have been reported to have significantly low strength compared to parent materials [2]. Notwithstanding, the metal concentration in the polymer can result in optic, conductive, magnetic, or other desired properties in the hybrid [2].

Joining is currently the most popular and reliable method of developing polymer-metal hybrid parts. Studies in the scope of polymer-metal joining are multidisciplinary and include various aspects of materials science, joint chemistry, and joint

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mechanics. The ability to join together different materials with engineered properties has enabled continuous exploration into different methods of joining. The bonding is based on the adhesion at the polymer interface and the metal part. Hence, the basic method of joining is adhesive bonding. It involves the application of adhesives, such as silicon, at the joint interface causing the formation of inter-molecular forces between polymer and metal substrate [3]. However, adhesively bonded joints develop gradual joint problems. For instance, the joints easily degrade in unregulated temperatures, humidity, and moisture environments. Therefore, the durability of adhesively joined parts is uncertain. Another difficulty is the non-reliability of carrying out non-destructive testing. Adhesive-bonded joints oftentimes fail instantaneously rather than progressively when used in demanding structural applications [4]. Mechanical fasteners have also been applied to overcome the limitations posed by the adhesive joining. The process involves clamping or fastening parts with screws, bolts, or rivets to join the workpieces. However, this method has rarely been reported in the development of intricate joints. This may be due to the developed products' limitations, such as increased weight and the development of stress around the joint parts, consequently inducing corrosion and degradation of the joint [5]. More recently, weld-based joining techniques such as ultrasonic welding, friction spot welding, and laser welding have been tried. Nevertheless, manufacturers are faced with the challenge of controlling parameters at the interface of the metal and polymer. For instance, Schricker K. et al. [6] conducted a thermal efficiency study on laser-assisted joining of polymer–metal composites. The study investigated the influence of sheet thickness, focal diameter, and energy per unit length on temperature distribution. The findings reported that these many factors had a decisive effect on the absorbed laser beam and the thermal distribution. Therefore, without an integrated control mechanism, the polymers can easily degrade due to elevated temperatures or melt unevenly due to insufficient and nonuniform temperature distribution [7]. Hence, for effective use of these methods, a good understanding of the process and material behavior is necessary, as well as the capabilities and limitations of each process. Owing to manufacturing diversification in advanced and high-tech applications, engineering designers and manufacturers have continued to explore innovative ways of bonding polymers to metals for increased reliability and unlimited design flexibility.

This paper aims to present the use of additive manufacturing, particularly fused deposition modeling or fused filament fabrication(FFF), in the development of polymer-metal joints. Foremost, the basics of the process will be outlined, and recent studies reviewed. Thereafter, the applied polymer and metal will be presented. Finally, the testing standard and technique used to evaluate the strength of the joint will be explained.

II. ADDITIVE MANUFACTURING

Additive manufacturing (AM) is a novel manufacturing technology used to create engineering products by building the part in layers. The successive assemblage of materials in layers to create three-dimensional objects is referred to as 3D printing. The process builds the three-dimensional objects from a computer-aided design (CAD) model. This manufacturing technology can be applied in creating polymer/metal joints by depositing a polymer substrate on top of a metal substrate. However, in some cases, the polymer and metal parts can be manufactured separately and bonded through a welding technique. For instance, Tang et al. [8] demonstrated the joining of 3D-printed Acrylonitrile butadiene styrene (ABS) polymer to SLM-fabricated 304 type of stainless steel. Three different sub-millimeter cellular structures consisting of circular holes and channels were printed on the metal plate. These structures were suggested to affect the shear and tensile strength of the joint. The FDM-printed ABS polymer and SLM-developed stainless steel plate were then directly joined by means of an ultrasonic welding process. In yet another study, Silva et al. [9] developed a hybrid SLM/SLS additive manufacturing technique to produce a customized polymer/metal dental implant. Using the combination of the two additive techniques, they demonstrated the possibility of producing bio-mechanical devices with high joint strength and optimal material mass/volume ratio. More recently, Chueh et al. [10] integrated two 3D printing technologies for joining polymers to metals. They employed fused filament fabrication(FFF) for polymer fabrication and laser-based powder bed fusion(PBF) for printing substrate. The techniques were employed to develop Polylactide/ Stainless steel type 316L joint substrate. The joint interface was enhanced with interlocking structures that were proposed to strengthen the polymer/metal bond. Guo et al. [11] applied the ultrasonic additive manufacturing (UAM) technique in joining carbon fiber and aluminum AA 6061. In this work, the achieved joint strength was by mechanical interlocking of CF loops within the AA, reaching a strength of 125 Mpa.

