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Feasibility of laser material processing in the design and manufacture of small scale devices

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1. Introduction

Micro- and milli-scale devices are small systems or production units with typical feature dimensions in the range of 200 μm – 2 mm. The devices discussed in this study were designed to mix fluids or to separate components. One of the main features of these kinds of devices is their high surface-area-to-volume ratio, which makes it possible to reach high heat and mass transfer rates simultaneously [1]. High heat flux enables accurate temperature control. The small internal size of the microreactors results in well defined residence time distribution and reduces the amount of raw materials present in the system. Together these make the handling of hazardous materials safer than inside a conventional reactor. These are the main reasons why chemical microprocessing technology has very promising applications within chemical, medicine, biochemical and pharmaceutical industry [2, 3].

Manufacture of small scale devices has conventionally been done by mechanical or chemical micromachining techniques like wet etching (lithography), deep reactive ion etching, LIGA (Lithographie, Galvanoformung, Abformung), abrasive jet machining (powder blasting) and electrical discharge machining [4]. Especially in chemical industry small scale devices are usually manufactured with wet etching.

Laser micromachining can also be used to manufacture these small devices. At the moment, there are not many real applications for small scale laser processing aside from laser marking. Cases presented in this study are possible applications for laser processing in chemical industry. The interest for laser micromachining stems from the realization that existing manufacturing techniques are not optimal; they are time-consuming, complex, environmentally risky, expensive, or the machining quality is not acceptable. Of course, the fact that lasers can not only cut and scribe materials, but also mark and weld as well only encourages further scientific study. The processes of laser micromachining are numerous: micro-cutting, welding, drilling, scribing and sintering. Combining different laser technologies is usually beneficial when small devices are manufactured. For example parts of the device can be laser cut and then welded together to form a new design [5].

Laser processing is a contact-free and flexible without toxic chemicals or masks, which makes it a promising alternative for wet etching. It has been accepted for the manufacture of small scale devices due to low and controlled heat input, high precision, good repeatability and flexibility which enables joining together similar and dissimilar materials without any additional filler or bonding materials. Laser welding can be scaled down to very small dimensions where other techniques are not applicable. Laser welding creates less distortion and has a smaller heat affected zone than conventional welding. Linear and non-linear shapes with narrow kerf can be laser cut. Lasers can readily be used to fabricate micro and milli-scale devices with clean, oxidation-free cuts [3, 6, 7].

The real benefits of using laser processing are typically based on creating new opportunities through cheaper product price, improved quality, faster throughput, and better design. Despite the high investment costs, typically defined to be a major drawback of laser processing, the advantages gained can usually ensure such a remarkable improvement that the use of laser processing can be justified [8]. The new generation of lasers will typically make these advantages even clearer due to improved efficiency and reduced thermal load [9]. On the other hand the lasers suitable for this type of production are not very expensive.

Some disadvantages of laser processing are: setting up and using a ready work station can be complex and difficult unless you are buying a turn-key system, finding optimal parameters can be time-consuming, quality of machining can vary slightly even though the same system and parameters are used due to some minute differences, and – more specifically to this case – difficult width and depth control when making grooves, except when machining with almost heatless ablation. Then the disadvantages are low material removal rate, expensive and complex machinery, and often small working area.

In 2008 Rimašauskas et al. studied the impact of laser and other high technologies on manufacturing efficiency in Lithuanian and Finnish sheet metalworking industry. They state that to achieve the expedient results the companies have not only to possess modern technologies; they have to exploit them optimally [10]. This study illustrates how to effectively utilize such a modern manufacturing technology in fabrication of small devices.

In this study the suitability of laser processing in the manufacture of small devices requiring precise engineering was investigated. Three small scale devices were designed and manufactured based on theory of chemical engineering and utilizing the advantages of laser processing; micro-distillation column, micro-vapor-liquid-equilibrium (VLE) device and the reactor turbine trip (TT). Laser welding was used in the manufacture of the distillation column and the micro-VLE device, laser cutting in the manufacture of the distillation column, and laser scribing

in the manufacture of the TT-reactor. Finally, the micro-VLE device and the microdistillation column were tested and found to operate as planned.

It was noticed that laser welding and cutting in milli-scale can save time and effort due to flexibility in design and accurate processing. Laser scribing is an accurate manufacturing method. Bottom and walls of the channels of the TT-reactor were smooth and straight.

