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Mechanical Features of PMMA Microfluidic Chips Implemented by Carbon Dioxide Laser

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Abstract:

An experimental investigation of the laser engraved process is carried out on.2.5 mm.thick acrylic Polymethyl Methacrylate (PMMA).using Carbon Dioxide,(CO_2) laser. PMMA is a typical polymer.suitable for manufacturing microfluidic chips (Y shape). Fabrication parameters have an influence on the mechanical properties of the manufactured components. The effects of laser power (20, 40, and 60 W) and scanning speed (250, 350, and 500 mm /s) were evaluated on the microstructure and mechanical characteristics of microfluidic chips. With an increase in laser power and a decrease in scanning speed, the stacking of melt pools became more organized, pores were less visible, and mechanical characteristics improved. At a power density of 60 W and a speed of 250 mm/s, the best mechanical parameters were obtained, including a yield strength of 20.72 MPa, an ultimate tensile strength of 30.81 MPa, and an elongation of 1.163 percent. For the same laser energy density, however, change in laser power has a greater influence on the pore defect than variation in scanning speed.

Keywords: PMMA microfluidic chips, CO_2 laser ablation, mechanical properties, and surface roughness.

الميزات الميكانيكية لرقائق الموائع الدقيقة PMMA المنفذة بواسطة ليزر ثاني أكسيد الكربون

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الخلاصة:

في هذا العمل الحالي تم إجراء دراسة تجريبية لعملية النقش بالليزر على (Polymethyl Methacrylate، PMMA) سمك 2.5 ملم من الاكريليك باستخدام ليزر ثاني أكسيد الكربون (CO2), PMMA نموذج مناسب لتصنيع رقائق موائع الدقيقة (شكل Y). تؤثر معلمات التصنيع على الصفات الميكانيكية للمكونات المصنعة. قيم المؤلفون تأثيرات طاقة الليزر (20 ، 40 ، 60 واط) وسرعة المسح (250 ، 350 ، 500 م / ث) على البنية الدقيقة والخصائص الميكانيكية لرقائق الموائع الدقيقة. مع زيادة طاقة الليزر وانخفاض سرعة المسح ، أصبح تكديس أحواض الذوبان أكثر تنظيماً ، وكانت المسام أقل وضوحًا ، وتحسنت الخصائص الميكانيكية. عند كثافة قدرة 60 واط وسرعة 250 م / ث ، تم الحصول على أفضل المعلمات الميكانيكية ، بما في ذلك قوة الخضوع 20.72 ميجا باسكال ، وقوة شد نهائية تبلغ 30.81 ميجا

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باسكال ، واستطالة بنسبة 1.163 في المائة. بالنسبة لكثافة طاقة الليزر نفسها ، فإن التغيير في طاقة الليزر له تأثير أكبر على عيوب المسام من التغير في سرعة المسح.

1. INTRODUCTION

Microfluidic technology has extensively been used in the chemical, biological, environmental, and medical domains to enable precise liquid management (micro or nanoscale). Microfluidic chips were first produced using glass or silicon by fabrication procedures derived from Micro-Electro-Mechanical Systems (MEMS), which often entailed sophisticated photolithography and physical/chemical etching [1]. These approaches, however, are time intensive and need complex equipment. Additionally, lithography technology often needs the employment of a series of fabrication operations in a cleanroom environment, which adds to the fabrication process's expense.

