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Laser Engraving on a CNC Milling Machine

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Abstract

This article details how a commercially available diode laser (VoidMicro LD4070HF Pro) can be integrated into a conventional 3-axis CNC milling machine (HAAS Mini Mill Edu). Thanks to this development, the CNC milling machine is now able to perform a new machining process. The laser module has a major impact on the development of the secondary time, in addition to the rapid execution of engraving operations, i.e. by reducing the production lead time. During the production of a part, the marking of the product, such as QR code and barcode, is also carried out on a single machine tool, thus reducing the production cost. An additional benefit of integrating a laser engraver is that the CNC milling machine can also be used for laser cutting thin plastic and wood panels.

Keywords: *Laser diode, CNC milling machine, Engraving, Arduino.*

1. Introduction

The aim of the research is to make the 3-axis CNC milling machine (HAAS Mini Mill Edu) at the Bánki Donát Faculty of Mechanical and Safety Engineering of Óbuda University suitable for a new machining process. By integrating a commercially available laser engraving head (LD4070HF Pro), laser engraving operations are also carried out on the CNC milling machine.

Therefore, an additional machining operation can be carried out on the CNC milling machine, so that marking or engraving tasks can be fulfilled on a single machine, thus saving significant time and costs.

1.1. The justification for laser engraving today

Today, the dynamic evolution'of the competitive market is forcing machining companies to make better use of technical innovations. In the case of series production, the emphasis is on shortening the primary and secondary machine times (62 % of production costs **[1]**) and on the economical use of production tools, which enables manufacturing companies to optimise their production costs. Reduction of manufacturing lead, and lead times can be achieved by using new machining processes (e.g. trochoidal cutting (TPC), high-speed cutting (HSC), high-performance cutting (HPC) **[1]**) and new generation tools (multi-tasking tools (MTC)). In addition, we can reduce downtime and costs by trying to manufacture products using as few machining and production support machines as possible **[2]**.

1.2. Laser marking

In classical engraving, a small amount of material is cut from the surface of the workpiece at different depths, which creates the desired pattern, image, inscription or number sequence readable on the workpiece. Nowadays, almost all products are provided with an identification number, barcode or QR code (QR = quick response) to identify the product, so marking equipment, and marking lasers, are now used for these markings to increase productivity. Laser marking is most commonly used for metal and plastic parts **[3]**.

1.2.1. Laser marking of metal parts

Three types of marking processes are used by industry for metal parts **[3]**. One is engraving, where the laser beam power is so high that the material melts and partially vaporises (evaporates) during machining. This results in indentations of 10–50 μm in the workpiece [4]. In the case of deep engraving, laser engraving must be repeated several times at different depths to avoid distortion. With good alignment parameters, the cross-sectional shape of the engraving is U-shaped. The readability of the engraving is due to the fact that after the process the engraved surface is reflected differently by the light, thus making the laser engraving pattern readable. The process requires the usage of a high-power laser ($P > 50$ W)), such as a pulsed mode laser, Nd: YAG (neodymium-doped yttrium aluminium garnet) or Nd: YVO_4 (neodymium-doped yttrium orthovanadate). The focal spot of the laser beam is placed on the surface of the workpiece. This process is most commonly used in tool and die manufacturing or for engraving vehicle identification numbers [3, 4].

The other metal marking method is heat treatment and colouring. The process changes the structure of the material so that melting does not occur. The laser beam heats the material of the workpiece to a temperature below the melting point, which can change the fabric structure of the material and form a corrosion product on the surface with air components. The surface of the workpiece will then appear in different colours. In contrast to laser engraving, this process can be performed with a much lower energy pulse, allowing the use of machines with continuous wave lasers. The lasers used for laser colouring are continuous or pulsed transistors, pulsed Nd: YAG or Nd: YVO_4 lasers. In laser annealing or colouring, the focal length must be set above the surface of the workpiece, so that the laser beam only applies a large amount of heat to the surface, but does not melt it. This marking process is most often used by industry to mark medical devices, as it avoids the formation of indentations that can harbour bacteria. It is also widely used for marking measuring instruments (e.g. calipers) and tools. The disadvantage of this process compared to laser engraving is the longer machining time, so engraving is preferred by industry for mass production [3].