2. Microdistillation column

To scale-up a new chemical process from the laboratory stage to the industrial scale, it is prudent to thoroughly test it first on a smaller scale. In the process development this is called the pilot phase. The scale of a pilot plant and the number of process units utilized depends on the phenomena studied and the specific goals. As a rule of thumb, a pilot plant must include as many units as required to obtain full confidence of the process. When studying the accumulation of impurities, the required units are the reactor and the separation steps used to recycle unreacted feed back to the reactor. Limiting factor in the reduction of the pilot-plant size is commonly the separation step [11]. The distillation column presented was designed to allow a significant reduction in the pilot-plant scale.

The advantages of laser processing were taken into account already in the design phase, which allowed the selection of a long and narrow shape instead of more robust one. These shapes would have been extremely difficult to fabricate using conventional manufacturing methods. However, selection of the fabrication method was done on a stage-by-stage basis [12]. Similar approach has been used with good results by Salminen et al and by Väistö [13, 14] for a bit larger components.

Fig. 1 shows the finished distillation column. The brass cylinder on the left was the reboiler section. It was used for the boiling of liquid inside the distillation chamber. Rest of the column was encased inside a steel shell. Temperature of the shell was controlled with electric heating cable to reduce heat losses of the column. The space between the steel shell and separation unit was filled with cellular foam. The reboiler and the protective shell were manufactured easily with conventional methods so this study focuses on the distillation chamber where vapor and liquid resides. Because of elevated temperature, wet and slightly corrosive conditions and small dimensions it was investigated whether laser technology would bring benefits in manufacturing such a device.

Fig. 1 Microdistillation column

2.1. Distillation chamber

Distillation chamber for the column is highlighted in the 3D drawing in Fig. 2. It was a 289 mm long square stainless steel tube with cross-sectional outer dimensions of 11×11 mm^2 and with a wall thickness of 3 mm. Straightness of the tube is critical in order to reach uniform liquid flow in the channel. Arc welding of a long thin tube with low enough distortion is nearly impossible, but the lower distortion of laser welding was acceptable. Despite the apparent simplicity of the distillation chamber, there were still many different ways to manufacture it. Welding it from four slides of steel was the first design. After cutting the strips with a 2.5 kW CO_2 laser, it was noted that the thermal effect of the cutting was negligible, but the internal stresses within the initial billet were high enough to bend the strips in two dimensions. It was not critical, though, and with a proper clamping system, the strips could well still be welded. However, other, better profile designs were found, as shown in Fig. 3.

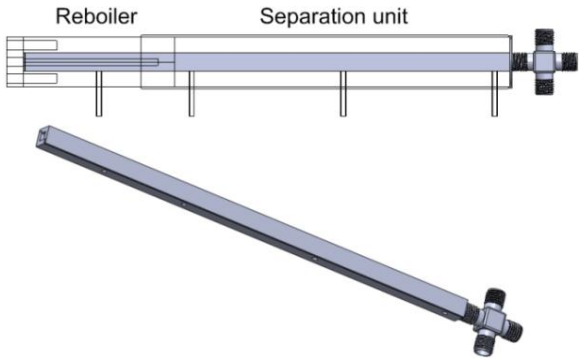


Fig. 2 Distillation chamber tube and a union pipe fitting

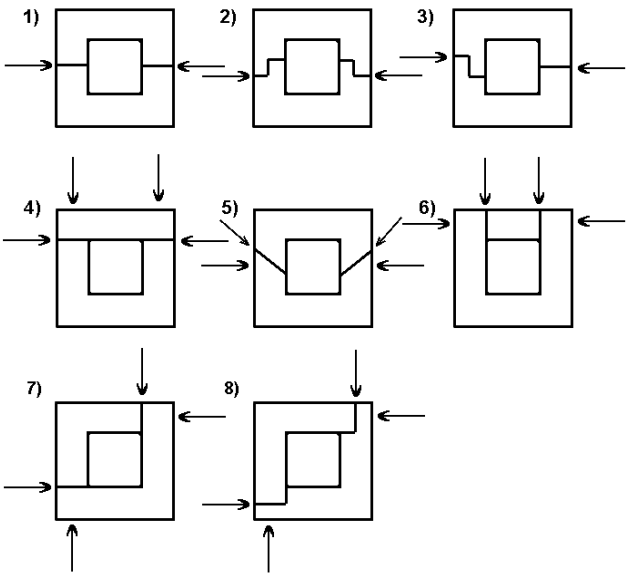


Fig. 3 Different chamber profiles. Arrows denote possible welding directions for laser welding

Options 1, 4 and 6 seen in Fig. 3 would probably be problematic because of the difficulties in aligning the parts. On the other hand, the joints are placed in such a way that positioning and aligning errors might be irrelevant (because the joint would not be in the corner) as long as the chamber can be machined to fit inside the reboiler. Option 2 shows a self-positioning design; Option 3 is a simpler version of it. Option 5 would be difficult to manufacture but is an interesting possibility for laser bevel cutting. Option 8 was chosen due to simplicity of manufacture and the ease of aligning the parts.