During the last decade, polymers have replaced glass/silicon materials in microfluidics since they provide a variety of physical, chemical, and optical characteristics, and they are, in comparison to glass/silicon, often less expensive and easier to process, with a variety of production processes. Currently, thermoplastics, like poly-methyl methacrylate (PMMA), often referred to as acrylic, have been widely employed in microfluidics and used in optics applications instead place of glass. This kind of material has a variety of important qualities that distinguish it from other polymeric materials. The primary characteristics of this class of polymers are their great chemical stability, mechanical strength, lightweight nature, and ease of fabrication[2]. PMMA has been used in various applications, including the automotive sector, optoelectronics, and microfluidic chips, as well as in certain medical applications, equipment, aerospace, and architecture[3]. To develop a direct, controlled, and low-cost manufacturing procedure for polymer-based microfluidics, an increasing number of researchers have done numerous studies in laser ablation processing microfluidic chips. Currently, the most commonly used laser systems are the CO_2 laser (10.6 μm) to create, microchannels.on transparent,PMMA surface. As PMMA has a high transmittance, about (95%), it is very suitable and convenient for CO_2 laser machining. PMMA, upon heating, starts to, change its phase, then melts and subsequently vaporizes at different temperatures.
CO_2 laser machining can be used to cut metals and nonmetals; it creates very few microcracks and has an excellent cut quality [4, 5]. It is a noncontact cutting technology that is simple to maintain and economical since it removes the need for jigging and clamping. Additionally, even elaborate forms may be created easily.

The objective of this study was to design and manufacture Y-shaped microfluidic chips, using a commercial CO_2 laser machining system, to better understand the effect of laser system parameters such as laser power and scanning speed on the mechanical properties and surface roughness of chips.

2. Fabrication

2.1 Materials and instruments

To create microchannels on PMMA, a commercial 60-watt power CO_2 laser system (LiaochengJK-4060, Laser Engraving, Cutting, and Machine, China) was employed. The output power of the laser may be adjusted between 0 and 60 W, depending on the scan speed of the laser head (between 250 and 500 mm/s), the laser's wavelength is 10.6 μm, and the diameter of the concentrated laser point is around 50 μm. The microchannels were created using Corel DRAW (Graphic Suite X7) and converted to laser pathways using the laser cutter's integrated software. The laser settings of the cutting stage were adjusted using this program by altering the laser power and scan speed. Channels were engraved on the surface of 2.5 mm thick cast polymethyl methacrylate (PMMA) sheets (Jumei Acrylic Manufacturing,

Shanghai, China) using various combinations of laser power (20, 40, 60 W) and scan speed (250, 350, 500 mm/s). The protective coating was removed from the engraved side of the PMMA sheets before laser machining to prevent interfering with the laser ablation process,

2.2 Manufacturing Procedure

The manufacturing technique for the microfluidic chips made of PMMA is as explained. The PMMA substrate, which served as the foundation for the whole stack of components, was sliced into a rectangular Y form using CO_2 laser ablation. The material stack's exterior dimensions were 1.9 cm by 4.9 cm. All PMMA samples were cleaned and washed after microchannel construction. Wipes containing DI water, solvent, and isopropanol were used to remove polymer residues. The PMMA substrate was covered with a layer of chloroform (Chloroform Minimum Test, GC, 99.0 per cent, Chemical Zone, Umbernath 4210501, India) to act as an adhesive. It was attached to another layer of PMMA (of the same thickness) containing three holes (two inlets and one outlet). Finally, the PMMA substrate was attached to another layer of PMMA (same thickness) containing holes to completely seal the manufactured microchannels. The PMMA-Chloroform-PMMA complex was gently squeezed by fingers to increase bonding, resulting in smooth channel surfaces, as shown in Figure (1). The inlet and exit pipes were then attached to the holes to complete the manufacturing of the microfluidic chip. The fluid was injected into the channels using syringe pumps by pipes (connecting between channels and syringe pumps) Figure (2) so the fluid spontaneously fowed into the channel due to the capillary action.

Figure 1: Microfluidic chip Y straight-line microchannel.

