J. Adv. Manuf. Eng. 1(4) (2020) 93–100

JOURNAL OF ADVANCES IN MANUFACTURING ENGINEERING

Improving the RF Performance of Ceramics Using Laser Assisted Machining

Emre Gungor[1,4,*], Ebrar Ozbek[2], Seymur Shukurov[3], Orhan Cakir[4]

[1]TSI Seats Inc., Istanbul, Turkey
[2]PROFEN Communication Technologies Inc., Istanbul, Turkey
[3]Department of Electrical and Electronics Engineering, Yeditepe University, Istanbul, Turkey
[4]Department of Mechanical Engineering, Yildiz Technical University, Besiktas Campus, 34349, Istanbul, Turkey
Received:25.11.2020 *Accepted: 19.12.2020*

Abstract

The radio frequency (RF) performance of military missiles depends largely on the dimensional tolerances of the ceramic radome (Si_3N_4, Mullit, Al_20_3) in the missile. Small deviations and differences in precise tolerances on both the inner and outer surface of the radome affect the insertion loss of the radome wall, which has a negative impact on the RF performance of the missile. When these effects are taken into consideration, it is seen that surface sensitivity and surface integrity are important parameters in the machining process of ceramics. Ceramics are difficult to process with conventional processes because they are hard and brittle, as well as high costs. The current method for machining ceramic radome surfaces is the type of machining made with conventional CNC machines using a special cutting tool and cooling system. In this study, laser assisted machining (LAM) technique was proposed to overcome the disadvantages and reduce the surface roughness. While the approximate loss of insertion value for ceramic radomes produced by conventional methods is around 2.5 dB, it was predicted that this value can be obtained around 1.5 dB by laser assisted processing which is one of the hybrid manufacturing methods. Computer aided simulations were performed based on the surface roughness values obtained from the surface roughness measurements made after both machining methods. From the results of these simulations, it is seen that laser reinforced processing method has a significant contribution to the signal transmission efficiency of ceramic radomes.

Keywords: *Hybrid Manufacturing, Laser Assisted Machining (LAM), Ceramics, RF Performance, Insertion Loss Simulation.*

1. Introduction

The increasing engineering needs of the developing technology have led to a rapid and large increase in the use of ceramics. Ceramics are known to have high strength, hardness and wear resistance. Due to these properties, ceramic materials are frequently used in the leading fields of aviation, space, communication and automotive industry. Because of their hardness and high tensile strength, they are very difficult to machine using simple and conventional manufacturing techniques. This results in low material removal rate and reduced tool life. Moreover, they are very expensive and time consuming [1]. Even though diamond grinding can meet the demands for dimensional certainty and surface

[*]**Corresponding author:** Emre GÜNGÖR
E-mail: f2317024@std.yildiz.edu.tr / ORCID: 0000-0002-9424-035X