The third metal marking method is laser marking using a special paste. The main advantage of this method is that it can be used with low-power lasers ($P < 50$ W) For this reason, „laser paste” marking (available in spray, tape or diluted form) is the most common method of marking with CO_2 lasers. This procedure is only applicable to uncoated metals [3].

1.2.2. Laser marking of plastic parts

In the case of laser marking plastics, four laser marking processes are distinguished [5]. One of the marking process produces bubbles when heat is applied to the surface, and is therefore called foaming marking. During the process, the surface and surface roughness of the workpiece is changed, which makes the marking on the surface of the workpiece visible [3, 5].

The other method is thermal colouring, also known as marking of metallic workpieces. In this process, no material is removed from the surface of the workpiece, only the tissue structure of the material particles on the surface of the workpiece are altered by laser radiation, which can be either thermal or photochemical. In the case of thermal dyeing of plastics, it is also possible to perform thermal dyeing using a much lower power laser ($P < 50$ W) Both processes can be performed using pulsed lasers, Nd: YAG, Nd: YVO_4, CO_2 solid-state lasers and diode lasers [3, 6].

The third method is the engraving process presented for metallic components, while the fourth marking variant is coating removal by laser beam [5].

2. Methods

In the first part of the design, we identified the main tools to be used. The main criteria for the choice of the laser module were the price/performance ratio and ease of availability. In the case of a CNC milling machine, the main criteria for choosing the machine were the machine availability and the possibility of breaking the machine enclosure. In connection with control electronics, we also sought to ensure reliability and a favourable cost price, while ease of programming was also taken into account.

2.1. LD4070HF Pro engraving head

For the engraving head used, a laser module, LD4070HF Pro, manufactured by VoidMicro and widely used in hobby engraving machines, was chosen (Figure 1). The laser module produces a beam at 450 nm wavelength and a constant focal length (15 mm from the focusing lens). The input power is 40 W and the output power is 7.5 W. The system operates at 12 V and its power is controlled by a pulse width modulation (PWM) signal. The engraving head is not only capable of engraving due to its power, but also of cutting wooden sheets up to 3–5 mm thick and plastic sheets up to 3 mm thick [7].

Fig. 1. *LD4070HF Pro engraving head real and virtual appearance.*

Fig. 2. *Haas Mini Mill EDU*

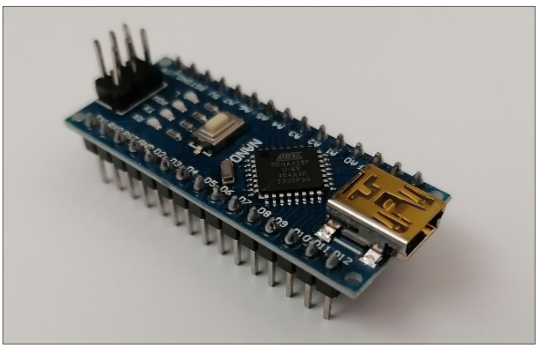

Fig. 3. *Arduino Nano microcontroller.*

2.2. Haas Mini Mill EDU CNC milling machine

The laser module application was designed for the Haas Mini Mill EDU CNC milling machine (Figure 2).

The CNC milling machine has a maximum speed of 4000 rpm and a maximum power of 5.6 kW. The machine tool has a working area of 406×305×254 mm. But does not have cooling system and automatic tool changer [8].

During the design phase of the project, the objectives of the project were defined taking into account the characteristics of the machine (CT 40 main spindle end [8], lack of cooling and tool change system).

2.3. Arduino Nano

The PWM (pulse-width modulation) signals used to control the laser module are controlled by an Arduino microcontroller in the case of custom digital controllers.

Arduino is a generic term that includes both a simple electronic circuit (hardware) and an open-source platform (software) based on a software development environment. The hardware consists of an electronic circuit built around an Atmel AVR microcontroller, while the software part is a C-based program called Arduino IDE, using the C++ programming language. Arduino can be used to create interactive objects, as it can receive and send digital signals and also process analogue signals. It can even control motors, sensors, lights, etc. The program, written with the Arduino IDE software, can be programmed to the microcontroller via USB after being translated into the appropriate language. The program consists of two main parts. The setup section contains the basic settings, while the loop section contains the actual operations to be performed. Consequently, the setup part runs only once, while the execution of instructions in the loop part is repeated in an infinite loop [9].