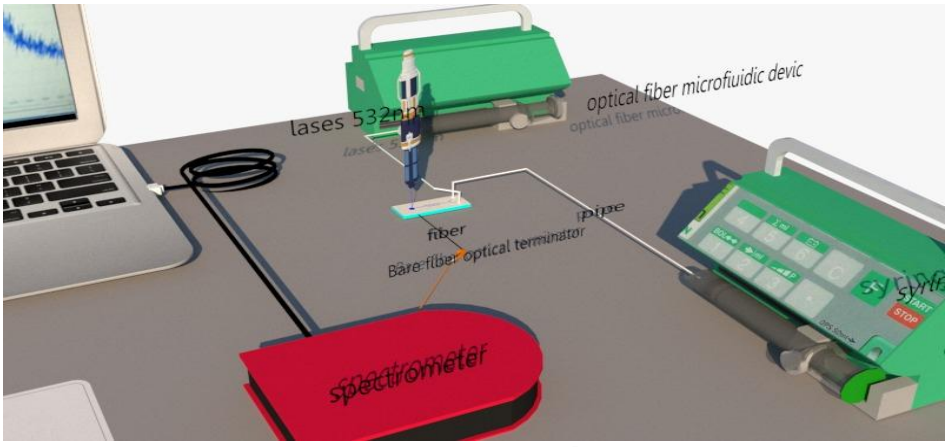

Figure 2: Experimental set up.

3. Results and Discussions

3.1 Surface characterization

Energy dispersive X-ray (EDX) was engaged for the elemental analysis of the polymer samples. Chloroform was used as an intermediate layer to create PMMA–PMMA constructs. Chloroform adhesive was chosen as it is considered to be biocompatible, thereby removing concerns about direct contact with materials inside the microchannels. Figure (3) shows sharp peaks due to the following elements: carbon (45.49 %), and oxygen (16.51%) in addition to chlorinel. Figure (4) shows the enery-dispersive X-ray (EDX) spectra for the elemental composition of PMMA and the chloroform adhesive. The results showed that PMMA was mainly composed of carbon (C) and oxygen (O), confirming their acrylic-rich nature. The occurrence of these elements generates charges on the surface of the polymer and create electrostatic forces of attraction between the sample and chloroform solution. These results agree with those of agree with Khamar and Prakash[5] and Hassanpour-Tamrin et al.[6]

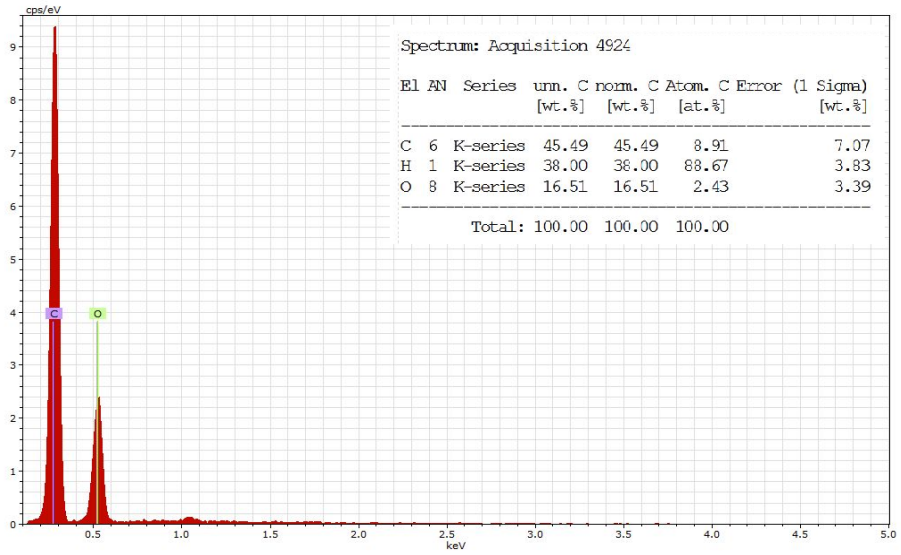

Figure 3: PMMA energy-dispersive X-ray spectrum.