This self-positioning version has locally quite low material thicknesses and considerable difference in material thicknesses to be joined, which both makes conventional

welding risky as a lot of heat is introduced. Laser welding on the other hand is a gentler process and thus suitable for this application.

Fig. 4 shows the two parts of the chamber, ready to be welded together. A steel plate that seals the reboiler end of the chamber is also shown. The plate was tungsten inert gas (TIG) welded after laser welding the longitudinal welds. Fig. 5 shows the welding set-up. The chamber was welded with an IPG 5 kW fiber laser. Used laser power was 1.5 kW, welding speed was 3 m/min, focal point was on the surface and argon with a 25 dm^3/min gas flow was used as shielding gas.

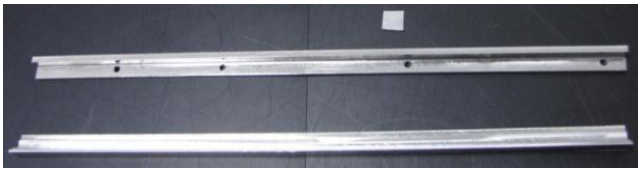


Fig. 4 Chamber walls; length 289 mm, width 11 mm

Welding head can be seen in the upper right corner of the Fig. 5 and the chamber clamped tightly in the center. The welding resulted in a narrow, hermetic, good quality weld with 1.5 mm penetration, which required no post-processing. Despite the small and long figure of the piece, no significant welding based distortions were observed.

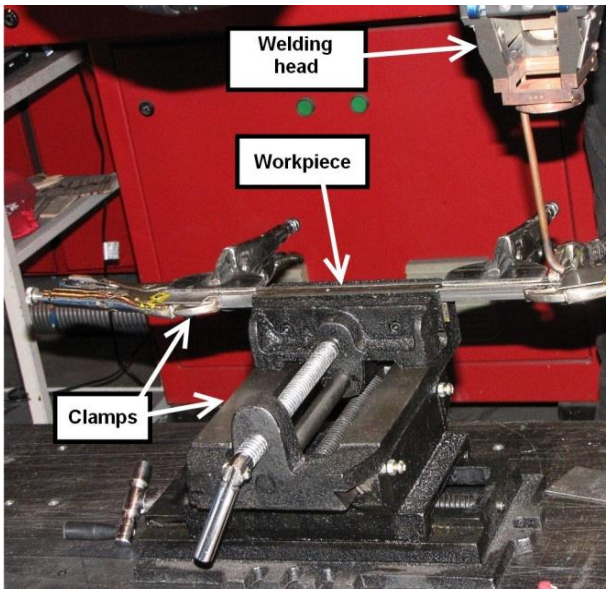


Fig. 5 Welding of the distillation chamber in experimental fixture

After the main body of the chamber was welded, a square stainless steel plate was TIG-welded onto the reboiler end and a union pipe fitting to the other end. Four 1/8" pipes were then soldered to the four holes in the body. Fig. 6 shows the finished part.

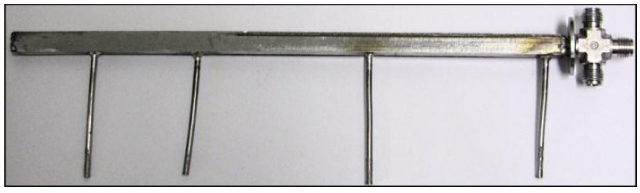


Fig. 6 Distillation chamber as welded

One part of the distillation chamber design was also to figure out how to attach metal foam packing inside the chamber. It was decided that whole of the chamber should be filled with foam, as seen in Fig. 7.

The foam was 3 mm thick open cell type nickel-chromium metal foam, manufactured by Recemat International. Model of the foam was RCM-NC-2733.03. It was cut into required dimensions with a 200 W fiber laser. Two slides of foam can be seen in Fig. 7, one is 3 mm thick and the other 2 mm. The 2 mm thick slice was manufactured by laser cutting one millimeter off of another 3 mm thick slice. In this case laser cutting was a superb method thanks to its low and precise heat input. The cut edges of the foam were of high quality and straight, and the pores of the metal foam were not clogged since the edge had rather vaporized and practically not melted at all, or, like in case of mechanical cutting, flattened.

