Laser engraving of chip-breaker geometry on ceramic cutting tools

E Ukar1*, J I Arrizubieta1, J E Ruiz1, M Ostolaza1 and A Lamikiz1

1 Department of Mechanical Engineering, University of the Basque Country (UPV/EHU), Faculty of Engineering of Bilbao, Plaza Torres Quevedo 1, 48013 Bilbao (Spain)

*Corresponding author: eneko.ukar@ehu.eus

Abstract: Laser texturing is a process that allows the selective removal of material by applying a high energy density over a small area during a very short time interval. Although it is generally common to use ultra-short pulse (ps or fs) lasers for tool engraving, in certain applications it is possible to use short pulse (ns) lasers. In this work, the material removal rate of an ns laser has been evaluated in chip-breaker milling on Al2O3 cutting inserts reinforced with SiC whiskers. The results obtained show that by milling chip-breaker geometries it is possible to reduce the cutting forces, however, the process parameters used are key to obtain an adequate surface finish without embrittlement of the tool. By means of an adequate design, a reduction in cutting forces of 20% was achieved; additionally, it has been proved that there is a high dependence between tool life and the milling strategy used.

Keywords: Laser engraving, Chip-breaker, Reinforced ceramic cutting tool, Cutting forces.

1. Introduction
In metallic materials, ultra-short pulse lasers, with pulses in the range of 10^{-15} seconds, are capable of vaporizing the material with almost no melting and no thermal damage, on the contrary, short pulse lasers, with pulses in the range of 10^{-9} seconds, although they allow working with higher pulse energies and material removal rates, in addition to vaporizing, they also melt part of the material that later solidifies on the surface and makes it difficult to achieve sharp edges in engraving or texturing operations [1-3]. Generally speaking, ultra-short pulse lasers are an order of magnitude more expensive than short-pulse lasers and are less flexible. In certain applications, if the process parameters are suitable, short-pulse lasers can provide an acceptable result [4,5]. An interesting application of laser engraving is the generation of chip-breaking structures in ceramic cutting tools. Due to the high melting temperature and pressure required for their manufacture, it is not possible to obtain ceramic inserts with chip breaker geometries from sintering [6]. Laser engraving process is an alternative to selectively remove material and reach curved surfaces [7]. In applications such as chip breaker engraving, the high surface roughness led by the laser in the rake face can adversely affect the chip flow.

The use of chip-breakers makes sense only in continuous cutting operations such as turning, where a continuous chip can become entangled and accumulate in the cutting zone resulting in a poor surface finish [8]. An excessively fragmented chip can also result in an unstable process with large variations in cutting forces resulting in poor surface finish and potential vibration problems. Various chip-breaker geometries are available in the industry depending on the type of material to be machined. Softer materials are machined with high speed steel (HSS) or carbide tools with positive tool geometries. In
these cases, the chip breaker has the task of fragmenting the chips and facilitating their evacuation in the cutting zone. In hard or abrasive cutting materials, the tools must be more resistant. In highly abrasive materials, such as aluminum with high silicon content, extremely hard tool materials such as PCD or CBN are used to maximize tool life, however, cutting forces are significantly reduced compared to cutting forces in heat-resistant alloys and the chips generated are fragmented without the use of chip-breakers [9]. On the other hand, heat-resistant alloys, such as Inconel 718, are abrasive materials while undergoing strain hardening that makes machining difficult and requires the use of hard and wear-resistant tools. Alumina ceramic tools (Al₂O₃) present high hardness and wear resistance; however, for their use in machining of heat-resistant alloys, it is necessary to include some type of reinforcement to increase toughness. Alumina tools reinforced with SiC whiskers are an alternative that offers a good compromise between hardness, wear resistance and toughness [10]. Tools of this type are manufactured in simple geometries with negative cutting edge angle so that the cutting edge resistance is adequate. Due to the absence of chip breaker structure, the chip generated in the process is irregular and results in relatively high cutting forces [11]. An alternative to improve process stability and reduce cutting forces is the generation of a chip breaker in these ceramic cutting tools.

This work focuses on the characterization and optimization of the removal strategy and parameters for ceramic material cutting tools (Al₂O₃ with SiC whisker reinforcement). Main variables have been identified and a new two-step strategy has been developed for chip breaker engraving operation.