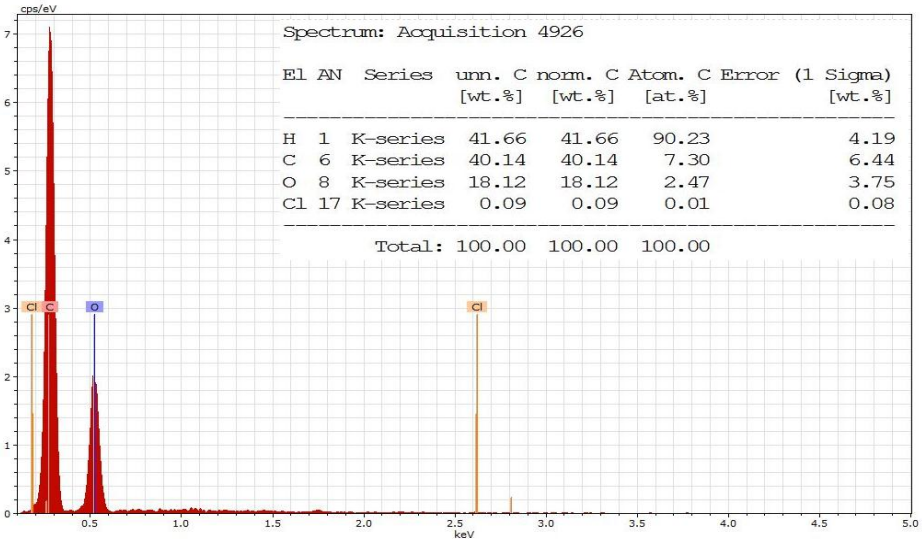

Figure 4: X-ray energy-dispersive spectrum of PMMA microfluidic chips with chloroform film as adhesive.

3.2 Fourier Transform Infrared Spectroscopy (FTIR):

The PMMA microfluidic chips with chloroform film as adhesive were studied with a Fourier transform infrared spectroscope (FTIR, IRAffinity-1S, and Shimadzu, United States). The FTIR spectrum of PMMA is shown in Figure (5). The FTIR spectrum of PMMA provides information on the functional groups present in the produced material. Due to the presence of ester, carbonyl group stretching, and vibration C=O, a strong intensity peak at 1720 cm^{-1} occurred. The stretching vibration of the C-O (ester bond) and. C-O-C may explain the large peak between 1260 and 1000 cm^{-1}. The band at 1431.8 cm1 is due to the bending vibration of the –CH3 group's C–H bonds. The wide band, 950-650 cm^{-1}, is caused by C-H bending. The large peak between 3100 and 2900 cm^{-1} is caused by the presence of stretching vibration. The FTIR spectra of PMMA microfluidic chips with a chloroform film adhesive and PMMA without an adhesive layer are remarkably similar, with notable variations in the locations of the lines suggesting wetness, which is consistent with prior results [7– 10].””

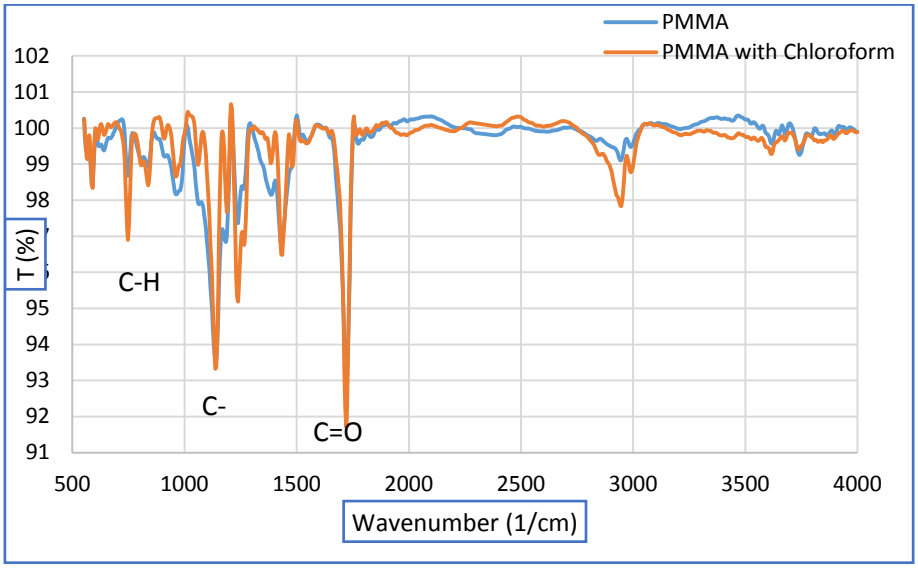

Figure 5: FTIR spectrum of PMMA microfluidic chips and FTIR spectrum of PMMA microfluidic chip with chloroform adhesive.