To save space, the laser module was controlled using one of the smallest commercially available Arduino Nano microcontrollers (Figure 3).

3. Building and controlling a custom engraving head

The design phase started with the reverse engineering of the engraving laser elements using Catia P3 V5R21 CAx software.

The factory laser module was built up of 30 parts, including screws, spacers and the control circuit board in addition to the main building blocks.

After reverse engineering, the mounting options in the main spindle were investigated. In the first concept, the original fan was replaced by two radial turbo fans, which would have been placed on the side of the laser module. As a consequence, the original length of 113.7 mm is shortened, making the laser module more robust and the cooling more intensive. The disadvantage of this concept is that the radial fans could be damaged during manual tool change, so we decided to use an axial fan instead of a radial fan based on the second concept. To further reduce the length size, it was considered appropriate to relocate the laser module controller.

During the reverse engineering, a mounting error was found in the original engraver's heat sink (hole enlargement with a hand tool). A mismatch of 0,3 mm was measured between the diameter of the laser diode and the bore of the heat sink. The laser diode was fixed with a M3×8 mm hexagon socket head screw (DIN 916 standard), which pressed the laser diode radially against the wall of the heat sink bore (**Figure 4**, area marked with yellow). Consequently, the significant heat generated by the laser diode was transferred along an edge to the heat sink, making the cooling efficiency questionable at a maximum laser power of 40 W. Due to the aforementioned shortcomings, we decided to design and manufacture a custom cooling fin and its custom mounting elements instead of the original laser diode housing.

3.1. Individual heat sink

In addition to maximising the cooling of the laser diode, the main considerations in the design of the custom heatsink were reducing its length, ensuring an adequate power supply, avoiding contamination of the focusing lens and measuring the temperature of the laser diode. The housing elements were made of AW-6082 aluminium. The chosen material has good strength, good machinability and good thermal conductivity.

The cooling intensity of the laser engraver was increased in several ways. In addition to creating fins in the cooling component, heat dissipation was increased by circulating compressed air in 14 holes around the laser diode sheath. At the laser diode location, a Ø20.7 mm H7 hole was drilled to ensure a seal between the sheath surfaces. To increase heat transfer, a heat-conducting paste was applied between the heat sink and the diode laser (**Figure 5**).

To measure the current temperature of the diode laser, we use an NTC 10K thermometer, whose signals are processed by the Arduino Nano. The measuring range of the thermometer is –30 –120 °C, while the accuracy is between 4–50 °C ± 2%. The measuring device can be integrated into DC 2.2–12 V electrical systems.

The electrical connection is solved by a 6-pin Pogo pin connector. To avoid damage to the Pogo pin contacts, 2 to 2 contacts are used to connect the diode laser to the controller. Due to the limited space availability, we designed a unique pin

Fig. 4. *Factory Cooling System Failure of the Laser Module.*

Fig. 5. *Top view of the heat sink.*

board for the Pogo pin connectors. The plastic element of the custom engraving enclosure was by made using a 3D printer (Creality Ender 3 v2) from PLA (Polylactic acid) material.

Since the CNC milling machine has no cooling system either outside or inside the main spindle, a compressed air-cooling system had to be built as part of the project. The compressed air is supplied to the cooling fins through a Ø6 mm pipe coil (Aventics TU1-S-PUR 006-0105-NT-100) via a pneumatic connector (Aventics QR1-AAN G014-DA06). The compressed air, in addition to cooling the heat sink, prevents contamination (soot build-up) of the focusing lens by directing the compressed air out of the laser diode housing in front of the lens, parallel to the laser beam.

The length of the case we designed is 85 mm, 25 % smaller than the original 113,7 mm. The new laser diode housing can be easily fixed by using industry-standard tool clamping devices (e.g. ER cartridge tool clamps). The symmetry axis of the custom heatsink can be adjusted within a range of 1 mm using 3 cage screws positioned at 120°, allowing the heatsink to be made uniaxial to the main spindle.

The final construction is made up of 62 elements, including screws, electrical connectors and gaskets in addition to the main components **Figure 6** illustrates a virtual model of the custom heat sink and the fabricated and assembled laser diode housing.