machining but this method has high cost, which is for 60–90% of the total cost of the end product [2]. Besides all of its strength, LAM has also number of disadvantages such as local melting, which results in dissipate of the surface material; heating is the reason of microstructure changes for the workpiece surface material and increases tempering and quenching; microcracking can also cause undesirable situations in the processing of ceramic of metal machining. However, LAM technology is needed for process quality, dimensional certainty and surface roughness [3]. Konig et al. who practiced the first successful use of LAM to machine ceramic material when its temperature exceeded 1200 °C [4]. Similarly, Konig and Zaboklicki realized LAM to both turning and milling ceramics, when they disregarded the effects of laser energy on workpiece temperature and the impact of temperature on tool wear, they obtained low cutting force, tool wear, and a high material removal rate [5]. Chang and Kuo conducted a study to advocate that LAM provides higher material removal rates as well as better control of workpiece properties and geometry, since the material is locally heated by a dense laser source before removal. Additionally, they found a reduction of 20–22% in cutting force with a better surface quality during laser-assisted planning of alumina ceramics [6]. Dong et al. showed that the cutting mechanism of ceramics changed from brittle fracture to plastic deformation at an elevated temperature. Dong et al. found that the temperature at the onset of quasi-plastic deformation and hence the minimum material removal temperature required was approximately 1100 °C for LAM of silicon nitride. Subsequently, Dong et al. suggested that the softening of an amorphous glassy phase at the silicon nitride grain boundaries was responsible for the quasi-plastic deformation in LAM of silicon nitride. In these preliminary studies on LAM of ceramics, good surface roughness comparable to that by grinding was achieved at temperatures between 1100 ° and 1300 °C, but deterioration in surface quality was observed at temperatures beyond 1300 °C due to the oxidation of the materials [7]. Laser-assisted milling is more complex than laser-assisted turning compared to a custom laser installation and in the case of brittle materials, milling is significantly more subjected to work piece edge chipping than turning [8]. Yang et al. by heating the material above the softening point, it is concluded that the edge chipping is reduced due to the reduction in cutting forces. By further heating the material, the edge toughness of Si_3N_4 is significantly increased above the brittle/ ductile transition temperature, resulting in further reduction of edge chipping [9]. Likewise, Lei et al. qualified the plastic deformation properties of silicon nitride in the shear deformation region. They found viscous flow of the glassy grain-boundary phase material and reorientation of the β-Si_3N_4 grains. This study shows that the stress reduces with the increase of workpiece temperature [10]. Przestacki et al. performed an experimental surface roughness analysis using laser assisted machining (LAM) method. With their work they presented an alternative method in which the process on a conventional turning requires special polycrystallic diamond (PCD) or cubic boron nitride (CBN) inserts, which are still very expensive. The silicon nitride sample processed with three different cutting tool and was recorded the Ra and Rz results. They compared the obtained surface roughness values with the surface roughness values obtained from conventional turning machine. Also they assessed the machining parameters influence on surface roughness parameters. The 3D surface topographies were measured using optical surface profiler. The analysis of power spectrum density (PSD) roughness profile were analysed [11]. Song et al. in their experimental study, they showed that they can machine fused silica with improved efficiency and precision by laser assisted processing (LAM) by heating with CO_2 laser beam. The Taguchi method was used to determine the optimum process parameter and to analyze the results obtained. In addition, the surface roughness values of Song in this study are taken as the reference [12]. Rozzi et al. performed an experiment of silicon nitride that come out of a Computer-Numerically Controlled Turret Lathe, 1.5 kW CO_2 laser with focusing optics, and a laser assist gas. For temperatures exceeding 650° C, a fiber optic, single wavelength, laser pyrometer was used to perform surface temperature measurements every 0.027 second. The distance between the laser spot and the pyrometer was specified by focusing on the pyrometer. As a result of silicon nitride for constant laser power and rotational speed, the workpiece close chamfer surface decreases with increasing feed rate. This effect can be attributed to a reduction in processing time and therefore to the amount of laser radiation absorbed by the workpiece. A reduction in the near surface temperature of the chamfer also increases the specific cutting energy rate as it increases the local material flow stress, which is reduced by thermal softening [13]. Rebro et al. focused on the evaluation of laser assisted machining (LAM) of sintered mullite ceramics Because of Mullite's low thermal diffusivity and tensile strength, they have developed a new method of laser application to prevent cracks and fracture in the part. They investigated the effect of different parameters on surface roughness and machining process. They also studied the SEM images of the machined parts in detail [14]. Variations of LAM process may be classified according to mechanical effects, phase-change effects and physico-chemical interactions. The temperature rise of the workpiece surface is typically below the material's melting point at moderate laser power intensity. For this reason, the workpiece is locally heated, the material softens and thermal stress gradients occur. Mechanical effects as loss of stiffness, local yielding, thermal cracking, or local buckling may occur. The intensity of the laser power can raise the temperature of the workpiece surface above the melting point of the material, high enough to change the phase, causing the material to melt or evaporate. If chemically reactive, simultaneous physico-chemical reactions can occur between the assisting material and the workpiece. As a consequence, burning, sintering, soldering, alloying phenomena are activated. In any laser machining operation one or more of the above mentioned phenomena are involved. Analytical and numerical modelling have contributed to the learning of these processes [15].