3.3 Effect of laser power and scanning speed on mechanical properties

Many of the parameters used to describe the mechanical properties of metals—such as yield and tensile strengths—are also used to describe the mechanical properties of polymers. For the characterization of several of these mechanical properties for various polymeric materials, the basic stress-strain test is used. For the most part, polymer mechanical properties are quite sensitive to the rate of deformation (strain rate). Figure (6) displays the microfluidic chip tensile strength as a function of laser power for various scan speeds, which is the typical stress-strain behavior. With a crosshead speed of 2 mm/min, the bonding strength was assessed using a standard lap-shear test apparatus (Tinus Olsen, H 50 KT, UK). Table 1 lists the mechanical properties that were tested for various laser powers of 20, 60, and 80 W and scanning speeds of 250, 350, and 500 mm/sec. These properties include tensile strength, elongation, and yield strength. As can be noted, the 60 W laser power and the scanning speed of 250 mm/s gave the best mechanical qualities of microfluidic Y shapes: yield strength of 20.72 MPa and tensile strength of 30.81 MPa, but the worst elongation value of 1.163 per cent. The best elongation value was at a laser power of 20 W and a scan speed of 500 mm/s. On the other hand, as the scan speed was reduced, the mechanical characteristics of the material increased. As shown, although laser scanning speed substantially influences tensile strength, the laser power has a greater effect on the mechanical characteristics, which is

consistent with its greater effect on pore defect. It is desirable to increase the laser power while decreasing the scanning speed, in order to obtain a smaller pore defect, a larger melt pool, improved mechanical characteristics, and high efficiency, it is desirable to increase the laser power while decreasing the scanning speed.

Elongation, the lengthening of the sample near the breaking point, is also a valuable characteristic. Elongation indicates how far a material can be stretched before it fractures. It can be noted from Figure (7) that when laser power is raised, the elongation-at-break of the microfluidic chips for form (Y straight channels) decreases. To a certain degree, an increase in tensile strength often results in a reduction in elongation. Effectively, the laser power leads to an increase in plasticity which reduces elongation. This is why microfluidic chips of 60 W power and 250 mm/s scan speed have the highest tensile strength but the lowest elongation-at-break. Due to the remelting process, the tensile strength rose. This enhanced contact between the two layers, which resulted in improving bond strength. The best yield strength value was at a laser power of 60 W and a scan speed of 250 mm/s shown in Figure (8). As seen in Table 1, all microfluidic chips have a yield strength that is lower than their tensile strength.. When a laser scanning speed of 250 mm/s was used, more heat was generated in the remelting zone per unit area and unit time than when a higher laser scanning speed was used. When the laser scanning speed was increased to 500 mm/s, with low laser power, the remelting zone became smaller. As a result, the influence on the tensile characteristics reduces also. The microfluidic chips of 60 W laser power and a scan speed of 250 mm/s have the best tensile qualities. This phenomenon may be explained by the fact that improved surface qualities reduce the likelihood of cracks and enhance the quality of mechanical properties. The finding that mechanical characteristics increase as laser power increases and scanning speed decreases is consistent with other results that have been reported [3, 6, 11– 13].