More recently, in situ joining AM technique using fused filament fabrication has been proposed to minimize the post-printing welding processes.

III. FUSED FILAMENT FABRICATION

Fused Filament fabrication is a plastic material extrusion technique involving the uncoiling of plastic filament from a spool which then goes into an extrusion chamber for heating, melting, and ejection through a nozzle. Depending on the diameter of the nozzle, a layer of thickness ranging from 0.1 mm to 0.5mm is deposited layer by layer on the build platform of the printing equipment. X, Y, and Z direction movement occur with 3D computer-aided design data processing. The necessity is that a newly deposited material is bonded correctly to the previous layer and that the filament with a proper diameter is used to supply enough material for the building process. Fig. 1 shows a schematic of the process.

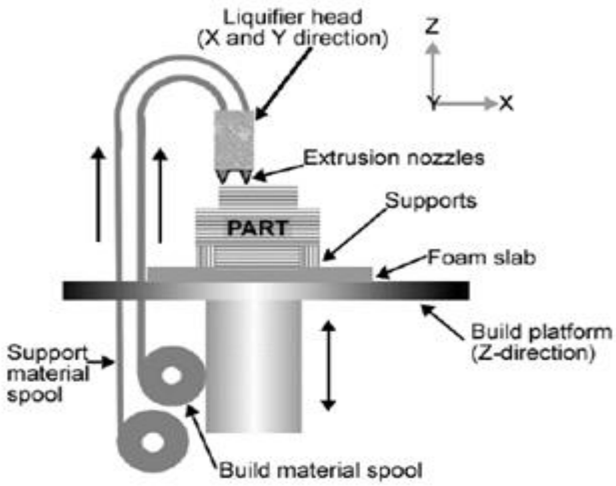

Fig. 1 A schematic of Fused Filament Fabrication [12]

Falck et al. [13] developed a novel additive manufacturing joining procedure named "AddJoining" for layered hybrid polymer-metal parts. Fused deposition technology was used to fabricate the parts by 3D printing the polymer in a step-by-step procedure. The practicability of the process was demonstrated using a combination of two materials; aluminum 2024-T3 with alternating layers of polyamide-6 and carbon fiber-reinforced polyamide-6 in a single lap joint configuration. The technique's feasibility was demonstrated successfully as the joints in the case study showed high ultimate lap-shear strength. Ozlati et al. [14] also developed an alternative additive manufacturing-based joining method to create polymer/ metal hybrid structures. Using the FDM technique, molten polypropylene polymer filament was used to create a lap joint of polypropylene substrate and surface modified Al-Mg alloy sheets that interlocked between the additive part and aluminum base sheet. Effects of processing parameters, including preheating temperatures, layer height, extrusion width, and printing speed, on the quality of the joint formed, were investigated. They reported significant effects of these parameters on the polymer/metal joint.

Although these pioneering works of fused filament fabrication have reported successful breakthroughs in polymer-metal joining feasibility studies, there remain a few scientific gaps that need to be addressed. For instance, many variables are known to influence the strength of hybrid aluminum–polymer joints, but their principle of action and the degree of influence remain unknown. These variables, which could be process-related or material parameters, require further investigation. The work presented in this paper will form a basis for determining the influence of such variables. In particular, the influence of surface preparation and surface roughness on the strength of the joint will be determined and quantified.

IV. METHODOLOGY

A. Material Selection

In order to achieve the stated objective, polymeric and metallic parts are chosen. These types of polymer and metal are selected based on potential industrial application, recyclability, and their role in the circular economy. Acrylonitrile butadiene styrene (ABS) polymer and aluminium (En Aw 6060) alloy were considered. Acrylonitrile Butadiene Styrene (ABS) is an impact-resistant engineering thermoplastic & amorphous polymer. It is made of three monomers: acrylonitrile, butadiene, and styrene. It is a preferred choice for structural applications, thanks to its physical properties such as high rigidity, resistance to impact, abrasion, and strain. It finds use in electronic housings, auto parts, consumer products, and pipe fittings. Aluminium alloy En Aw 6060 is a medium strength general commercial alloy. The alloy is superior in corrosion resistance, formability, and weldability. It is commonly used for architectural sections for windows, doors, curtain walls, interior fittings, lighting, furniture and office equipment, and structural applications where surface finish is essential. Table 1 shows the relevant properties in the joining process.