2. Used equipment and methodology

To generate the chip-breaker, an ns fiber laser Trumark 5050 was used. With wavelength of 1064 nm and 50 W average power the laser source is able to reach a minimum pulse duration of 7 ns and a maximum pulse frequency of 1,000 kHz. This laser provide pulses with an energy level of up to 0.93 mJ concentrated in a spot of 50 µm in diameter. The machining tests were carried out on a CMZ 25TBY lathe with Fanuc Series 31i Model A control and cutting forces were measured using a KISTLER dynamometer 9257b.

The first step consisted in characterizing the material and obtaining the material removal and polishing parameters. The tests were carried out on Al₂O₃ cutting inserts reinforced with SiC whiskers from NTK manufacturer with WA1 structure specific for turning heat resistant alloys. In laser engraving, the amount of material removed depends on the energy used in each pulse, as well as, on the feed or scanning speed of the laser (vᵣ) and the hatching distance. Thus, the energy released in each pulse is obtained from the ratio between the average power during the pulse and the pulse frequency, i.e., the number of pulses per unit time (PRR). For a laser with a given spot diameter, the energy released in each pulse is distributed over a surface area that depends on vᵣ. For higher speeds, during the emission of the pulse, the laser travels a greater distance and the energy density, energy per unit area, decreases. On the other hand, each material has a different radiation absorption capacity [12].

A first experimentation was carried out to achieve the parameters for selective elimination of material. Based on previous studies, it was decided to set the feed rate vᵣ at 200 mm/min and to carry out tests at different frequencies with different pulse durations (table 1).

| Power (W) | Feed Rate vᵣ (mm/s) | Radial step (mm) | Freq (kHz) | Pulse duration (ns) | Energy Pulse (mJ) | Pulse Energy density (J/mm²) |
|----------|---------------------|-----------------|------------|---------------------|-------------------|-----------------------------|
| 50       | 200                 | 0.02            | 50         | 250                 | 1                 | 0.509                       |
|          |                     |                 | 55         | 230                 | 0.91              | 0.462                       |
|          |                     |                 | 60         | 210                 | 0.83              | 0.424                       |
|          |                     |                 | 65         | 190                 | 0.77              | 0.391                       |
|          |                     |                 | 70         | 170                 | 0.71              | 0.363                       |
|          |                     |                 | 75         | 150                 | 0.67              | 0.339                       |
The tests consisted of individual 2×2 mm² pockets operating with the values recorded in Table 1. A sample of pocket with one laser surface hatching is shown in Figure 1(a). Using a Leica DCM 3D confocal profilometer, profiles were extracted (Figure 1(c)) and the material removal rate was evaluated by measuring the depth reached in the pocket after several sweeps with a Zigzag strategy. The result summarized in Figure 1(b), shows an almost linear behavior and similar material removal rate in the test.

![Figure 1](image.png)

**Figure 1.** Examples of (a) 3D pocket with 60 kHz and 210 ns, (b) material removal rate for different parameters and (c) extracted profile for 60 kHz and 210 ns test.

Between levels, the trajectories have been rotated at an angle of 17º to avoid possible effects associated with the directionality of the scan. In each of the tests, the material removal rate was evaluated by measuring the depth of the pocket to obtain the removal rate curves. The results show that with a pulse energy of 1mJ the removal rate is maximum, however, the pulses used are excessively long and the proportion of molten material is excessive. Table 2 shows surface roughness and measured burr height after 10 hatchings. The final selection of the process parameters was carried out by means of the relationship between the obtained removal rate and the burr height at the edge of the pocket.

| Hatchings | Frequency (kHz) | Pulse duration (ns) | Roughness (Sa) | Depth (µm) | Burr Height (µm) |
|-----------|----------------|---------------------|----------------|------------|------------------|
| 10        | 50             | 250                 | 2,45           | 633        | 20               |
|           | 55             | 230                 | 2,20           | 627        | 15               |
|           | 60             | 210                 | 1,36           | 626        | 10               |
|           | 65             | 190                 | 1,75           | 630        | 12               |
|           | 70             | 170                 | 2,24           | 646        | 20               |
|           | 75             | 150                 | 2,02           | 640        | 18               |

The best results were obtained for a frequency of 65 kHz and a pulse duration of 210 ns, where minimal burr height of 10 µm and lowest surface roughness of 1.36 Sa was achieved (Table 2).