Table 1: Tensile Y shapes

Power W	Scan speeds mm/s	Tensile strength MPa	Elongation %	Yield strength MPa
20	250	13.83	3.58	9.68
40		18.42	1.78	12.42
60		30.81	1.163	20.72
20	350	11.68	5.57	7.73
40		14.55	2.42	10.1
60		26.22	1.307	18.41
20	500	7.09	7.2	6.79
40		11.8	3.13	8.25
60		20.81	1.577	15.83

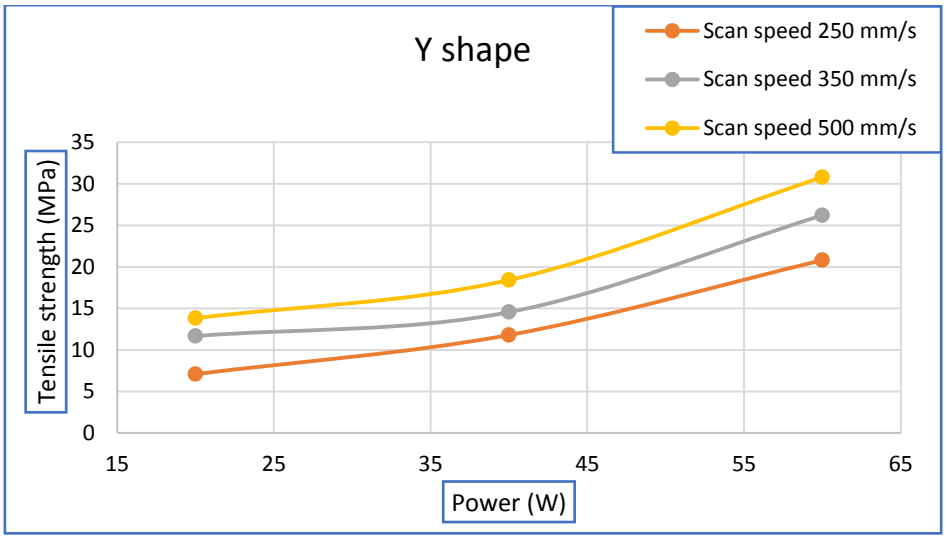

Figure 6: Tensile stress-strain curves of PMMA microfluidic Y straight-line microchannel. Laser powers of (20, 40, 60 W) and laser scanning speed of (250, 350, and 500 mm/s).

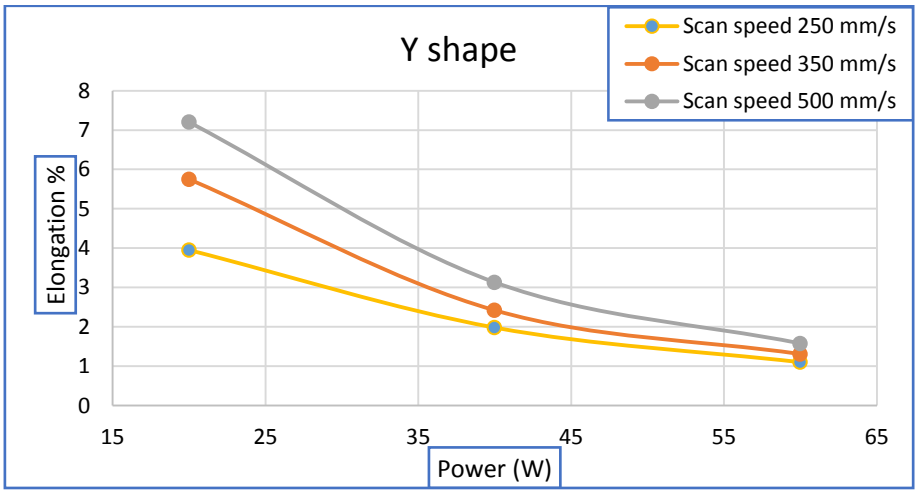

Figure 7: Elongation curves of PMMA microfluidic Y straight-line microchannel. Laser power of (20, 40, 60 W) and laser scanning speed of (250, 350, and 500 mm/s).