A hybrid ABS-Al(EN- AW 6060) part would offer the versatility in applications mentioned while simultaneously creating the possibility of exploring new applications, mainly where lightweight needs are of higher importance.

Table 1. Polymer and Metal Properties

Physical & Mechanical Properties	**ABS**	**EN AW 6060**
Density $[g/cm^3]$	1.0 - 1.05	2.710
Thermal Conductivity [W/mK]	0.14 – 0.21	170
Linear Thermal Expansion Coefficient [10^{-6} [m/mK]]	73.8	23.5
Melting Point o_C	200	582
Tensile Strength [MPa]	22	140 - 230
Tensile Modulus [MPa]	1360	70000
Tensile Elongation [%]	6	13

B. Experiment Standards

The International Organization for Standardization (ISO) and the American Society for Testing Materials (ASTM) provide fundamental standards for designing and testing specimens [15] [16]. ASTM D3163-01 and ISO 4587 standards are recommended for testing the lap shear strength of the samples produced, as shown in Fig. 2.

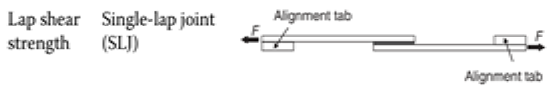

Fig. 2 Single-lap joint testing standards [17]

The standards also define the dimension of the workpieces, the testing parameters, and the equipment configuration. The recommended sample dimensions are as shown in Fig.3.

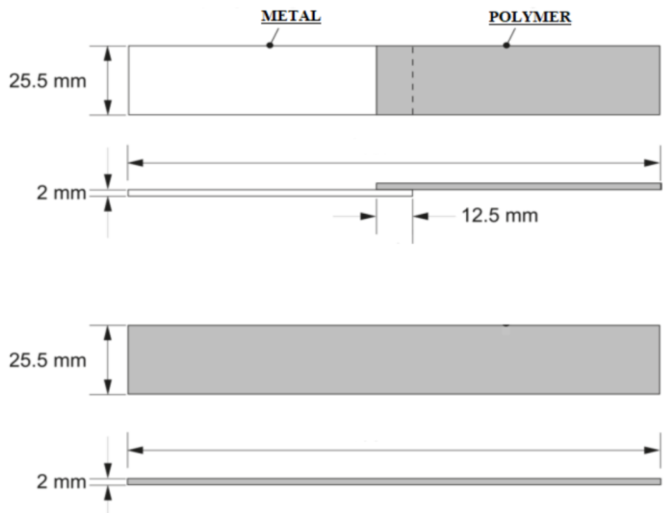

Fig. 3 Cross section sample dimensions

C. Surface Preparation

The structure of the metal surface is an important parameter in determining the adhesion strength of the polymer to the metal [18]. The aluminium alloy surface is subjected to surface texturing before printing to study the extent of micro and macro interlock bonding. The alloy surface was sandblasted with micro-particles of sand using HGH 60 40 sandblasting machine. A schematic of the sandblasting process is represented in Fig. 4. The process involved directing the blasting gun held by protected hands to the metal samples placed in the sandblasting chamber. After sandblasting, the samples were removed from the chamber, cleaned the dust with a soft brush, and wiped the surface with a cloth dipped in an ethanol solution. The modified surface roughness was verified using a Hommel Tester LV 15 equipment. The device monitored the surface roughness of the metal samples and provided tabulated measured data. The roughness tests were conducted for the sandblasted and non-blasted metal pieces to compare the results. Afterward, a thin coating of the polymer solution made of ABS dissolved in acetone was applied on the sandblasted alumiunum surface and left until dry.