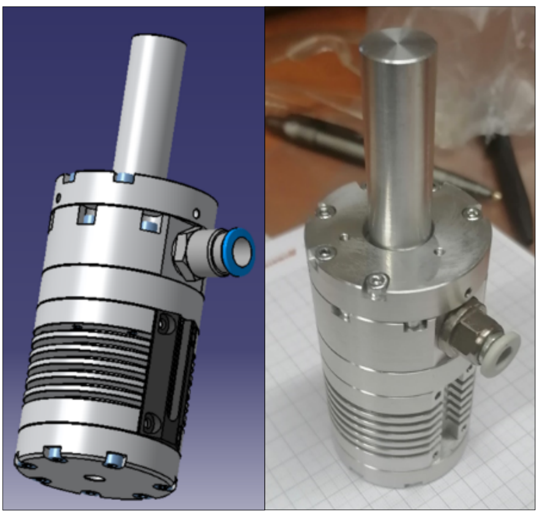

Fig. 6. *Virtual and real appearance of the assembled laser diode house.*

3.2. Housing of the power supply module

The electronic systems operate on 12 V and 5 V supply voltage. The electrical system of the CNC milling machine could not be used due to the warranty contract, so the power supplies for the electronic systems were built using the 115 V power socket on the side of the CNC milling machine. Since the Arduino control electronics system is sensitive to small voltage fluctuations, we used an AC/DC switching power supply module (PXK-2412DC-12V) to generate the power supply voltage for our electronics systems.

The power supply module was used to convert the 115 V (AC) voltage coming out of the power socket of the CNC milling machine to 12 V (DC) voltage. The resulting voltage is now suitable for powering the electronics of the engraving head, but further transformation is required to power the Arduino electronics. The generation of the voltage for the Arduino system is detailed in section 3.4.

For the electronics enclosure, we used a computer power supply enclosure. The cooling fan in the original power supply was used to cool the electronics. To ensure safe operation, we can interrupt the incoming 115 V voltage using a two-position toggle switch (ST 1/BK (MRS-1)), thus completely de-energizing the electronics we want to control. During machining, it is not possible to access the rocker switch due to the CNC milling machine door housing, so thanks to the CNC machine emergency stop switch housing, the 12 V generated by the power supply module can be interrupted by installing an Eaton m22-k01 opening contact. This ensured that the use of the emergency stop button not only locked the movements of the CNC machine, but also switched off the laser module and the electronics controlling the laser module. In addition, a digital voltmeter was installed in the power supply circuit to monitor the 12 V supply. To measure the laser diode power, we used an ACS712 5A Hall-element current sensor module, also mounted inside the power supply module housing (**Figure 7**).

3.3. Housing of the laser diode electronics

We designed a separate housing for the electronic control unit of the LD4070HF Pro engraving head, which we wanted to place on the side of the main spindle of the CNC milling machine. When designing the housing of the laser module's electrical circuit controller, we took into account that the engraving head manufacturer distributes