The chip-breaker geometry was obtained after analyzing the different options recommended for heat resistant alloys machining with carbide inserts. The machining of heat-resistant alloys is demanding from the tool point of view and it is common to use cutting inserts with negative geometry. Taking as a reference the chip-breakers used in carbide, the profile of Figure 2 has been designed in order to maintain the robustness of the cutting edge and different configurations more or less favorable to the chip flow have been tested. To avoid edge embrittlement the distance to the edge has been kept constant at 0.2 mm. As chip breaker variable the chip entry angle α, chip exit angle β, and chip breaker depth h have been
considered figure 2(c). Figure 2(a) shows an actual Al₂O₃ ceramic tool after engraving and figure 2(b) shows the detail of the cutting edge in 3D.

**Figure 2.** Examples of (a) textured insert (b) 3D measurement of cutting edge and (c) extracted profile with identification of chip-breaker geometry features.

The values of \( \alpha \), \( \beta \) and \( h \) have been taken as a reference from previous studies and are summarized in table 3. In the same table the measured cutting forces and tool life time are given. The cutting forces were measured using the reference axes defined in ISO 841:2001 standard, where the \( Z \) axis on a lathe corresponds to the rotation axis of the workpiece and the \( Y \) axis corresponds to the vertical direction (on a horizontal lathe), where the highest cutting forces are obtained.

**Table 3.** Tests carried out and measured cutting forces and tool life.

| N Test | \( \alpha \) (°) | \( h \) (mm) | \( \beta \) (°) | \( F_x \) [N] | \( F_y \) [N] | \( F_z \) [N] | \( F_{mod} \) [N] | \( T \) [s] |
|--------|----------------|------------|-------------|-------------|-------------|-------------|----------------|--------|
| Ref    | 0              | 0          | 0           | 377.53      | 692.36      | 675.78      | 1040.28        | 85.58  |
| 1      | 40             | 0.4        | 20          | 270.05      | 639.04      | 485.50      | 847.74         | 28.55  |
| 2      | 40             | 0.5        | 20          | 285.17      | 555.92      | 441.81      | 769.60         | 80.62  |
| 3      | 40             | 0.6        | 20          | 334.61      | 659.61      | 585.16      | 944.56         | 75.50  |
| 4      | 50             | 0.4        | 30          | 353.03      | 584.86      | 461.75      | 830.13         | 35.82  |
| 5      | 50             | 0.5        | 30          | 267.57      | 560.30      | 391.24      | 735.38         | 35.98  |
| 6      | 50             | 0.6        | 30          | 1667.07     | 881.18      | 1597.51     | 2477.09        | 33.31  |
| 7      | 60             | 0.4        | 40          | 413.59      | 793.48      | 1069.17     | 1392.46        | 32.30  |
| 8      | 60             | 0.5        | 40          | 452.59      | 867.79      | 1603.24     | 1889.66        | 31.01  |
| 9      | 60             | 0.6        | 40          | 397.32      | 829.70      | 1086.30     | 1437.51        | 31.25  |

The turning parameters were kept constant in all tests, with a cutting speed of 300 m/min, a feed rate of 0.15 mm/rev and a depth of cut of 1.5 mm. All tests were carried out with cutting fluid.

3. Results

The results represented in figure 3 show a maximum reduction in the resulting cutting force of up to 25 %, with the most notable reduction being in the Z-axis force component, where the maximum reduction is 35 %. The \( Y \)-axis force component is the highest, since it is the one corresponding to the cutting operation, while the \( Z \) component corresponds to the forward motion and the \( F_x \) is the normal reaction. The maximum reduction in \( F_y \) is obtained for test No. 2, corresponding to an entry angle \( \alpha \) of 40°, a chip exit angle \( \beta \) of 20° and a maximum chip breaker depth \( h \) of 0.5 mm. For other geometries, such as the one corresponding to test No. 5, similar cutting force reductions were achieved, and even slightly lower, if the total resultant of the cutting force is considered, however, tool life is significantly reduced in all cases.
The results obtained show that it is possible to obtain a significant reduction of cutting forces, in the range of 25 %, in the turning of heat-resistant alloys compared to the cutting forces in a tool without chip-breaker. Regarding engraving process, Al$_2$O$_3$ cutting inserts reinforced with SiC whiskers exhibit good absorptivity when processed with an ns fiber laser. In each laser pass, a thickness of 30 µm is removed, giving a milling cycle time of less than one minute for each insert. Before tool flank wear occurs, the cutting edge undergoes brittle fracture in all cases. Figure 4(a) shows a picture of the chip breaker and cutting edge before machining and figure 4(b) shows the tool after breakage for test in table 3.