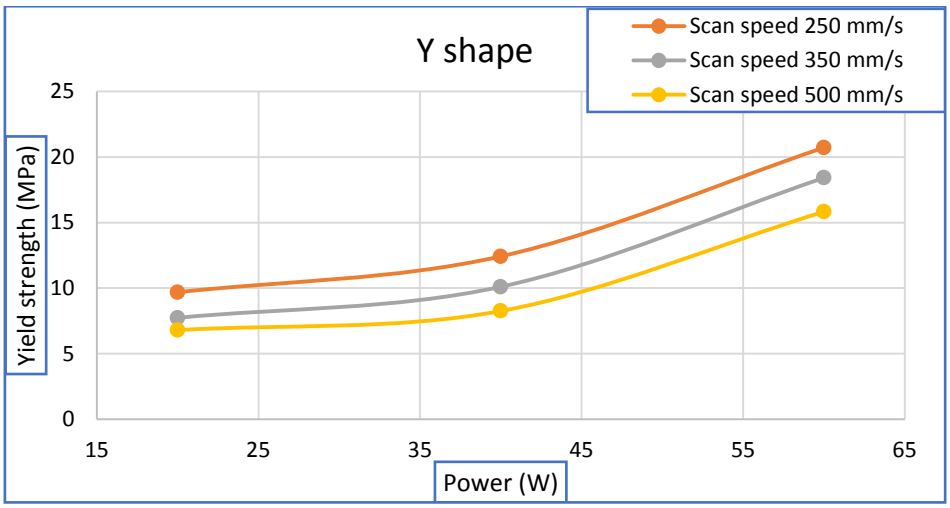

Figure 8: Yield strength curves of PMMA microfluidic Y straight line microchannel. Laser power of (20, 40, 60 W) and laser scanning speed of (250, 350, and 500 mm/s).

3.4 Surface roughness

Measurements of surface roughness were made with an RT-6210 surface roughness tester. The results of which are displayed in Figures 9 and 10 for a constant laser power of 20 W and various scanning speeds of 200, 350, and 500 mm/s, respectively, and in Table 2 for a scanning speed of 250 mm/s and various values of laser power (20, 40, and 60 W). Prior to and after laser machining, the surface roughness of PMMA substrates was assessed. Surface roughness of PMMA before laser machining is 0.45µm.

The data showed that after laser machining, PMMA's surface roughness increased because, during the ablation process, the PMMA sublimated right away. As the heat diffusion process, like all other diffusion processes, is random on the nanoscale, the PMMA surface was etched randomly on the atomic scale, resulting in increased surface roughness. Because the laser beam cannot ablate the whole material at the specified speed and power levels, some material remains in a liquid condition after the laser passes and re-solidifies later. As a result, the residual surface becomes smoother than before ablation. As seen in Figure (10), with a scan speed of 250 mm/s, a lower laser scan results in a smoother surface, Increasing the laser scanning speed (the number of times the laser passes) leads to a decrease in the depth of the channels along with a decrease in the roughness as well. This is because the second laser pass removes the roughness resulting from the previous laser passing pattern. This result agrees with those of Duan et al. [9] and Huang et al. [14].