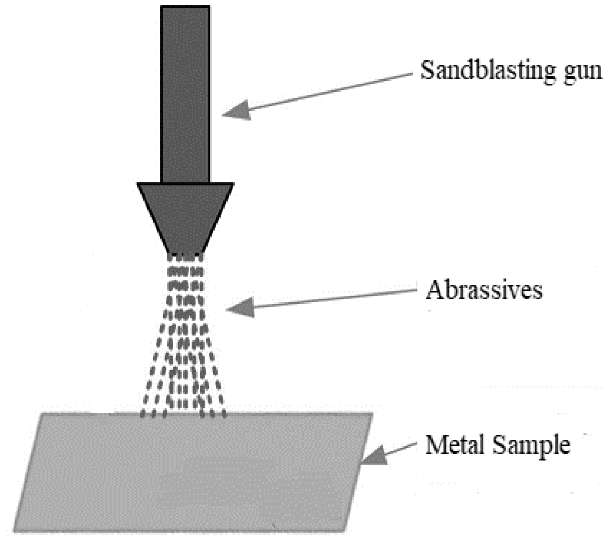

Fig. 4 A representation of the sandblasting process

D. 3D Printing Procedure

The model was designed in SolidWorks 3D CAD software and saved as an STL file. The file was later exported to a PrusaSlicer, an open-source slicing software that converts the file into G-code instructions to be used by the Prusa i3 MK3S+ FFF printer to build the part. The printing process and material parameters are determined and chosen in the software. The printing process involves inserting the aluminium alloy samples to be part of the build platform while printing the polymer. The original Prusa i3 MK3S+ 3D printer was used to fabricate the ABS/Al 6060 joint. The printer was loaded with ABS filament with a diameter of 1.75 mm. Other preselected parameters were the bed temperature of $100^0 C$, the nozzle temperature of 215 and a print layer height of 0.2 mm.

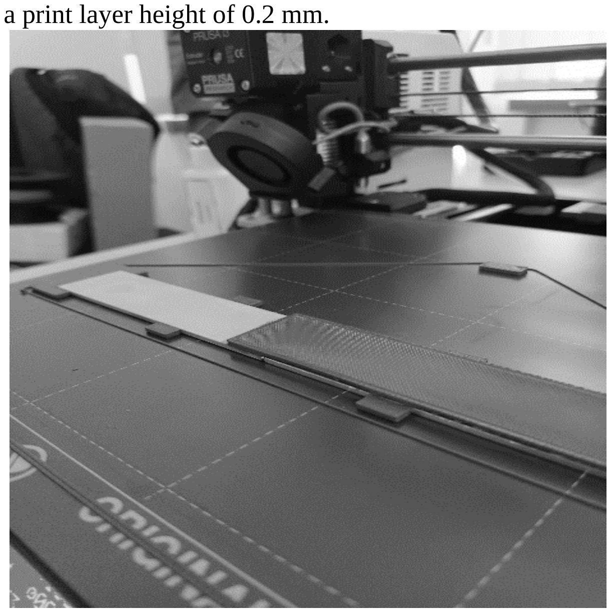

Fig. 5 Printing Process

The ABS polymer was printed on the metallic sheet attached to the build platform on the bed, as shown in Fig 5. The supporting structures secured the joint in lateral and transverse directions to provide a firm printing base. Four ABS/Al 6060 joint samples named 'SBAL2, SBAL3, SBAL4, SBAL5' were fabricated and ready for tensile strength testing. One non-blasted sample was also printed to compare the strength.

E. Testing the Joint

The printed ABS/Al 6060 joint samples were subjected to a tensile strength test based on the recommended experiment standards. A Hegewald & Peschke Meß- und Prüftechnik GmbH equipment was used. Fig. 6 shows one of the specimens in the test runs.

25 mm of wedge grips were placed from both ends of each specimen for axis alignment and good work holding with the mechanical wedge action grips with coarsely serrated faces.

