Effect of laser beam cutting parameters on productivity and dimensional accuracy of miniature spur gears of stainless steel

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Abstract. Product quality and process productivity are one of the major indicators to evaluate the performance of any manufacturing process. The quality of any product covers its appearance, geometric and dimensional accuracy, and surface finish and integrity that majorly include microstructure, micro-hardness type of parameters. Whereas, the productivity can be determined using material removal rate. Laser beam cutting is an important advanced machining process and has been scarcely explored for miniature gears. This paper reports, the effect of laser beam cutting parameters on one of the quality parameters i.e. dimensional deviation of miniature spur gears of stainless steel and material removal rate. Box Behnken design of experiments methodology has been adopted to conduct a total of twenty nine experiments where four important laser parameters i.e. power, cutting speed, focal position, and gas pressure have been varied at three levels each. The manufactured external spur gear of stainless steel consists of ten teeth, 0.750 module, 9.04 mm outside diameter, and 4.5 mm face width or thickness. The investigation found that cutting speed significantly affected material removal rate and laser power affected dimensional deviation. Individual effects of laser parameters on both material removal rate and dimensional deviation are discussed in detail in the chapter. The investigation identifies laser beam cutting as a viable substitute of conventional manufacturing processes for fabrication of quality miniature gears with high productivity.

1. Introduction
Modern manufacturing trends have shifted towards miniaturization as industries like aerospace, automotive and bioengineering have an increasing demand for small devices, which are called micro electromechanical systems (MEMS) [1]. We all experienced the transformation of society by the emergence of computers and communication systems, information technology, microelectronics and knowledge-based industry, but the computer systems evolution is the one that started the miniaturization process of the electronic components involved. Although initially the miniaturization was mainly applied to two-dimensional electronic circuits, nowadays this is applicable to three-dimensional devices and systems with greater potential for revolutionary technological and
economical changes in our society. The major advantage of miniaturization is the extreme reduction in
cost as minute components and devices require less material and energy to be produced, less space for
storage, transportation and disposal which ultimately equates to much better use of resources and
minimized adverse effect on the environment [2].

The challenge in the fabrication of miniaturized devices remains the capability to manipulate
material at micro and nano level and to achieve that in an economical way. A basic approach to direct
downscaled corresponding system to microscopic scale is not practical due to scaling effects
therefore, a major shift in approaching design and manufacturing processes is expected.

Micro gears are one of key components of miniaturized devices and on their quality depends the
functional characteristics of these devices therefore, requirements for an accurately controlled
manufacturing process are high. The gears with an outside diameter less than 10 mm are generic called
miniature gears with a further classification as meso-gears for outside diameter between 1 and 10 mm
and micro-gears for an outside diameter less than 1 mm [1, 2]. These gears may have power
transmission requirements or precision requirements. The precision miniature gears have a relative
fine pitch and are usually smaller in diameter and require a combination of motion transmission and
high index accuracy with low backlash. Their precision is required not only in precision instruments
and timing devices, but also in micro-motion devices for speed reducers, robotics, and automotive.

Among the many types of gears, the spur gear is the most commonly used type that connects two
parallel shafts and, due to its simpler tooth profile, it is easier to accurately manufacture and measure.

Gear accuracy requires an objective assessment of the deviations of various basic parameters from
their theoretical geometrical form. Gear dimensions such as thickness of tooth, span, outside diameter
etc. are also responsible to some extent for their performance [1, 2]. Miniature gear micro and macro-
geometry parameters determine their functional performance characteristics. It majorly includes
variation in profile, pitch, tooth thickness, outside diameter etc. Outside diameter represents the
maximum distance measured over two balls or rolls placed in diametrically opposed tooth spaces of a
gear. This measurement can also be done by magnifying gear using high end microscopes. Involute
spur gears with deviations in geometrical and dimensional form, will not engage in a proper conjugate
action causing a non-uniform motion or deviation from ideal motion transmission conditions with
influence the operational characteristics like vibration, noise, life span of the gears, etc.

The conventional type manufacturing processes for miniature gears have some limitations in many
aspects and commonly they all need the assistance of post finishing operation to achieve the desired
surface finish, integrity and geometrical and dimensional accuracies [3-6]. This supports the need to
explore alternative manufacturing processes that can overcome the limitations of the conventional
processes. Laser beam cutting (LBC) is a noncontact thermal process with high production rate and no
additional tooling required therefore in the current work its potential to be a great alternative to the
traditional processes when manufacturing miniature gears will be thoroughly investigated. Laser is the
basically the abbreviation of Light Amplification by Simulated Emission of Radiation [7]. In other
words, laser is a monochromatic, coherent and cohesive electromagnetic radiation beam with
wavelengths ranging from ultraviolet to infrared. The use of a laser beam for cutting, trimming and
drilling holes has been around for more than five decades and since then has evolved into an
extensively used method of material removal with cost effective solutions for manufacturing
processes.