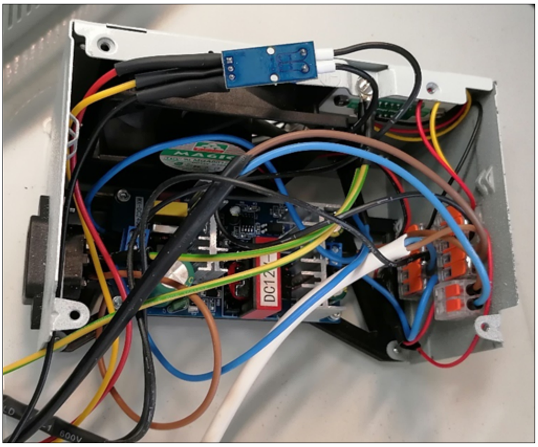

Fig. 7. *Housing of the assembled power supply module.*

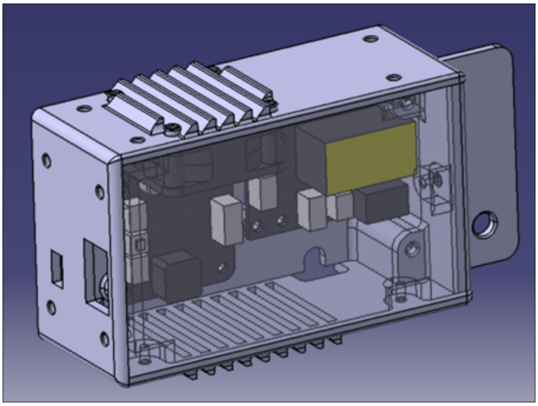

Fig. 8. *Virtual 3D drawing of a laser control circuit housing.*

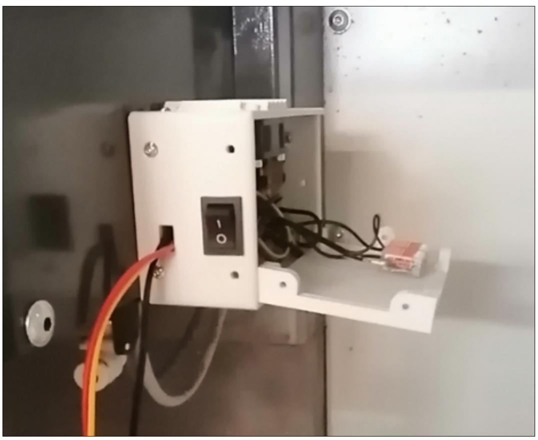

Fig. 9. *The control housing of the assembled laser engraver.*

an additional electronics interface and adapter board, which is used to provide several electrical connections to supply the laser module's electrical and control power. By using the aforementioned hub board, we decided to connect the electrical wiring through the pigtail on the hub for easy installation. In addition, the design of the enclosure took into account the need to cool the laser module's control electronics to avoid overheating at high power consumption. To this end, we can ensure cooling of the electronics by using the cooling fan in the original engraving head, so that a control built into the control electronics turns on the fan when the power consumption of the laser head reaches 3 % of the maximum power. **Figure 8** illustrates the virtual elements of the laser control electronics housing.

The housing enclosure elements were printed using a 3D printer using PLA in RAL 9016 colour code (**Figure 9**).

3.4. Housing of the controller electronics

Using the Arduino Nano, as described in chapter 2.3, it was possible to control not only the engraving head, but also other control electronics simultaneously. The designed Arduino program will be presented in chapter 4.1, in this chapter we will only detail the electronics to be incorporated and the housing designed to mount them.

For ease of assembly, a standardized terminal adapter board has been added to the Arduino Nano slot board. A voltage of 12 V is used by the LEDs of the pushbuttons (V19-11R-12G/R) in the custom enclosure. The operating voltage of the Arduino Nano is 5 V, so to transform the 12 V supply voltage, we used a STDN-3A24-ADJ factory number 3 A adjustable step-down DC-DC switching power supply module. To enable the Arduino to control the 12 V LEDs in the pushbuttons, a 4-channel bi-directional logic level-shift driver LS-BIDI-4 was used, which causes a 5 V signal connected to any of the 4 inputs of the circuit to produce a 12 V output signal.

When designing the engraving head control, we took into consideration the CNC milling machine's operating conditions. The push buttons „cycle start" (Eaton 216512 M22-D-G-X1/K10) and „feed hole" (Eaton 216510 M22-D-R-X0/K01) on the CNC milling machine not only allow to control of the start and stop of the active machining program on the CNC milling machine but also influence the operating status of the laser head by means of the Eaton 216376 M22-K10 contact elements mounted in the push buttons.

To generate and control the PWM signal, a 100 kΩ analogue 270° rotating potentiometer was used, so we could adjust the laser diode power during machining.

In addition to the electronics listed above, the electronics (pull-down resistor) for the NTC 10K type thermometer described in section 3.1 were also incorporated here. In order to facilitate the control of the laser diode, a 1602 LCD (Liquid Crystal Display) and associated control electronics were used to display data during the operation of the laser diode.

The design of the custom enclosure was not only based on the size of the electronic components, but also on aspects of ergonomics and aesthetics. When designing the enclosure components, we had to take into consideration the manufacturing conditions, so we had to keep in mind the range of motion (x-y direction) of the 3D printer used (Creality Ender 3 v2). In addition, the enclosure has been designed with a modular approach to allow for future expansion. The enclosure we have designed is illustrated in **Figure 10**.