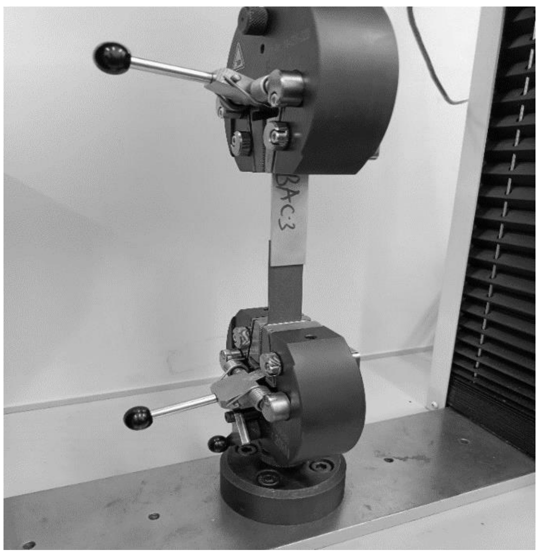

Fig 6. Sample Under Tensile Test

V. Result and Discussion

A. Surface roughness

Fig. 7 and Fig. 8 show the values of Ra and Rz that were determined for surface roughness of the non-blasted and sandblasted samples, respectively. The values show the deviation in the direction of the normal vector of the actual surface from its ideal form. While Ra gives average surface roughness, Rz gives information for any pore, hole, or surface deformities detrimental to strength. From the surface roughness results, it can be concluded that the sandblasting of the metal samples resulted in the added structuring of the surface. The extent of the surface modification is expected to highly influence the flow of the polymer into the created pores. As a consequence, the adhesion of the polymer to the metal surface will improve.

B. Joint Strength

The force-displacement curve for the four ABS/Al 6060 joint samples named 'SBAL2, SBAL3, SBAL4, SBAL5' and the non-blasted sample named *Serie*6 is shown in Fig. 9.