A calculation tool based on analytical methods was developed by Sharif et al. to simulate surface roughness after grinding. In developing this tool, they have benefited from some stochastic properties called trend, irregularity and burst that they see in each cycle in the surface roughness graph [16]. Kundrak et al. investigated a new method to estimate the value of standard 2D or 3D surface roughness characteristics of surfaces after surface milling. In his studies, they used regression analysis to determine the relationships between the theoretical and measured (real) values of surface roughness. In order to calculate the theoretical values, they created a CAD model that simulates the surface milling process. In addition, they carried out experimental studies for the actual surface roughness values [17]. It is well known that the micro-scale mechanical properties have significant impact on the RF (Radio Frequency) performance of the machined component. However, perfect surface finish is often difficult to obtain from the machining operation due to the limitation of the cutting tool geometry and machining dynamics [18]. In presented paper, the effect of surface roughness on RF performance was investigated by using finite element method. The surface roughness values required for simulation are taken from the literature, and no experimental study has been done for these values.

2. Finite Element Model

The 3D roughness model was created to simulate surface roughness effect on a RF performance. The surface roughness of the ceramic Si_3N_4 is modeled in 2D to show the surface roughness values of the material obtained by conventional/classical machining (CM) and laser-assisted machining (LAM). The surface roughness values for CM and LAM were modeled as 4 μm and 0.8 μm, respectively as shown in Figure 1 and Figure 2. For the surface roughness values, Song's study in 2018 was taken as a reference [12].

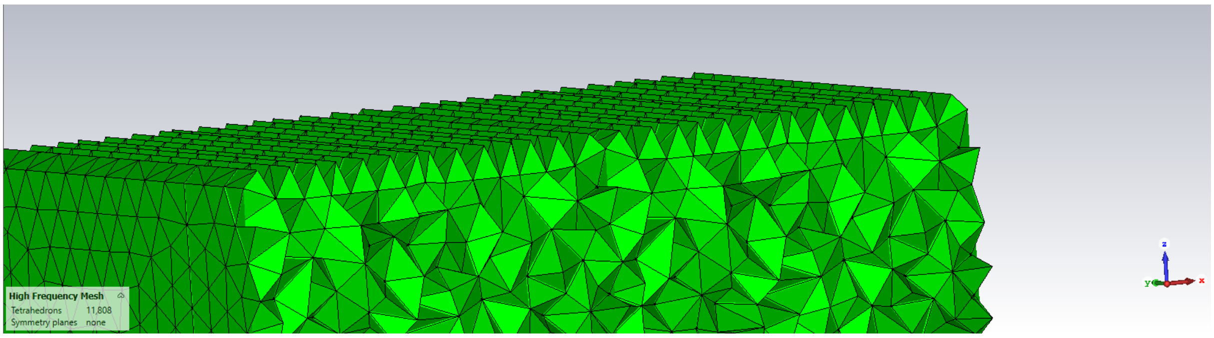

Figure 1. Surface roughness design for classical machning (CM)

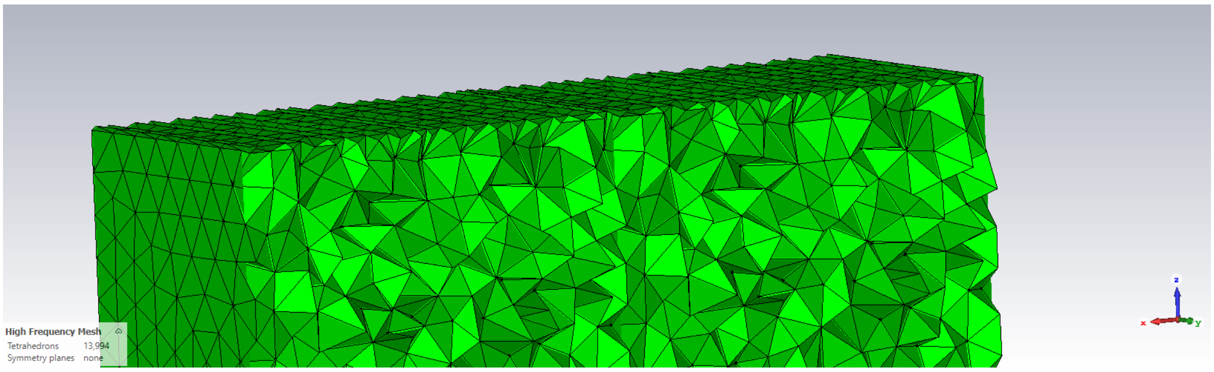

Figure 1. Surface roughness design for laser-assisted machning (LAM)

In the surface roughness models of CM and LAM materials, 11808 and 13994 tetrahedron mesh were applied, respectively. Only representative unit volume of 0.1 mm^3 is modeled. By means of the program used, this representative unit volume is modeled to have infinite boundary conditions and mesh is applied.