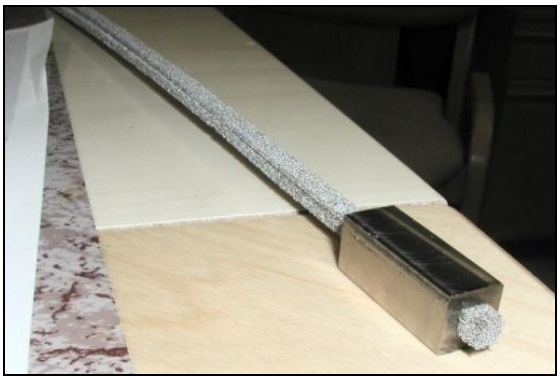


Fig. 7 Two slides of metal foam inside a shortest chamber

2.2. Final product

Fig. 8 shows all parts of the finished distillation column. Two hose clamps shown in the figure are for tightening the shell of the separation unit.

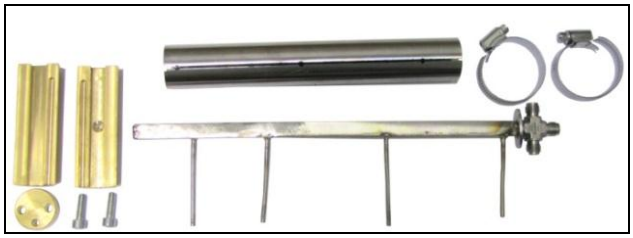


Fig. 8 Microdistillation column disassembled

2.3. Test methods and results

The finished product was tested by distillation experiments. Hot end of the column was heated with an electrical heater embedded in the brass cylinder. The temperature of cylinder was measured with a K-type thermocouple and the temperature was controlled with a proportional-integral-derivative controller (PID-controller). The column was insulated using a 9 mm thick layer of cellular foam. The steel shell was placed on top of the insulation layer and heated with an electric heating cable. The heating cable was insulated with a second layer of cellular foam. The condenser, located to the left in Fig. 9, was water cooled. The condenser was connected with Tygon®-pipe to the cold end of the column. Temperature of the cold end was measured through the union cross with a thermocouple.

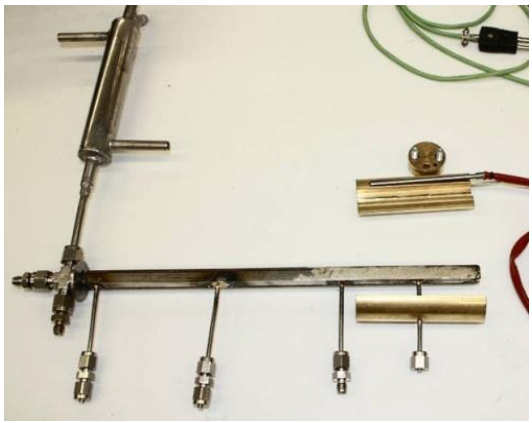


Fig. 9 The distillation column with condenser

The column was tested using an equimolar mixture of n-Hexane and Cyclohexane as feed mixture. Feed flow rates varied from (0.1 to 0.5) cm^3/min. Product hexane molar fractions were 0.405 and 0.735. Fig. 10 shows the number of theoretical stages (NTS) equivalent to measured concentrations at various feed flow rates.

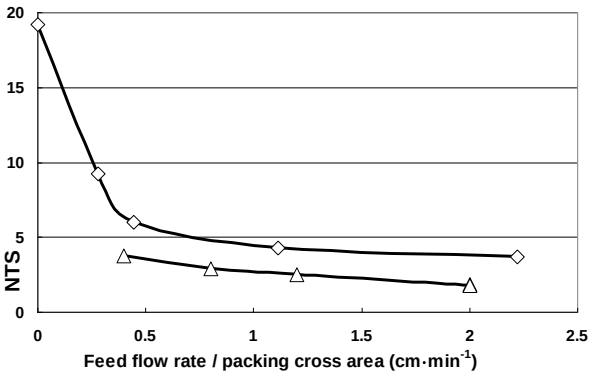


Fig. 10 Separation efficiency of the distillation column. ◇ represents a column with 30 × 3 mm^2 cross section. [15]; △ represents a column with 5 × 5 mm^2 cross section. X-axis is the feed flow rate relative to cross section (cm^3/cm^2 min). Lines are for visual aid

3. VLE device

Vapor-liquid equilibrium (VLE) is defined as a state in which the component flux between the phases is equal in both directions. Concentration in vapor phase depends on the relative volatility of the components. Distillation, which is the predominant separation method in chemical industry, is based on this phenomenon [6].

The purpose of this micro-VLE apparatus was to enable rapid temperature changes and to reach equilibrium faster. This was achieved with the help of miniaturization. Volume of the chemical inside the unit was reduced by a factor of 50 compared to traditional VLE-devices, which improved the safety of the experiments conducted with the unit.

