Development of Epoxy Resin-Based Elastomeric Microfluidic Devices Using CO₂ Laser Ablation for DNA-Amplification Point-Of-Care (POC) Applications: Assessment of Microchannels' Dimensions and Quality

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Abstract

Microfluidic devices are a rising technology to automatize chemical and biological operations. In this context, laser ablation has significant potential for polymer-based microfluidic platforms’ fast and economical manufacturing. Nevertheless, the manufacturing of epoxy-based microfluidic chips is considered highly cost full due to demand for cleanroom facilities that utilize expensive equipment and lengthy processes. Therefore, this study targeted investigating the feasibility of epoxy resins to be fabricated as a lab-on-chip using carbon dioxide laser ablation. The chemical structural properties and thermal stability of the plain epoxy resins were characterized by Fourier transform infrared spectral analysis (FT-IR) and thermogravimetric analysis (TGA). Moreover, a specific migration test was performed to quantify potential migrants by gas chromatography coupled to mass spectrometry (GC-MS) to prove that the cured epoxy resin would not release unreacted monomers to the biological solution test, which caused inhibition of the sensitive biological reactions. By investigating the impact of this process on microchannels’ dimensions and quality, a laser technique using CO₂ laser was used in vector mode to engrave into a transparent epoxy resin chip. The resulting microchannels were characterized using 3D Laser microscopy. The outcomes of this study showed considerable potential for laser ablation in machining the epoxy-based chips, whereas the microchannels were produced with minor bulges’ height (0.027 µm) with no clogging. Moreover, a reasonable depth of 99.31 µm with roughness (Ra) of 14.52 µm was obtained at a laser speed of 5 mm/s and laser power of 1.8 W. This process can produce epoxy resin-based microfluidic chips without the need for cleanroom facilities that require expensive equipment and lengthy process.

Introduction

During the past few decades, advances in micro-fabrication and nano-technologies enabled the development of analytical devices characterized by new capabilities and small sizes practical for diagnostic, pharmaceutical, analytical, and medical industries. Miniaturization of analytical devices has reduced sample and reagents consumption, in addition to new functionality, enhanced the sensitivity, reduced the time and cost than that of conventional analytical techniques [1]. Microfluidic chips are one of these miniaturized devices that have emerged as a promising technology recently in the last two decades. It has proved its competence astonishingly. Therefore, it experienced exponential developmental growth and became a prevailing tool with vast potential [2]. Microfluidic devices can be broadly defined pertaining to systems that manipulate or process small quantities of fluids (10⁻⁹ to 10⁻¹⁸ L), using microchannels of tens to hundreds of micrometers in dimensions [3–4]. More comprehensively, microfluidic devices are usually made up of miniaturized manipulation flow and fluid components, for instance, microchannels, micropumps, micromixers, and microvalves [5]. These miniaturized components forming the microfluidic chips are implemented and integrated with analytical and detection approaches such as chromatography, electrophoresis, fluorescence, and electrochemical detection) on microfabricated platforms to achieve the desired features such as on-chip reaction (microreactor), cell
culture (organ-on-a-chip), or on-chip analysis, i.e., separation and detection of various compounds or pathogens (lab-on-a-chip) [6].

It is worth mentioning that the microchannel particularities are greatly affected by the material type and microfabrication techniques. Therefore, choosing the optimum material for the device fabrication process is one of the fundamental steps in microfluidic technology [2], [7]. Specific essential properties must be considered when selecting the material, such as durability, biocompatibility, transparency, chemical compatibility with the implied reagents, ease of fabrication, withstanding the pressure and temperature conditions required for the reaction, and the feasibility of surface functionalization[7].

Numerous classes of materials were developed to match such properties and can be used to manufacture microfluidic devices. Typical substrates include glass, silicon, metals, polymers, and ceramics. However, each material has advantages and disadvantages, depending on its destination use. Polymers are broadly used in manufacturing microfluidic devices because of the diversity of the materials and the ability of chemical modification, providing a wide range of surface/material properties. There are various methods available for device fabrication, including casting, hot embossing, injection molding, soft lithography, micro-machining, etching, and laser ablation, in addition to lower cost with strong bio-chemical performances[2]. So far, Polydimethylsiloxane (PDMS), polymethylmethacrylate (PMMA), fluoropolymers, cyclo-olefin polymers, and copolymers (COPs/COCs), and thiolene polymers (TEs) are the most commonly used polymers for microfluidic device manufacturing [8].