3. Simulation of Surface Roughness

RF performance simulations were performed in a computer supported environment using CST STUDIO SUITE commercial software. The effect of CM and LAM based roughness values on the behavior of electromagnetic waves on ceramic material was investigated by insertion loss analysis with the help of this program. For each roughness, eight simulations were conducted and it is found that surface roughness has effect on RF performance.

As a result of simulation studies, we aimed to see the effect of surface roughness on the performance of electromagnetic waves coming from different angles. In order to evaluate RF performance, analyzes were performed for W-band (75-110 GHz) insertion loss and reflection loss values. Also, The dielectric properties (dielectric constant-ε: 7.3 and loss tangent-tan δ: 3e-3) of the sintered Si_3Ni_4 ceramic material used in the simulations were used from the literature [19]. During the simulation, theta angle was kept constant at 45° angle and phi: 0-30-60-90° angles were analyzed, as shown in Figure 3 to Figure 6. In addition, the phi angle was kept constant at 0° degree and theta: 0-15-30-45° angles were analyzed, as shown in Figure 7 to Figure 10. The results are shown in the graphs below and the results are close to each other.

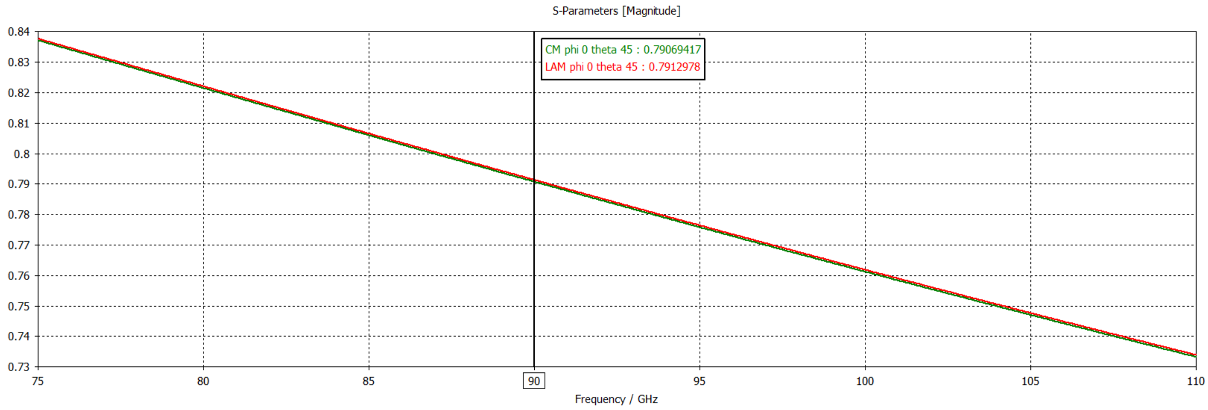

Figure 2. Insertion loss analysis of CM and LAM surface when Phi angle is 0° degree