![Figure 3. Recorded mean cutting forces.](image)

### 3.1. Influence of tool shape features.

The engraved chip-breakers show a similar evolution in the different components of the cutting forces. A chip entry angle of 40º ($\alpha$) provides a significant reduction in cutting forces; however, angles of 50º and 60º give the opposite result, increasing the cutting force components. On the other hand, the effect that the chip-breaker depth ($h$) has is less determinant, there being little variation for depths of 0.4, 0.5
and 0.6 mm when the angle $\alpha$ is 40º. For angles of 50º and 60º the chip exit angle also increases, suggesting excess chip deformation at the chip breaker, resulting in increased cutting forces.

![Figure 5](image)

**Figure 5.** Detail of chip formation with reference tool and in each test.

The chip generated during the process confirms this point and it can be seen that the more aggressive geometries with higher entry and exit angles as well as a greater depth, corresponding to tests 8 and 9, result in a continuous chip, while tests 1, 2 and 3 with an entry angle of 40º are the ones that generate a segmented chip and lower cutting forces. Figure 5 shows the difference between the chips for each test. The reference tool provides an irregular fragmented chip while an angle $\alpha$ of 40º gives a slightly longer and a bit more deformed chip.

![Figure 6](image)

**Figure 6.** Measured cutting forces (a) in $X$ direction (b) $Y$ direction and (c) in $Z$ direction.

This is consistent with a reduction in cutting forces. On the other hand, steeper angles of 50 and 60º result in a longer chip that is less desirable for the process. Regarding the cutting forces, if the average force values in each of the components are analyzed separately, it is observed that, in the three cases, $F_x$ in figure 6(a), $F_z$ in figure 6(b) and $F_z$ in figure 6(c), a similar evolution is followed, with the lowest stresses occurring for an angle $\alpha$ of 40º and a depth $h$ of 0.4 mm corresponding to geometry No. 2. It should be noted that in the case of the geometry milled with an angle $\alpha$ of 50º and a depth $h$ of 0.4 mm, corresponding to test No. 6, the registered $F_x$ component were unusually high, reaching values 5 times
higher than those recorded in the reference tool. In the case of the Fy and Fz forces, this difference is noticeable, but not as pronounced. This behavior is consistent with a partial breakage of the cutting edge at the beginning of machining and to the fact that the cutting forces have been recorded with the damaged cutting edge. In figure 4, for cutting edge No. 6, part of the chip can be observed adhered to the cutting edge, which suggests that the tool has been machining with the damaged cutting edge.

3.2. Reduction of tool life

One aspect that has been observed in all tests is the embrittlement of the cutting edge after laser processing. In all cases, in order to avoid modifying the geometry of the cutting edge, the laser trajectories have been programmed with a distance of 0.2 mm to the cutting edge; however, with the parameters used, the heat accumulation is high and in some cases the chamfer area of the cutting edge has been affected, as can be seen in figure 7 obtained for tool No. 6, which is the one that has given the worst result. Depending on the number of planes used for engraving and the swept area according to the angles $\alpha$ and $\beta$ selected, the heat accumulation has been different. Figure 7(a) and figure 7(b) in more detail show some surface asperities and small cracks due to excessive heat accumulation. This fact was also registered in the literature in previous work developed by Leone et al. [13]. In addition, in this case figure 7(c) shows also an over melt in the edge that is critical and has contributed also to the edge breakage during machining. Some tools, such as No. 3 and 9 show obvious signs of excessive thermal damage, while others such as 1 or 4 show less thermal damage, as shown in figure 4(a).

![Figure 7. (a) Detail of cutting edge in tool Nº 6 and (b) 3D measurement showing heat affected cutting edge.](image_url)

A possible solution to minimize the effect of energy buildup is to mill tools with a tool cooling interval between planes and to use less aggressive process parameters with a lower material removal rate. This would minimize the energy build-up effect.