Epoxy resin is an oligomer with a three-dimensional cross-linked network solidified by hardeners to form thermosetting plastics [9]. Owing to the superior characteristics of epoxy resins, they are considered significant engineering materials and are widely utilized in structural applications and protecting coatings [2]. Epoxy resins are among the most important thermosetting polymers that have attracted considerable attention in microfluidic technology because of their exceptional biocompatibility, good mechanical, chemical resistance, thermal stability, and toughness. [9].

Remarkably, indirect fabrication techniques like photolithographic techniques require the generation of masks and transforming techniques that need the fabrication of master molds. These techniques have lower flexibility and add a step to the microfluidic chips fabrication process, requiring access to clean-room facilities [10].

Microfluidic device creation using lasers has become a robust technology. CO\textsubscript{2} laser ablation provides several advantages, including low cost, quick prototyping time, and no requirement for chemicals or cleanroom facilities. Laser engraving has much potential for making polymeric microfluidic devices quickly and cheaply[11]. Glass, quartz, PDMS, polytetrafluoroethylene (PTFE), polycarbonate (PC), polystyrene (PS), cyclic olefin copolymer (COC), laminates, and paper have all been used in CO\textsubscript{2} laser patterning [12]. There is no study in the literature that we are aware of that uses applying CO\textsubscript{2} laser ablation to epoxy resin. This process can produce epoxy resin-based microfluidic chips without needing cleanroom facilities requiring expensive equipment and lengthy processes.
As a result, researchers are still seeking novel materials and inventing new fabrication processes to suit the criteria of high flexibility, quick turn-around, and low cost in producing microfluidic devices. Such requirements are considered a stepping stone along the pathway towards commercialization. Therefore, in this study, the casting method and CO$_2$ laser micromachining to develop epoxy resin-based elastomeric microfluidic devices that could be rapidly prototyped for molecular diagnosis (DNA- amplification Point of Care (POC)) applications.

**Materials And Methods**

The epoxy resin is composed of two components; resin: diglycidyl ether of bisphenol-A (DGEBA) and hardener: modified cycloaliphatic polyamine (Green Build Egypt company) with epoxide equivalent mass of the resin (185-190) and shore D Hardness =80.

**Preparation of Epoxy resin**

Epoxy resin was prepared (2:1.25); resin: hardener to obtain the minimum number of unreacted species cross-linked networks. Then the mixture was prepared by slowly stirring to avoid bubble formation. After evenly mixing the blend, the air was removed by applying a vacuum and then poured into a silicone mold. The curing process occurred at room temperature overnight.

**Characterization of Epoxy resin**

The epoxy resin's chemical structure and thermal properties were fully characterized by Fourier transform infrared spectrometry (FT-IR) (Shimadzu FTIR-8400 S, Japan) and Thermogravimetric analyzer (Shimadzu TGA-50, Japan), respectively.

**Migration Test**

A migration test was performed according to [13]. Briefly, to extract the migrants, a known surface of the sample was put in contact with a volume of distilled water for 2h on a magnetic stirrer at 150°C then, an aliquot of the extracts (2 mL) was evaporated, and the remaining were weighted in a sensitive balance then dispersed in 2 ml methanol. Finally, the resultant solution was analyzed to identify potential migrants by gas chromatography coupled to mass spectrometry GC-MS (Shimadzu GC-MS-QP2010, E-JUST) to prove that the cured epoxy resin would not release any unreacted monomers to the biological solution test, which cause inhibition of the sensitive biological samples.

**Autoclavability**

This test aimed to analyze the sterilization technique's influence and compare the material's characteristics before and after the epoxy chips' sterilization. Sterilization is vital for any item involved in medical procedures or biological experiments because contamination could damage them. In order to sterilize items, a standard autoclave with high-pressure and saturated steam at 121°C (MaXterile 60, DAIHAN Scientific, Korea) was applied. Due to the high temperature and pressure applied in an autoclave,
not all materials can survive autoclaving. In order to prove whether the autoclaving would damage the epoxy-based microchips by causing an adverse effect on them, they were subjected to an autoclave at 121°C for 20 minutes [14]. The epoxy resin cured chip dimensions were accurately measured and weighted before and after autoclaving.