A systematic and detailed review of the available literature on manufacturing of miniature gears
reveals that micro and meso gears have been successfully manufactured by electric discharge
machining (EDM), micro-EDM, Wire-EDM, and abrasive water jet machining (AWJM) type
advanced machining processes [8, 9]. When it comes on LBM fabrication of miniature gears then the
scarcity of work is found. The research work presented and discussed in this paper fulfils the gap and
is a part of comprehensive investigation where laser beam machining has been explored in detail to
produce stainless steel (SS) 304 miniature gears.
2. Experimental details

In this research, the raw material is a stainless steel plate of rectangular shape and 4.5 mm thickness from which the miniature gears have been cut by laser beam cutting. A total of twenty nine experiments based on Box Behnken methodology have been conducted. Table 1 presents the values and levels of laser beam cutting parameters for miniature gear fabrication. The miniature gears have 10 teeth, 9.04 mm outside diameter, and 4.5 mm face width.

Figure 1 depicts the laser machine tool used to fabricate miniature gears in this research work. The involute profile gear samples were cut on TRUMATIC L3020 CO2 laser machine having a maximum output power of 3.2 kW. Nitrogen is used as an assist gas. Four important laser parameters, laser power, focal position, cutting speed, and gas pressure have been varied at three levels each as seen in Table 1. Results of pilot experiments, literature review, and machine constraints are the major factors considered to fix the values and ranges of parameters.

![Raw material](image1)

![Machine tool](image2)

![Cut samples](image3)

**Figure 1.** Experimental setup for laser beam cutting of miniature gears

In the present work, the productivity of laser cutting process in the form of material removal rate has been assessed as a function of cutting speed, kerf width and the thickness of the material. For the purpose of obtaining kerf width evaluation, rectangular block samples of 20 x 10 mm dimensions with a 15 mm length cut through the middle as shown in Figure 1, were cut simultaneously with the gears according to the experimental design. The kerf width was measured with Olympus BX 51M optical microscope on three places along the cut to obtain an average.

The dimensional deviation (DD) from the nominal outside diameter dimension was measured with ACCUD digital microscope. The outside diameter was measured across two opposite teeth as shown in Figure 2 and expressed as percentage deviation from the theoretical value.

| Parameter                     | Level 1 | Level 2 | Level 3 |
|-------------------------------|---------|---------|---------|
| 1 Laser power [W]             | 1500    | 2000    | 2500    |
| 2 Cutting speed [m/min]       | 1       | 2       | 3       |
| 3 Focal position [mm]         | -3.5    | -2.5    | -1.5    |
| 4 Gas pressure [bar]          | 10      | 13      | 16      |

**Table 1.** Process parameters of laser beam cutting for fabrication of miniature gears
Figure 2. Representation of dimensional deviation measurement

3. Results and discussion
Table 2 presents the twenty nine experimental combinations of laser parameters and material removal rate and dimensional deviation values. The effects of laser beam cutting parameters on material removal rate and dimensional deviation is discussed in the following section.

| Std | Run | Laser power [W] | Cutting speed [m/min] | Focal position [mm] | Gas pressure [bar] | MRR [mm²/min] | DD [%] |
|-----|-----|-----------------|----------------------|---------------------|-------------------|--------------|--------|
| 1   | 11  | 1500            | 1                    | -2.5                | 13                | 2020.30      | 1.0264 |
| 2   | 24  | 2500            | 1                    | -2.5                | 13                | 2364.29      | 1.0268 |
| 3   | 28  | 1500            | 3                    | -2.5                | 13                | 5353.33      | 1.5244 |
| 4   | 6   | 2500            | 3                    | -2.5                | 13                | 6189.06      | 0.9088 |
| 5   | 14  | 2000            | 2                    | -3.5                | 10                | 4559.10      | 1.6582 |
| 6   | 9   | 2000            | 2                    | -1.5                | 10                | 3310.71      | 1.2305 |
| 7   | 25  | 2000            | 2                    | -3.5                | 16                | 4283.61      | 1.0342 |
| 8   | 5   | 2000            | 2                    | -1.5                | 16                | 4538.32      | 1.5174 |
| 9   | 17  | 1500            | 2                    | -2.5                | 10                | 3241.74      | 1.3131 |
| 10  | 1   | 2500            | 2                    | -2.5                | 10                | 4502.19      | 0.9945 |
| 11  | 2   | 1500            | 2                    | -2.5                | 16                | 4184.55      | 1.3074 |
| 12  | 29  | 2500            | 2                    | -2.5                | 16                | 4519.06      | 0.7351 |
| 13  | 19  | 2000            | 1                    | -3.5                | 13                | 2338.04      | 1.0174 |
| 14  | 20  | 2000            | 3                    | -3.5                | 13                | 6340.24      | 1.3445 |
| 15  | 18  | 2000            | 1                    | -1.5                | 13                | 2070.81      | 1.5494 |
| 16  | 21  | 2000            | 3                    | -1.5                | 13                | 6121.94      | 1.4065 |
| 17  | 15  | 1500            | 2                    | -3.5                | 13                | 4044.73      | 1.2608 |
| 18  | 10  | 2500            | 2                    | -3.5                | 13                | 4283.95      | 1.3899 |
| 19  | 4   | 1500            | 2                    | -1.5                | 13                | 3879.66      | 1.9142 |
| 20  | 16  | 2500            | 2                    | -1.5                | 13                | 4180.18      | 0.9525 |
| 21  | 3   | 2000            | 1                    | -2.5                | 10                | 2097.63      | 0.9588 |
| 22  | 23  | 2000            | 3                    | -2.5                | 10                | 6204.26      | 1.2931 |
| 23  | 8   | 2000            | 1                    | -2.5                | 16                | 2078.99      | 0.9925 |
| 24  | 27  | 2000            | 3                    | -2.5                | 16                | 6355.23      | 0.8919 |
| 25  | 12  | 2000            | 2                    | -2.5                | 13                | 4010.75      | 1.0574 |
| 26  | 25  | 2000            | 2                    | -2.5                | 13                | 4071.45      | 0.9831 |
| 27  | 22  | 2000            | 2                    | -2.5                | 13                | 3814.42      | 1.0582 |
| 28  | 7   | 2000            | 2                    | -2.5                | 13                | 4092.38      | 1.0636 |
| 29  | 13  | 2000            | 2                    | -2.5                | 13                | 3983.22      | 1.0131 |
Effect of each individual laser parameters on the responses i.e. MRR and DD is graphically analyzed in order to ascertain the trend of each laser cutting input parameter on the specific response. The graphs show the variation of one input parameter while the others are kept at their mid values.