4. Conclusions

The work carried out shows the feasibility of the laser engraving process of Al$_2$O$_3$ tools reinforced with SiC whiskers with an ns pulsed laser. The results obtained show that it is possible to obtain a high material removal rate with a linear behavior. The proposed chip-breaker geometry has proven to be effective resulting in a reduction of the average cutting forces by about 25% in the machining of the heat-resistant alloy Inconel 718, which represents a significant improvement over conventional inserts without chip-breaker. For a geometry with an entry angle $\alpha$ of 40°, an exit angle $\beta$ of 20° and a depth $h$ of 0.5mm, the use of a chip-breaker results in the formation of a more regular chip and a more stable process. The most relevant parameter observed is the chip-breaker entry angle $\alpha$, there being notable variations in cutting forces when employing other angle combinations.
Although a significant reduction in cutting forces was achieved, in the study carried out a cutting edge embrittlement problem was detected, which has resulted in a tool life below the expected, being at best similar to the reference tool without chip-breaker. This problem is caused by two reasons, firstly, material removal parameters that cause an excessive accumulation of energy resulting in the generation of micro-cracks and, secondly, due to excessive material fusion, affecting the area corresponding to the cutting edge and causing its embrittlement.

Acknowledgements
This research was funded by Basque Government (Eusko Jaurlaritza) under the HAZITEK Program, TECH4CUT project and Spanish Ministry of Industry and Competitiveness under the PID2019-109220RB-I00 ALASURF project.

References
[1] Tran N G and Chun D 2020 Simple and fast surface modification of nanosecond-pulse laser-textured stainless steel for robust superhydrophobic surfaces CIRP Annals 69 (1) pp 525–528
[2] Esmail I, Yazdani Servestani H, Gholipour J and Ashrafi B 2021 Engineered net shaping of alumina ceramics using picosecond laser Optics & Laser Technology 135 p 106669
[3] Simões J G A B, Riva R and Miyakawa W 2018 High-speed Laser-Induced Periodic Surface Structures (LIPSS) generation on stainless steel surface using a nanosecond pulsed laser Surface and Coatings Technology 344 pp 423–432
[4] Malik I A and Barthelat F 2016 Toughening of thin ceramic plates using bioinspired surface patterns International Journal of Solids and Structures 97–98 pp 389–399
[5] Roitero E, Lasserre F, Roa J J, Anglada M, Mücklich F and Jiménez-Piqué E 2017 Nanosecond-laser patterning of 3Y-TZP: Damage and microstructural changes Journal of the European Ceramic Society 37 (15) pp 4876–4887
[6] Hong D, Yuan J, Yin Z., Peng H and Zhu Z 2020 Ultrasonic-assisted preparation of complex-shaped ceramic cutting tools by microwave sintering Ceramics International 46 (12) pp 20183–20190
[7] De Zanet A, Casalegno V and Salvo M 2021 Laser surface texturing of ceramics and ceramic composite materials – A review Ceramics International 47 (6) pp 7307–7320
[8] Bhuiyan M S H, Choudhury I A and Dahari M 2014 Monitoring the tool wear, surface roughness and chip formation occurrences using multiple sensors in turning Journal of Manufacturing Systems 33 (4) pp 476–487
[9] Buchkremer S, Klocke F and Lung D 2014 Analytical study on the relationship between chip geometry and equivalent strain distribution on the free surface of chips in metal cutting International Journal of Mechanical Sciences 85 pp 88–103
[10] Gervorkyan E, Rucki M, Pachenko S, Sofronov D, Chalko L and Mazur T 2020 Effect of SiC Addition to Al2O3 Ceramics Used in Cutting Tools Materials 13 p 5195
[11] Molaiekiya F, Aramesh M and Veldhuis S C 2020 Chip formation and tribological behavior in high-speed milling of IN718 with ceramic tools Wear 446–447 p 203191
[12] Schutz-Kuchly T, Slaoui A, Zelgowski J, Bahouka A, Pawlik M, Vilcot J P, Delbos E, Bouttemy M and Cabal R 2014 UV and IR laser induced ablation of Al2O3/SiN:H and a-Si:H/SiN:H, EPJ Photovoltaics 5, p 55201
[13] Leone C, Genna S, Tagliaferri F, Palumbo B and Dix M 2016 Experimental investigation on laser milling of aluminium oxide using a 30W Q-switched Yb:YAG fiber laser Optics & Laser Technology 76 pp 127–137