**Laser micromachining**

The experiments on a 3 mm thick transparent epoxy resin cast chip were conducted by a commercial benchtop CO₂ laser (Universal Laser System, VLS 3.5, USA) with a maximum power of 30W, as demonstrated graphically in Fig. 1. The computer-aided design (CAD) tool associated with the laser cutter is CorelDrawX5 2010 software, used to draw the desired microchannels, as indicated in Fig. 2, which shows a pattern of the most commonly used channel shapes. The CO₂ laser cutter program has two modes that can be used depending on the width of the lines in the layout. The first is vector cutting for line widths less than 200 µm, and the second is raster engraving greater than 200 µm. The laser source follows a two-dimensional path based on the established CAD pattern in a vector cutting manner, whereas, in raster engraving mode, the designed pattern image is divided into an array of dots (with a resolution of up to 1000 dpi) for cutting in raster engraving mode [15]. Due to the plotter’s ability to accommodate eight different laser settings in one pass, the design was plotted on eight lines at a time. In order to characterize the effect of laser parameters on channel morphology, a full spectrum of data was collected using various laser settings. For this CO₂ laser, the primary input parameters, which affect the microchannel fabrication, are laser power (W) and scanning speed (mm/s), as outlined in Table 1. The output characteristics for the resulting microchannel have been taken as width of the microchannel, depth of the microchannel, surface roughness (Ra), and bulges heights. All output characteristics have been measured using 3D Laser microscopy. A 3D profile measurements laser microscope (KEYENCE VK-x100) was used to measure surface roughness (Ra), channel width, and channel depth.

| Parameters          | Values |
|---------------------|--------|
| Laser power (W)     | 1.8    |
|                     | 2.4    |
|                     | 3      |
|                     | 3.6    |
|                     | 4.2    |
|                     | 4.8    |
|                     | 5.4    |
| Laser speed (mm/s)  | 5      |
|                     | 7.5    |
|                     | 10     |
|                     | 12.5   |
|                     | 15     |
|                     | 17.5   |
|                     | 20     |

**Results And Discussion**

**Characterizations of epoxy resin**

**FTIR**

The chemical structure of the epoxy resin is revealed by Fourier transform infrared spectral analysis (FT-IR). FT-IR spectra of resin, hardener, and the cured epoxy resin were recorded by (Shimadzu FTIR-8400 S, Japan) in the 400–4000 cm⁻¹ wavenumber range. The primary IR bands of epoxy resins, as shown in
Fig. 3, are in 823 cm$^{-1}$ (stretching C-O-C of Oxirane ring), 911 cm$^{-1}$ (epoxy bend CH2-O-CH), 1503 cm$^{-1}$ (stretching of C-C of aromatic), 1601 cm$^{-1}$ (stretching C=C of aromatic ring), 2919- 2857 cm$^{-1}$ (stretching CH of CH2 and CH aromatic and aliphatic) [16]. The band's emergence at 1108 cm$^{-1}$ is typical of C–N stretching vibrations; as cross-linking progressed, the primary amine groups in the polyamine dimer were changed to secondary and tertiary amines. The disappearance of the band 912 cm$^{-1}$ suggests that epoxy rings have opened [17], as well as the occurrence of the curing process by the opening of the Oxirane ring and formation of OH, as well as the appearance of strong broadband at 3342 cm$^{-1}$ attributed to O–H stretching vibrations, indicating the occurrence of the curing process by the opening of the Oxirane ring and formation of OH.

**Thermogravimetric analysis (TGA)**

With the Shimadzu TGA-50 Thermogravimetric analyzer, the thermal stability of the polymer was investigated at a rate of 10ºC/minute in a nitrogen atmosphere. Temperatures ranging from ambient temperature to 500°C were used for TGA. TGA can be used to examine mass loss as a polymer’s temperature rises, providing for the determination of the maximum process temperature and the assessment of thermal stability and decomposition temperature.

The epoxy resin is stable up to 100°C, as shown in Fig. 4, and no mass loss occurs. At temperatures around 150°C, the pyrolysis of the epoxy resin reached only 6% at 149°C, 50% weight loss at 377°C, and practically complete dissolution at 500°C. Laser ablation methods typically use a maximum process temperature of 100 to 150°C. Temperatures higher than 100°C have little influence on the pyrolysis of epoxy resin up to 150°C, as illustrated in Figure 4. This method has been utilized for different polymer resins and is covered extensively in several publications [18]. As a result, future research will concentrate on increasing the maximum process temperatures [19].