A 3D CAD model of the micro-VLE-equipment is shown in Fig. 11. Material of this device was SS316L austenitic stainless steel because of its corrosion resistance and weldability. The device consisted of a pressure sensor and two valves. Because the parts were rather small, the welding was done by laser. The laser used in this case was the 5 kW fiber laser with a focal length of 63.5 mm.

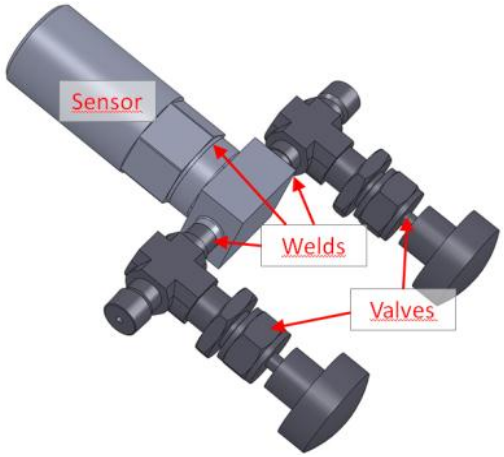


Fig. 11 Design of micro-VLE-device. Width of the device was 105 mm and length 115 mm

As the parts to be joined were small and the electronics of the pressure transducer (Druck PDCR 4021) was extremely sensitive to temperatures above the operating range (80°C) the heat input during laser welding had to be carefully controlled.

3.1. Preliminary welding tests

Aim and purpose of these preliminary welding tests was to find the right parameters for a good quality weld for the sensor with a diameter of 21.5 mm (Fig. 12, a) and the valves with diameters of 8.0 mm (Fig. 12, b).

a

b

Fig. 12 a) A preliminary test part for sensor (d = 21.5 mm); b) A preliminary test part for valves (d = 8 mm)

Parameters used in the preliminary welding tests are shown in Table 1.

Table 1
Parameters used for the preliminary welding tests of sensor and valves of the micro-VLE-device. Parameters used in samples 3 and 4 were chosen as welding parameters of the device

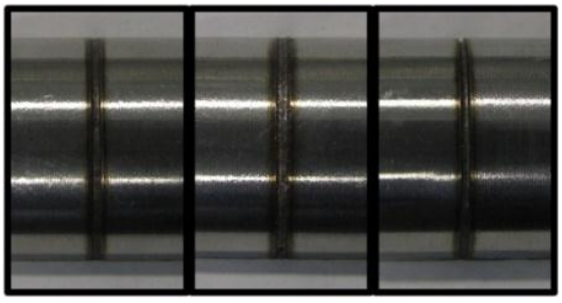
ID	Power, kW	Speed, m/min	Focal position, mm	Task	Comments
1	1.0	4.0	0	sensor	
2	1.5	4.0	0	sensor	
3	1.0	4.0	0	sensor	End slope
4	0.8	4.0	0	valve	
5	1.0	4.0	0	valve	
6	0.6	4.0	0	valve	4 tack welds, power 800 W
Laser: IPG 5 kW fibre laser, fiber diameter 150µm Welding head: Precitec welding head (focal length 63.5 mm) No shielding gas.					

In sample 3 laser power was reduced during the welding. In the beginning it was 1 kW then continuously reduced to 500 W during last 2 mm of the weld. Welding was continued approximately 2 mm longer to overlap the joint. Power was reduced from 500 W to 0 W during overlap. This was done for the sensor weld in order to improve visual quality and to ensure sealing of the joint.

Pictures depicting the visual quality of the welds are presented in Fig. 13. Joint cross section macrographs and penetration dimensions of the welding tests are presented in Table 2. Parameters used in tests 3 and 4 were selected for fabrication based on the results.

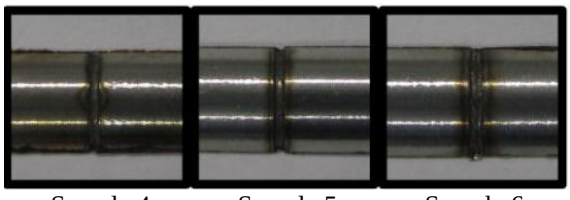
Results presented in Table 2 indicate that an increase in laser power changed the penetration depth and width of the weld. Too low laser power, as in samples 1 and 6, resulted in insufficient penetration. In samples 2 and 5, on the contrary, the laser power was too high and the weld was wider and the area of the weld was larger than in samples 3 and 4.