For the cladding, we also used 3D printing to create a large part of the elements we designed, using PLA in RAL 9016. The front panel was laser-cut from a 2 mm thick stainless-steel sheet (X5CrNi18-10) for aesthetic appearance (**Figure 11**).

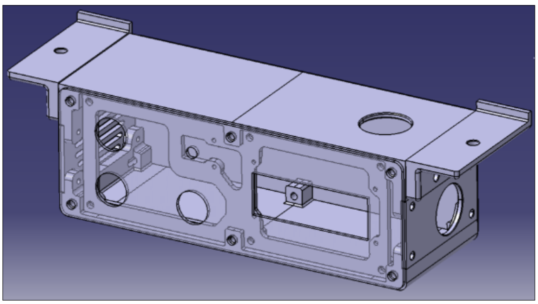

Fig. 10. *Enclosure of the electronics for the engraving head controls.*

Fig. 11. *Enclosures for laser head control electronics.*

4. Operating a diode laser using a CNC milling machine controller

The operation of the laser engraver was solved by 5 M-code controlled relays (I/O PCB output) on the Haas Mini Mill EDU controller electronics. The relays can operate in two ways. In the first case, by using the appropriate M-code, the contacts of the relays, which are isolated from the CNC milling machine circuits, can control up to 3 A current at 120 V AC. The relays are of SPDT (Single Pole Doble Throw) design, allowing one relay to control up to two devices simultaneously. In the other mode of operation, the relay can be put into operation by calling another M-code command, which operates until the controlled electronics sends an M-fin signal to the CNC milling machine controller, which switches the relay position to the home position **[10]**.

4.1. The driver program running on the Arduino

After supplying the Arduino Nano's input with 5 V supply voltage (STDN-3A24-ADJ), the program in the Arduino's Flash memory is run continuously. The Arduino IDE program mentioned in section 2.3 was used to create the program to control the electronics. During the creation of the program, we decided that we wanted to operate the engraving head in two different ways, so we designed and built the electrical systems accordingly.

Once the Arduino's system is powered on, the setup part of the program is run and then the „Test" mode in the loop part of the program is automatically started. In the test mode, we can manually operate the engraving head by pressing the V19-11R-12G (green LED) type push button connected to the digital leg 2 (input and output) of the Arduino. The laser module operates at the 10 % PWM signal level set in the program until the push button is pressed. This allows the laser module's operability to be tested, and also provides a visual indication of the exact position of the main spindle centre on the workpiece surface (a useful feature in case of orientation). In addition to the continuous illumination of the green LED mounted on the push button, the LCD display is also used to clearly inform the operator of the status of the control cycle (**Figure 11**).

Another mode in the loop part of the program running on Arduino is the Cycle mode. In Cycle mode, the Haas controller can control the laser module after several conditions are met. The cycle mode can be entered by pressing the pushbutton that remains in the position marked V19-11R-12R-S (red LED), which is connected to the digital leg 3 of the Arduino. The program then continuously checks whether the Arduino's digital leg 7 is receiving a signal from the relay M21, one of the relays that can be operated with code M as described in Chapter 4. In addition, by pressing the pushbuttons for the CNC milling machine's cycle start and feed hole (Eaton 216376 contacts marked M22-K10), the laser head can be turned on and off while the program is running on the CNC milling machine. Therefore, pressing the „feed hole" button will also turn the laser engraving head off when the CNC milling machine is paused, while pressing the „cycle start" button will resume the CNC milling machine program and turn the laser head back on. To indicate the cycle mode, the LED light of the pushbutton marked V19-11R-12R-S is lit red and the LCD display shows that the Arduino is currently in Cycle mode.

In its current state, the laser power (PWM signal magnitude) can only be controlled manually using the 100 kΩ analog 270° rotating potentiometer described in section 3.4. The middle output of the potentiometer is connected to the A0 leg of the Arduino (analog input 0), so I proportional the amount of resistance that can be influenced by the potentiometer to the value of the PWM signal level.