**GC-MS for migration test**

This test aimed to characterize and identify substances, mainly oligomers, present in an epoxy microfluidic chip and may migrate into PCR solution and cause inhibition of the test. GC-MS analysis was performed to guarantee that the cured epoxy resin would not inhibit the on-chip PCR reaction by releasing unreacted monomers to PCR components. The cured epoxy samples were heated to 150°C, much higher than the denaturation temperature used in the PCR technique (95°C)[20]. The peaks are shown in Fig. 5a only belong to the used solvent, indicating no unreacted monomers or migrants from the cured epoxy resin. In a control sample, Dichloromethane (DCM) was added to dissolve and release the epoxy oligomer. Many released substances in the DCM were detected and identified by GC-MS in Fig. 5b; none of them was detected under our test sample. These results suggest using the cured epoxy resin for PCR applications and any other biomedical Lab-on-a-chip applications.

**Autoclavability**
In most biological applications, sterilization is a crucial sample pre-treatment step to avoid contamination [21]. In microfluidics, the most common problem is sterilizing chips; due to the increase of cell culture chips and organs-on-chips, the sterilization step becomes critical in microfluidics for any equipment in contact with sensitive fluids. Heat-sensitive items are harmed or destroyed during steam sterilization (autoclave) at 121°C. It is, therefore, necessary to know whether epoxy-based chips can be autoclavable or not. Following the autoclaving procedure, the weight and dimensions of the chip were measured accurately to compare before and after [14]. The results showed no difference in epoxy chips' weight or dimensions before and after the autoclaving procedure (data not shown). Our results indicate that epoxy resin chips could be used in high sterile conditions because they can safely undergo autoclaving. In vitro cell culture can create physiologically realistic microenvironments, allowing the emergence of cell and tissue culture-based microfluidic systems. Special sterilization procedures are required for microfluidic cell culture. Sterilization of microfluidic chips is an integral part of the fabrication process before being used in biomedical applications by customers [22]. There are numerous processes, but autoclaving remains the most prominent due to its low cost, ease of processing, effectiveness, and lack of toxic compounds[23]. On the other hand, other hazardous sterilization techniques include ethylene oxide sterilization and Hydrogen peroxide. Ethylene oxide is toxic and flammable; ethylene oxide remains on the surfaces, can cause hemolysis, and become carcinogenic[24], and the sterilization period is lengthy. In order to achieve sterilization, hydrogen peroxide plasma generates many free radicals, which adversely affects the sterilized material's chemistry [25].

**Effect of laser parameters on the aspect ratio**

The aspect ratio is calculated using the equation: Aspect ratio = microchannel depth divided by microchannel width [26]. It is observed from Fig. 6 that the aspect ratio decreases with increasing laser power. The maximum aspect ratio was observed at a scanning speed of 10 mm/s and power of 2.4 W, which takes a value of 1.691. The correlation between laser speed and aspect ratio is fluctuating, as shown in Fig. 7. As the scanning speed increases from 5 mm/s to 10 mm/s, the aspect ratio increases at all tested laser powers except at 1.8 W. At 12 mm/s, the aspect ratio decreases, while at 15 mm/s, a vast decline appears.

**Effect of laser parameters on microchannel width**

Figure 8 establishes that the CO₂ laser-ablated microchannel width increases with increasing laser power. The highest microchannel width was lower than 200 µm (165.858 µm) observed at scanning speed 5 mm/s and laser power 5.4 W. A certain amount of heat is not available for evaporation, the heat required to warm up the substrate reduces the evaporation process. Depending on the number of passes and the amount of power used, this can result in wider or narrower width channels. The channel width is determined by the laser beam's spot size [27], which is defined as the diameter of the spot where the irradiance exceeds the threshold value for ablation. Because the laser beam irradiance has a Gaussian distribution, the spot size defined in this manner is thus time-dependent. As a result, a slower-moving laser beam creates wider channels than a faster-moving beam [28]. The microchannel width decreases with increasing scanning speed, as Fig. 9 demonstrates, which agrees with [27].
Effect of laser parameters on microchannel depth