A visible micro-crack was observed in sample 2. Higher laser power caused longer cooling time of the weld and impurities in the material concentrated into the center line of the solidifying weld, causing the cracks.



Sample 1 Sample 2 Sample 3

a

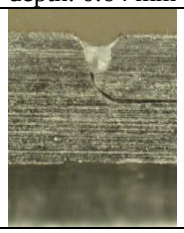


Sample 4 Sample 5 Sample 6

b

Fig. 13 a) Welds for sensor; b) welds for valves

Table 2
Cross profile pictures of trial welding tests. Width and depth are weld penetration dimensions

Welding of sensor, diameter 21.5 mm		
Sample 1 1 kW	Sample 2 1.5 kW	Sample 3 1 kW→0.5 kW → 0 W
width: 0.68 mm depth: 0.97 mm	width: 0.88 mm depth: 1.77 mm	width: 0.66 mm depth: 1.78 mm
		
Welding of valves, diameter 8 mm		
Sample 4 0.8 kW	Sample 5 1 kW	Sample 6 0.6 kW
width: 0.73 mm depth: 1.24 mm	width: 0.83 mm depth: 1.26 mm	width: 0.56 mm depth: 0.64 mm
		
Welding speed was 4 m/min and focal position 0 mm.		

Thanks to the reduced power used at the end of welding with sample 3 the quality of the weld at the ending point was improved. In visual examination no micro-cracks were found in samples 3 and 4. And also dimensions and the shape of the weld were clearly the best in these two samples.

3.2. Welding micro-VLE device

Welding was done using the same parameters as for samples 3 and 4 in the preliminary tests, shown in Table 1. First parts of the sensor were tack welded together to prevent the joint from opening during the welding. After this the part was fixed to a rotating unit and welding movement was carried out by rotating it.

Welds of the sensor and the valves are shown in Fig. 14. Based on visual inspection, the quality of the welds was acceptable.

3.3. Test methods and results

The device was leakage tested both in vacuum and in overpressure up to 5 bar (abs). The welds and the cell were found to be leak-proof and the pressure transducer was in operating condition. The preliminary VLE-test was conducted by measuring pure component vapor pressure for n-Butane over a range of temperatures. The purity as mass fraction according to the provider (Intergas) was 99.95%. n-Butane was degassed in the equilibrium cell by slightly opening the valve 4-5 times for a second. Then the cell was submerged in a temperature controlled water bath. Temperature of the bath was measured with a PT-100 sen-

sor connected to a temperature indicator (Ametek DTI 100). The pressure was measured with a Druck PDCR 4021 transducer (0-500 kPa full scale) connected to a Druck DPI-280 display. The results obtained from VLE measurement were compared with theoretical values based on the literature equations [16] as presented in Fig. 15. Average deviation was less than 2%.

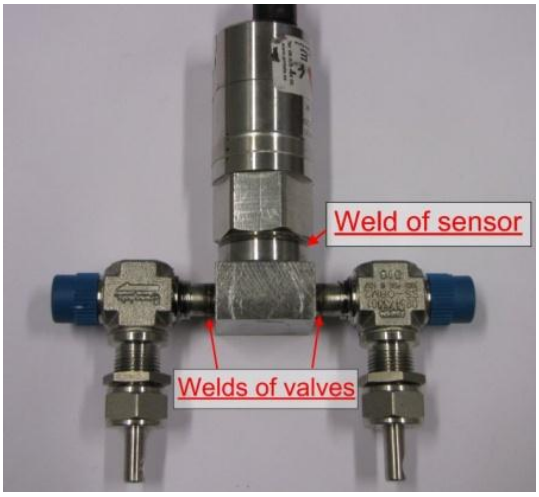


Fig. 14 Welded micro-VLE device

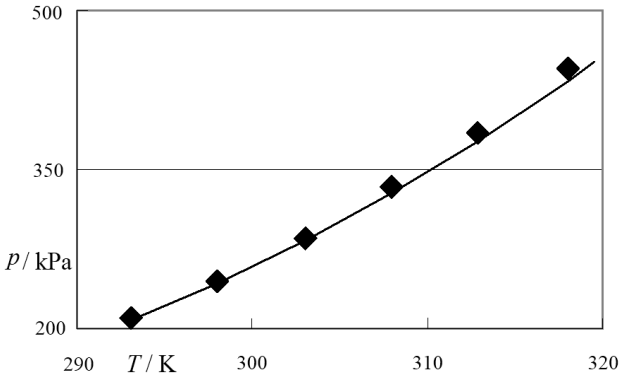


Fig. 15 Vapor pressure of ◆ n-butane. Solid line represents literature correlation [16]

Initial tests showed that the measured vapor pressures correlated fairly well with the pressures calculated from literature correlations. This shows that laser machining can be a valuable tool for manufacturing chemical micro process devices.