The effect of laser power as seen in Fig 3a shows an increase in MRR as the laser power is increased from 1500 W to 2500W. The MRR, as mention before, is linearly dependent on the kerf width and cutting speed. The higher laser power resulted in a kerf width increase thus, the increasing behavior of MRR. Similar effect of the laser power and assist gas pressure (i.e. the rise of gas pressure and laser power resulting in increase in kerf width) on the kerf width was observed by Yilbas [10, 11], Madic [12] and Miraoui [13]. As the gas pressure is varied from 10 to 16 bar the expected increase in kerf width will result in the increase in MRR as shown in Figure 3d.

When cutting speed is varied from 1 m/min to 3 m/min, the MRR is increasing, as expected. A faster feed rate will result in shorter cutting time hence, better productivity. The effect of cutting speed on MRR is shown in Fig 3b.

The focal position effect on the MRR, as shown in Fig 3c, reveals the highest value of MRR for a depth of 3.5 mm from the top surface of the focal point. A focal point position situated closed to the bottom surface of the workpiece will create a larger cut kerf width and that is beneficial for the melt removal rate. A similar conclusion regarding the effect of focal position and kerf width was expressed by Wandera [14].

The effect of laser power on DD as seen in Fig 3a shows that least dimensional deviation is obtained at maximum laser power. A high laser power provides high energy to the cut zone that creates a low density melt. This melt has better hydrodynamics and offer easier separation from the solid base material. At the liquid-solid interface, viscous forces contribute to the adherence of the melt onto the solid base material and, as the melt is expelled from the cut, a thin film is left to re-solidify on
the kerf surface. This thin re-solidified layer is a contributor to the difference from the nominal dimension that accounts for the dimensional deviation.

The variation of cutting speed, as seen in Fig 3b, shows a decrease in dimensional deviation as the cutting speed is decreased. At low cutting speed, the interaction time of the laser beam with the base material is longer hence, the increase in heat absorption per unit area. This results in good thermal diffusion that creates a melt with good melt flow properties that leads to less dimensional deviation.

A similar decreasing trend of DD is also obtained as gas pressure is reduced as shown in Fig 3d. The high gas pressure will induce some turbulence in the cut zone that will affect the flow of the melt out of the cut especially when abruptly changing direction to follow the path geometry.

Less dimensional deviation is obtained with the increase in focal point position depth within the material. Fig.3c shows a minimum variation of DD between focal position of 2.5 and 3.5 mm from the top surface of the workpiece. This position of high energy intensity situated around middle to bottom of the material thickness, provides a uniform temperature distribution along the cut depth hence a good stability conditions on the cut front that result in path geometry very closed to the theoretical one.

Further single and multi-performance optimization have also been done to secure the best values of MRR and DD, and other responses considered in this work that reduced DD to 0.6918% and increased MRR to 6322 mm³/min.

4. Conclusion
The paper presented the laser beam cutting of external miniature spur gears and effects of its parameters on material removal rate and dimensional deviation of miniature gears. The following conclusions can be drawn from this research work:

- The cutting speed has been identified as the main factor affecting the material removal rate (MRR) and laser power for dimensional deviation (DD).
- A decrease in DD is obtained when laser power is increased or focal position is decreased. When increasing cutting speed or gas pressure, a higher DD is obtained.
- Low dimensional deviation has been obtained at a combination of high laser power with high cutting speed and a focal point position situated between 1.5 and 2.5 mm from the top of the workpiece.
- Increase in laser power, cutting speed, focal position, and gas pressure increased MRR.
- Laser parameters setting for maximum MRR is: 2116 kilowatt-3 m/min-(-) 3.5mm-10 bar and for minimum DD is: 2451 kilowat-2.6 m/min-(-) 2.6 mm-15.8 bar.
- Laser beam cutting can be further explored for other gear types and materials and for sustainable manufacturing of precision miniature gears.

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