According to the experimental findings, the largest microchannel depth was obtained at scanning speed 7 mm/s, and laser power 3.6 W was 124.788 µm. By increasing laser power, the depth of the microchannels was fluctuating as shown in Fig. 10. The shallow channels were obtained at 15 mm/s at all tested laser powers, as demonstrated in Fig. 11. A microchannel with a depth of about 6 µm was successfully engraved at 15 (mm/s) and 4.8 (W), proving the potential of the laser-ablated epoxy resin to produce fine channels for various applications. Different laser powers and scanning speeds were tried in our preliminary studies. It was found that scorch and yellowish color began to appear by applying lower scanning speed and higher laser power. These affect the transparency of epoxy resin and make it challenging to monitor fluids that flow inside the microchannel.

Effect of laser parameters on microchannel quality

The heat introduced into the polymeric material while engraving a channel causes bulges running parallel to the channels or, in some cases, splashes [28]. This was noticed with the epoxy resin material under investigation. The bulges may impact the bonding efficiency in this area or even clog the channels [28].

Surface roughness and bulges heights are the two essential aspects of the quality of the microchannel for LOC applications. Bulges formed on the microchannel rim are a massive obstacle against bonding two materials to form closed and sealed microfluidic chips. Due to the gap formed from bulges, the fluid could leak, and the test will give wrong results. In addition, clogging formed from melted material would prevent the fluid flow inside the microchannel limit microfluidic technology [29].

Laser engraving has significant promise for the manufacturing of polymeric-based microfluidic platforms. The rapid and profitable quickly and affordably. However, the engraved areas of the manufactured devices have relatively bulky surface roughness, which disrupts smooth fluidic flow and damages sensitive biological components [11]. A 3D laser scanning microscope (Keyence VK-X100) was used to obtain the 3D topography of the channels in order to investigate the effect of different laser parameters on the surface quality properties and microchannels’ profile. The arithmetic roughness average (Ra), which is the average arithmetic height of surface irregularities (peaks and valleys) from the mean line during the scanning length, was adopted as a measure of surface roughness [22]. It is evident from Fig. 12a that the surface roughness increases as the laser power increases and decreases as the scanning speed increases. The best surface roughness was achieved from laser ablation of cured epoxy resin at high laser power (4.8 (W) and 5.4 (W)) and high scanning speed (15 mm/s and 20 mm/s), which showed the lowest values range from ≤8 µm to ≤2 µm, respectively.

Due to the laser’s long wavelength of 10.6 m, photothermal melting and evaporation are explained as the mechanism of CO₂ laser micromachining. [30]. The laser ablation process causes the ejection of the molten particles away by high-pressure evaporated gas. Bulges and clogging are formed from melted particles that resolidify at the rim or inside the microchannel [31], shown in the 3D laser microscope micrographs in Table 2 and Fig. 12b. At high laser powers, the bulge height increases up to 140 µm, while
no bulges are observed at low laser power (1.8 W). In addition to that, at high scanning speed (15 and 20) (mm/s), the height of the bulge was decreased to $\leq 40 \mu$m. Table 2 also demonstrates that microchannel clogging with varying laser power starts with partially clogging and ends with a totally clogged channel.

**Heat Affected Zone (HAZ)**

This section presents an investigation into the influence of the laser engraving factors on the heat-affected zone in CO$_2$ laser ablation of epoxy resin. Because of the unique qualities of laser light and specific material properties of polymers, laser ablation to produce microfluidic systems is only possible. Due to the obvious tremendous radiance of laser light, it is possible to generate extremely high irradiances at the workpiece surface[12]. A carbon dioxide laser generates light with a wavelength of 10.6 µm that is used for machining. [28]. Radial heat propagation beyond the laser-cut region of the polymer defines a zone in which thermally induced modifications are preserved: the polymer is usually distorted in this zone. This zone is referred to as the heat-affected zone (HAZ), and it can be detected in transmitted light by holding the laser-processed polymer between two crossed polarizers [32].

PMMA was laser ablated under similar conditions as epoxy resin and showed large HAZ width (493 µm), however after adding a thin layer of water to decrease HAZ; it was reduced from 493µm in case of air to 142 µm in case of water. The maximum HAZ obtained in air laser-ablated epoxy resin is less than 30 µm which is considered a small value compared with PMMA that showed HAZ width (493 µm) [32]. A more significant thermal conductivity of a material can lead to a larger HAZ [34]; The thermal conductivity of epoxy resin is extremely low. 0.2 Wm$^{-1}$ K$^{-1}$ [33], which explains the low HAZ in laser-ablated epoxy resin. It is evident from Fig. 13 that HAZ rises as laser power is elevated; even when scanning speeds are varied, the same pattern occurs at each speed, as illustrated in Fig. 14.