The effect of running the CNC program is to display the value of the potentiometer position in percentage on the LCD display, and in addition the power value calculated from the current value measured by the ACS712 5A Hall-element current sensor module described in section 3.2, the temperature measured by the NTC 10K thermometer described in section 3.1 is also displayed. This allows us to check the power value recorded by the laser module during machining and the magnitude of the thermal expansion due to the loss during laser diode operation.

While writing the Arduino program, we checked the correctness of the program parts in virtual space using Autodesk Tinkercad software. The circuit design module of the Tinkercad software can control the circuits assembled in virtual space, making it much easier to create a program running on the Arduino Nano, since in reality an electrical fault (for example: a short circuit) can cause fatal damage on the Arduino circuit. By using simplified virtual copies of the switches, resistors and other electronic components used in real life, we were able to design the wiring locations for the control electronics. In addition, when running the controller program, the Tinkercad program also visually displays any errors that may occur due to program errors (for example: LED malfunction).

After the control program was written in the Arduino IDE software and verified in the Tinkercad software to run without errors, we loaded the control program onto the Arduino Nano microprocessor we used. After some minor modifications (connecting the pull-down resistors), the control program worked perfectly.

Using Catia P3 V5R21 CAx software, we created an engraving etching cycle. After postprocessing, the on and off commands were replaced by M codes to control the I/O PCB output (relay). The test program run was executed without errors (**Figure 12**).

5. How to operate the laser safely

When using laser light, the operator's skin and eyes must be protected. Direct exposure to laser light can cause serious injury to the skin or eyes. However, even in the case of scattered (reflected) laser light, skin or eye injuries must be prevented. During the design of the project, it was determined that the enclosures of the CNC milling machine would prevent the skin from being damaged by scattered laser light. To protect the human eyes, protective goggles were required because the laser diode used is Class 4 according to IEC 60825. The required safety glasses have the property of being able to filter light from 190 nm to 540 nm with an optical density (OD) value of 5.

Fig. 12. *Laser engraving made by the test program.*

6. Conclusions

This article describes in detail how to integrate a diode laser in a commercially available laser engraving head (LD4070HF Pro) into an industrial CNC milling machine.

A cornerstone of our development project was to reduce the length of the original LD4070HF Pro laser engraving head to 113,7 mm. In the design, we thus sought to reduce the length dimension, so that the total length of the cooling fins and associated components of the laser engraving module we designed is 85 mm, which is 25 % less than the length of the original laser module.

In order to increase the cooling intensity of the diode laser, we have designed a custom heat sink. The cooling of the laser module was provided in several ways. A Ø20.7 mm H7 mating hole in the heat sink provides a temporary fit for the diode laser. A significant part of the heat generated during the operation of the laser diode is dissipated by compressed air flowing through 14 holes in the individual heat sink fins. The compressed air exiting the heat sink is forced to the focusing lens of the diode laser to prevent soot deposition on the lens.

This article describes in detail the electronic systems we have designed to operate the laser module and the specific enclosures we have designed for them.

It will also be shown how to operate the laser engraving head using the CNC milling machine controller. The laser engraving head we have designed (**Fig. 13**) and its associated accessories are capable of measuring and displaying the power drawn by the laser diode and the current temperature of the diode laser during machining.

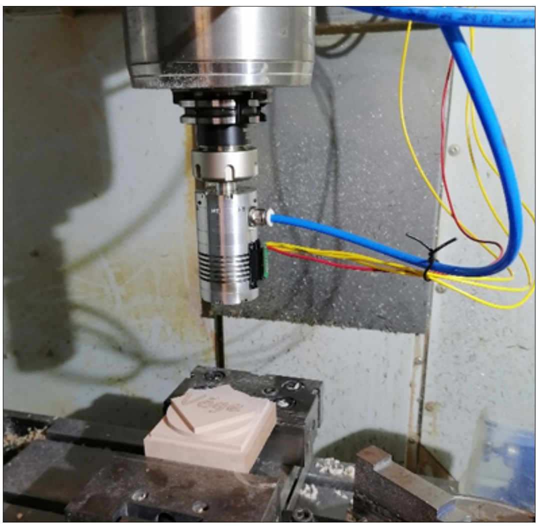

Fig. 13. *Laser engraver in the main spindle.*

The material cost of the project, which includes the electronics, wiring, fasteners, raw material for the cooling housing elements and the diode laser, amounted to 320 EUR.

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