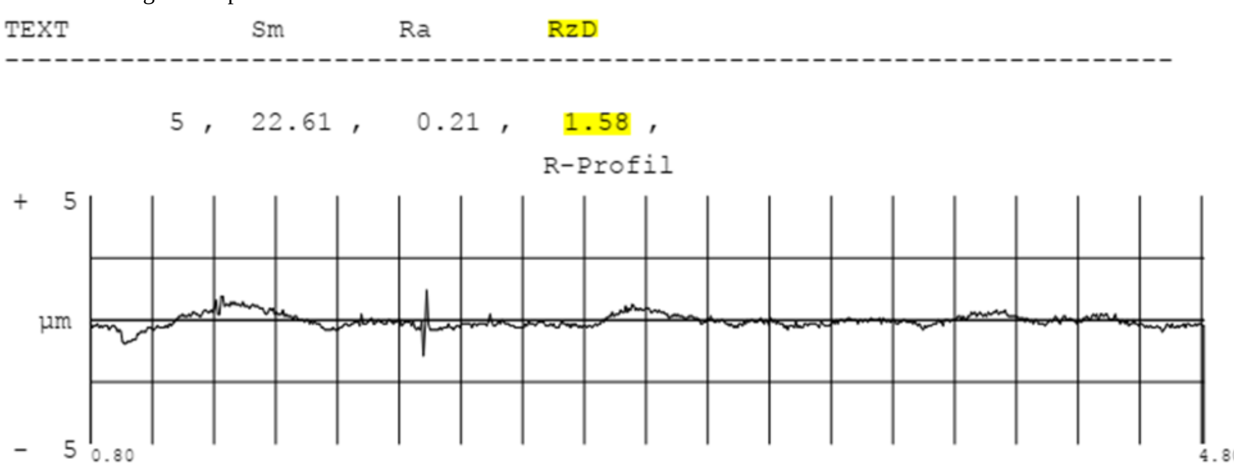

Fig. 7 Roughness Profile of a non-blasted sample

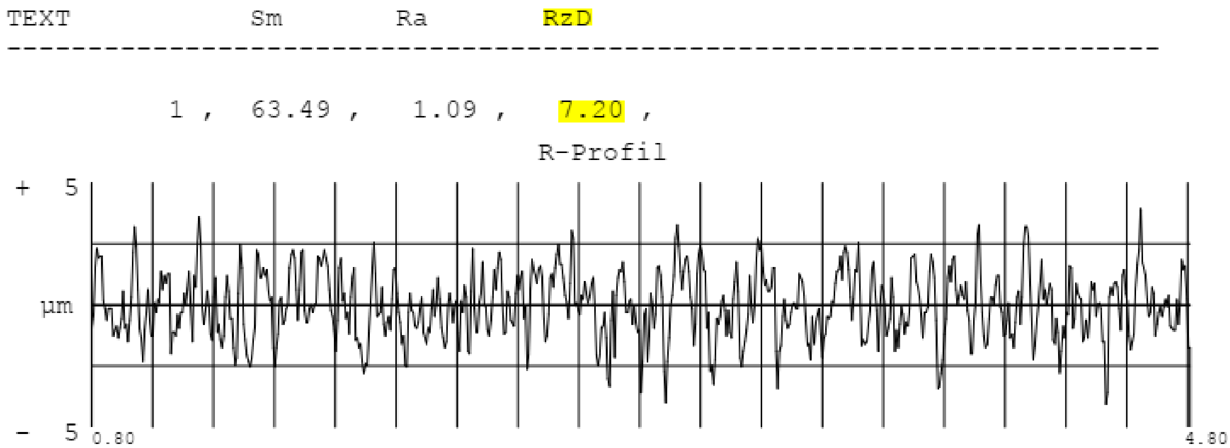

Fig. 8 Roughness Profile of a sandblasted sample

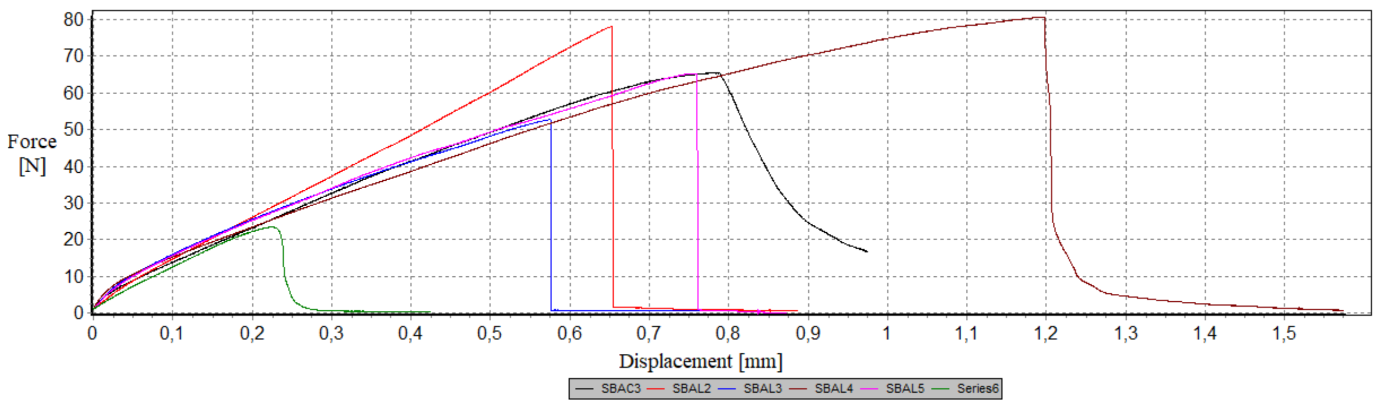

Fig. 9 Force-displacement curve of the tested samples

The behavior of the loading curve followed the same pattern for all the samples tested. The non-blasted sample recorded the lowest value of yield strength of 24 N. This is attributed to the fewer surface structures on the surface of the non-blasted sample, as indicated in Fig 7. The four sandblasted samples recorded higher yield strength values ranging from 50 N - 80 N. The higher value in comparison to the non-blasted sample is explained by the higher distribution of surface structures in the non-blasted samples, as observed from the roughness profile shown in Fig. 8. Higher distribution of surface structures resulted in a greater fusion of the molten polymer in the micro and macro pores of the metal surface. Thus, the bonding mechanism is enhanced for structured surfaces, that is, for the sandblasted samples. The variances in values of yield strength for the sandblasted samples could be attributed to the inhomogeneous nature of structures made from the hand sandblasting process.

VI. Conclusion

The 3D printing process of fabricating the polymer-metal joint has been elaborated. The samples made were tested for joint strength. From the investigation, it can be deduced that surface roughness is a crucial parameter influencing the bonding strength. Further morphological analysis must be conducted to characterize the surface and consequent bond formation. In addition, the influence of the pattern or the shape of the structures needs to be investigated for testing different load directions. Notably, the tensile strengths obtained in these preliminary tests are low for the suggested applications. The investigation of the influence of the surface micro and macro structures on joint strength must also be conducted in the ongoing study to characterize the joints further and investigate other parameters.

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