Table 3 Optical microscope micrographs of CO$_2$ laser-ablated epoxy resin
Conclusions And Future Work

Epoxy resin as a thermosetting material is evolving as a substitute for traditional material in microfluidic devices manufacturing owing to its higher flexibility, low cost, transparency, autoclavability, biocompatibility, industrial scalability, and easiness of handling. Here, we offer a method for fabricating epoxy resin microfluidic devices in a "mask-less" and cost-effective manner that can be used to construct a wide range of designs. Carbon dioxide laser-cut epoxy resin has been revealed to have the properties that make it a feasible substrate for lab-on-a-chip applications. We believe that this technique will offer for low-cost patterning of microfluidic networks with great automation throughput. The accessibility and flexibility of this method may pave the way for more cost-effective microfluidic technology. CO₂ laser micromachining was investigated for the first time with epoxy resin. Different laser powers range from 1.8 W to 5.4 W, and variable scanning speed (5 to 20 mm/s) were applied with cured epoxy resin. The results of our study demonstrated significant potential for laser ablation of epoxy-based chips, whereas...
the microchannels were produced with slight bulges' height (0.027 µm) with no clogging. Moreover, a reasonable depth of 99.31 µm with roughness (Ra) of 14.52 µm was obtained at a scanning speed of 5 mm/s and laser power of 1.8 W.

Further studies should extend this research into flow characteristics within these epoxy resin microchannels, which have not yet been analyzed. Further, the thermal stability can be improved by blending with flame retardant additives for more advanced applications. Another area of future study that could be pursued is the development of innovative epoxy composites for laser ablation microfluidics. This study will benefit lab-on-a-chip applications by providing insights into general channel topographies.

Declarations

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Availability of data and material The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate This paper is our original, unpublished work, and it has not been submitted to any other journal for review. The manuscript has been read and approved by all named authors, and that there are no other persons who satisfied the criteria for authorship but are not listed. All have approved the order of authors listed in the manuscript of us.

Consent for publication All the authors listed in the manuscript have approved the manuscript will be considered for publication in The International Journal of Advanced Manufacturing Technology.

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Author Contributions All authors contributed to the study's conception and design. Material preparation, data collection and analysis were performed by [Heba Mansour], [Ahmed M.R. Fath El-Bab], [Emad A. Soliman] and [Ahmed L. Abdel-Mawgood]. The first draft of the manuscript was written by [Heba Mansour], and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Tables

Due to technical limitations, table 2 is only available as a download in the Supplemental Files section.

Figures

![Graphical scheme of CO2 laser ablation process](image)

**Figure 1**

Graphical scheme of CO2 laser ablation process
Figure 2

The designed pattern a; 1 T-shaped channel, 2 straight channel, 3 cross-channel, 4 lateral channel and 5 Y-shaped channel. b Laser ablated cured epoxy resin. c and d Optical microscope and 3D laser microscope images for engraved microchannel
Figure 3

FT-IR spectra of a Hardener, b Resin, and c The cured epoxy resin
Figure 4

TGA of epoxy resin, max. Temperature 500 °C

Figure 5

GC-MS peaks. a Test sample and b Control sample
Figure 6

Effect of Laser power on the aspect ratio

Figure 7
Effect of scanning speed on the aspect ratio

![Graph showing the effect of laser power on microchannel width]

**Figure 8**

Effect of laser power on microchannel width
Figure 9

Effect of scanning speed on microchannel width
Figure 10

Effect of laser power on microchannel depth

Figure 11
Effect of scanning speed on microchannel depth

![Graph showing effect of scanning speed on microchannel depth.](image)

Figure 12

Effect of laser power on microchannel quality. a Ra (Surface roughness). b Bulges height

![Graph showing effect of laser power on microchannel quality.](image)

Figure 13

Effect of laser power on HAZ

![Graph showing effect of laser power on HAZ.](image)
Figure 14

Effect of scanning speed on HAZ

Supplementary Files

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- Table2.docx