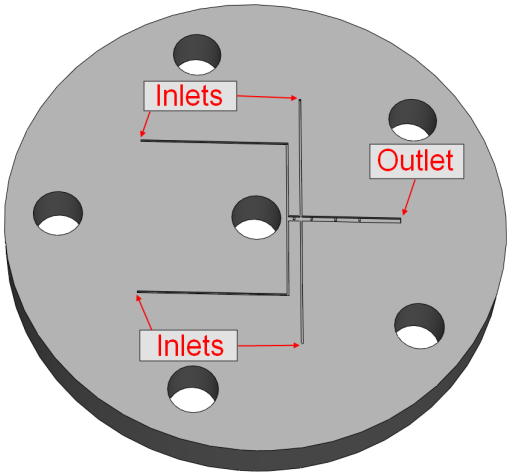
4. TT-reactor

Mixing of fluids is in the heart of most chemical reactions. Micro-channel mixers offer rapid mixing coupled with efficient heat transfer. They have very small internal volume which leads to a short and well defined residence time. They allow safer use of aggressive and hazardous chemicals and can be used even with fast exothermic reactions [5, 17].

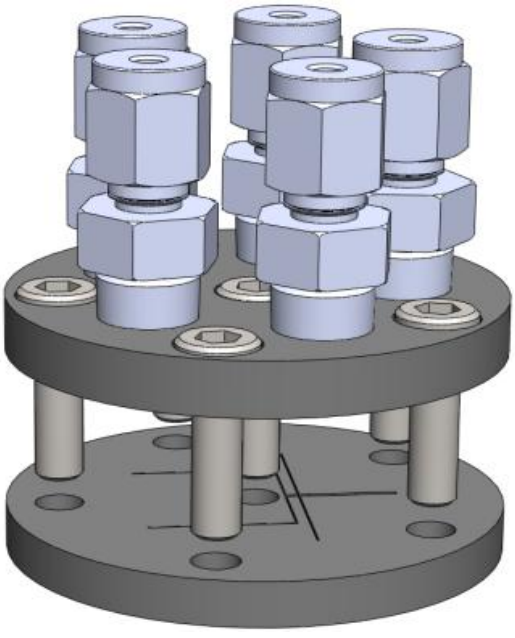
For the design of double-T micro-mixers (Fig. 16) variables on mixing efficiency was studied using computational fluid dynamics. The main design variables were channel depth, width and their ratio (aspect ratio), flow rate and channel configuration. The simulation results showed that all the variables had significant effect on the mixing efficiency. Thus, when designing this type of micro-mixer for a different purpose, careful attention has to be paid to the design variables [5, 17]. The TT–reactor manufactured in this study consisted of two circular metal plates, the top and the cover. They were manufactured from SS304 austenitic stainless steel. The channels were scribed on the cover plate with Lasertec 14 W diode pumped q-switched Nd:YVO_4 laser by Suomen EDM Oy. The choice of laser parameters was based on know-how of the company.

The TT-reactor had four inlet channels connected to an outlet channel. Mixing elements were scribed inside the outlet channel. Inlet channels were designed as 300 μm deep and 200 μm wide. Outlet channel was designed as 300 μm deep and 600 μm wide. Diameter of the four circular mixing elements was designed as 200 μm.

Scribing of the reactor took 3 hours using the Nd:YVO_4 pulsed laser. About 5.8 mm^3 of material was removed. Quality of the channels was found to be good, as shown in the Fig. 17. Both the bottom and the walls were very straight and smooth. The depth of the channels was measured with an Opto NCDT 1700DR optical profilometer.