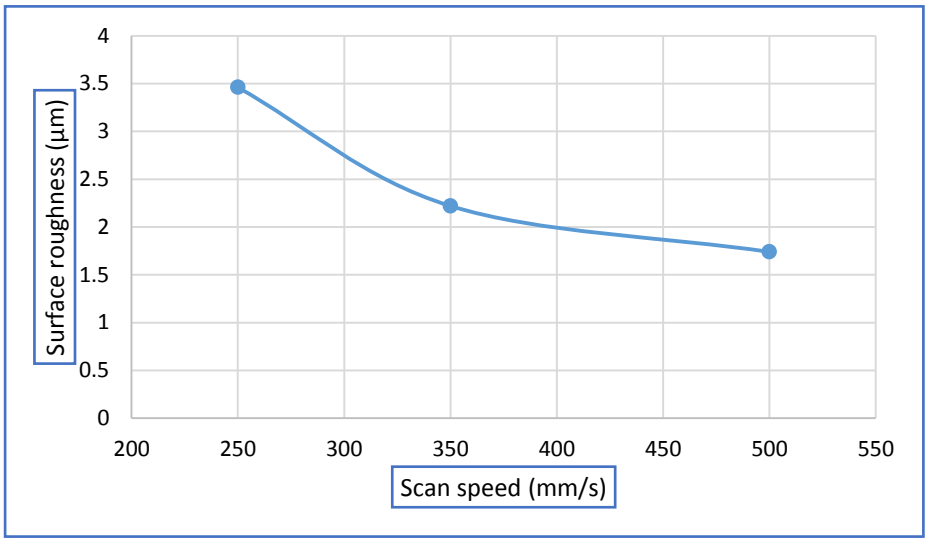

Figure 9: Surface roughness of PMMA microfluidic Y straight-line microchannel at laser power 20W.

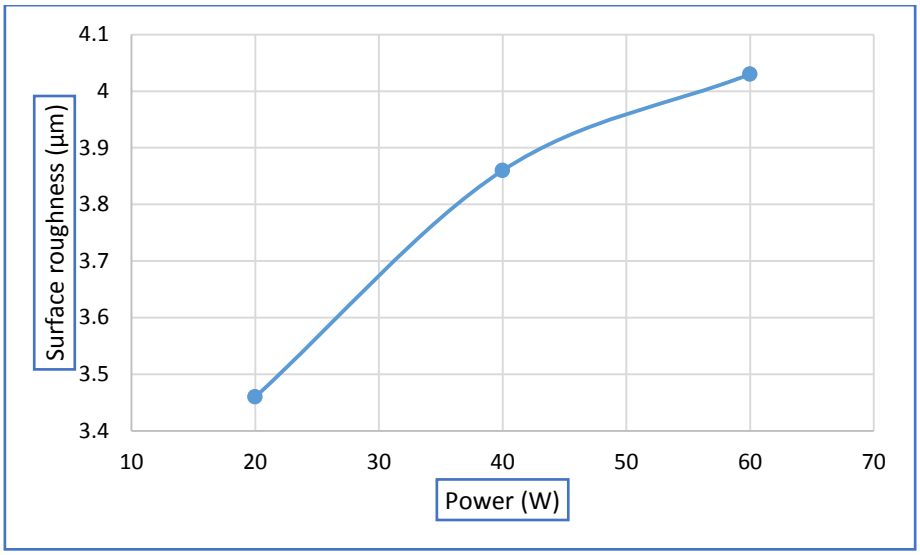

Figure 10: Surface roughness of PMMA microfluidic Y straight-line microchannel at scan speed 250 mm/s.

Table 2: Surface roughness measurements before and after laser machining.

Surface roughness measurements before the laser machining.		**0.45 µm**
Surface roughness measurements after the laser machining.		
Power(W)	Scan speed mm/s	Surface roughness (µm) Y straight line microchannel
20	250	3.46
	350	2.22
	500	1.74
20	250	3.46
40		3.86
60		4.03

4. Conclusion

Due to their increased adaptability, industrial scalability, cheap cost, and simplicity of handling and packaging, thermoplastics are emerging as a viable alternative to traditional materials in microfluidics chips with clinical or commercial applications. In this study, a technique for fabricating and assembling affordable PMMA microfluidic chips is presented. It was demonstrated that laser ablation is an appropriate technique for rapid and environmentally friendly channel engraving with a high degree of design flexibility, allowing engraving of channels with various dimensions, aspect ratios, and morphologies by controlling laser parameters. To assure repeatability, a combination of reduced power and scan speed was discovered to successfully minimize the surface roughness induced by the ablation process and thus prevent cracks growth. Additionally, the chloroform aided adhesive bonding enabling the attachment of PMMA layers at ambient temperature, even when surface imperfections exist. The accessibility and versatility of this technology as shown by our microfluidic devices together with the simplicity with which computer designs may be shared, may pave the way for cost-effective, microfluidic technologies with a high potential for translation from benchtop to clinic.

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