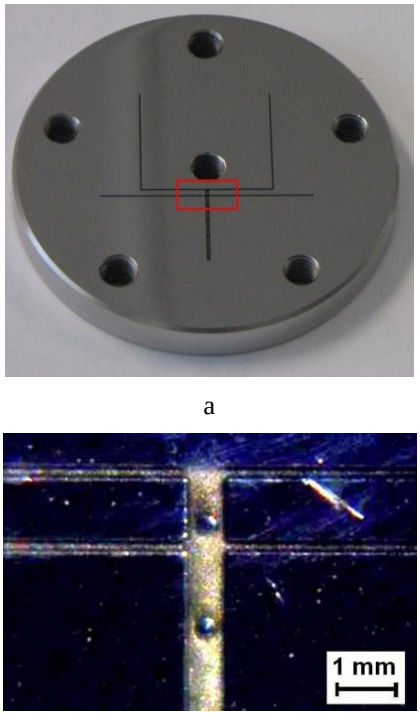
a



b

Fig. 16 TT-reactor model: a) channel plate, b) whole reactor model

Its measuring range was 10 mm and resolution 0.5 µm. Test grooves with known depth were used as a reference to test the accuracy of the measurements. It was found that the error of the depth measurements is 3% or less. The width was measured from the micrograhs. Depth and width of the inlet channels were 290 ± 20 µm and 200 ± 10 µm, respectively. Depth and width of the outlet channel were 290 ± 15 µm and 600 ± 10 µm. Diameter of the mixing elements was 280 ± 20 µm. No defects were observed. The slight deviation in both depth and width are within acceptable limits.



a

b

Fig. 17 a) Finished TT-reactor bottom plate; b) magnification of the mixing channel

5. Conclusions

Laser micromachining has gained considerable interest in the manufacturing industry. Lasers offer contact-free, flexible processing without toxic chemicals or masks. In this study suitability of laser processing in the manufacture of small scale devices that required precise engineering was investigated. Three devices were designed and manufactured utilizing the advantages of laser processing; micro-distillation column, micro-VLE device, and TT-reactor.

Main reasons for selecting laser processing for the fabrication of the microdistillation column were low and precise heat input and the freedom of the shape to be cut. Laser cutting was used to cut both stainless steel sheets and nickel-chromium metal-foam, which was used as distillation column packing. Laser welding was used to assemble the distillation chamber. Other steps of the manufacture were easier and more feasible to do with conventional methods. The final product functioned well with no leaking or other defects.

The cell for the micro-scale VLE-device was fabricated using conventional methods and assembled using laser welding. It was tested by measuring pure component vapor pressure. Results agreed fairly well with the literature correlation.

A TT-reactor was designed and manufactured for the purpose of mixing chemicals. Scribed channels and mixing element were fabricated very accurately without any defects. Scribing took 3 hours of time but the quality of the channels was very good. The bottom and the walls of the channels were smooth and straight.

Perhaps the best-known laser processes were used in this study. However, cutting of metal foam was an application not known in advance to be suitable for laser cutting prior to testing. It is a good example of a new application that is well-suited for laser processing.

It is important to realize three facts about laser processing: imagination sets the limits for applications; new lasers enable new working methods and new applications; laser is a cheap processing tool when used in full capacity. Laser processing is most productive when taken into account at the product design phase and not just as a last chance when everything else has failed. It enables designs based on product and customer needs rather than restrictions of manufacturing technologies. Declining laser prices along with affordable manufacturing services reduce the threshold of embracing this new technology.

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LAZERINIO MEDŽIAGŲ APDIRBIMO TAIKYMAS PROJEKTUOJANT IR GAMINANT MAŽŲ MATMENŲ ĮRENGINIUS

R e z i u m ė

Mažų matmenų įrenginių lazerinio apdirbimo ypatumai apdirbamojoje pramonėje yra aktualūs, bet realiai jie mažai naudojami. Šioje studijoje ištirtas trijų nedidelių įrenginių – mikrodistiliacijos kolonos, mikro-KIK (kintamo ilgio kodavimo) įrenginio ir TT (turbininio trapo) reaktoriaus – tinkamumas apdirbti lazeriu. Šie įrenginiai naudojami chemijos pramonėje, o jų matmenys yra nuo 200 µm iki 2 mm. Nustatyta, kad lazerinis apdirbimas tinka tokio tipo įrenginių gamybai dėl nedidelio ir tikslaus šilumos tiekimo suvirinant bei pjaustant ir laisvo tiek pačios medžiagos, tiek jos formos pasirinkimo, kas laikoma privalumu projektavimo stadijoje.

M. Hirvimäki, M. Manninen, A. Sundberg, P. Uusi-Kyyny, A. Salminen

FEASIBILITY OF LASER MATERIAL PROCESSING IN THE DESIGN AND MANUFACTURE OF SMALL SCALE DEVICES

S u m m a r y

Small scale laser processing has generated significant interest in the manufacturing industry but at the moment it still lacks real applications. In this study suitability of laser processing in the manufacture of three small devices that required precise engineering was investigated. These devices were: a micro-distillation column, a micro-VLE device and a TT-reactor. These devices are applications from chemical industry and have typical feature dimensions in the range of 200 µm – 2 mm. It was found that laser processing is well suited for the manufacture of these kinds of devices thanks to low and precise heat input when welding and cutting and freedom of shape and material to cut, which is an advantage best utilized already at the design stage.

Keywords: engineering design, laser processing, laser welding, microreactor, small device.

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