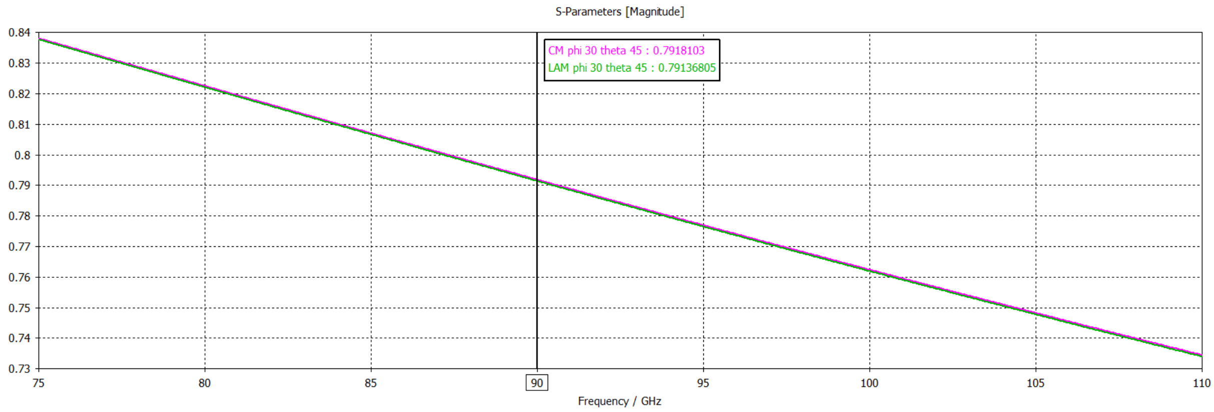

Figure 3. Insertion loss analysis of CM and LAM surface when Phi angle is 30° degree

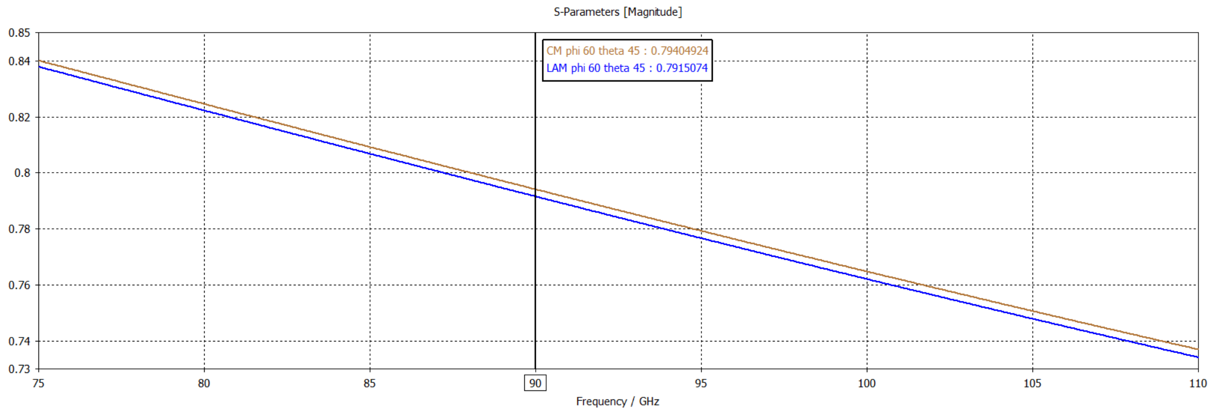

Figure 4. Insertion loss analysis of CM and LAM surface when Phi angle is 60° degree

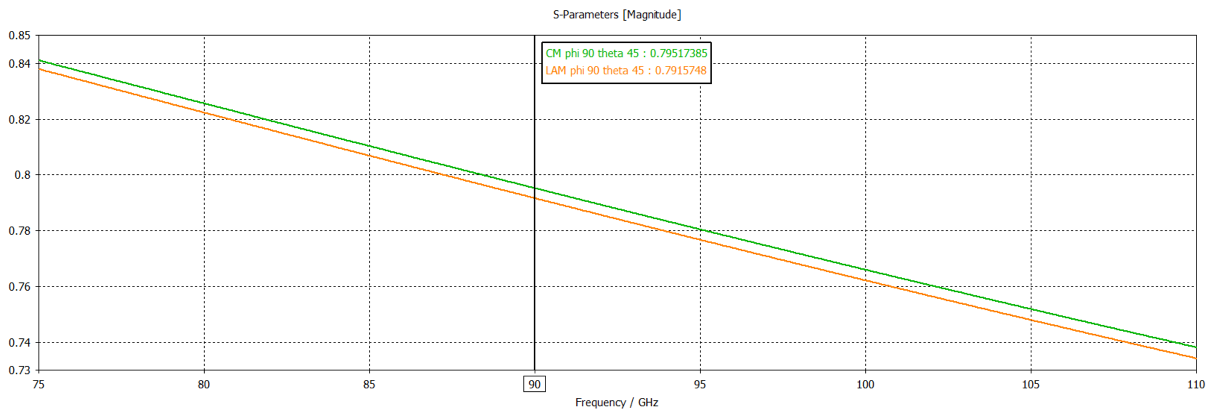

Figure 5. Insertion loss analysis of CM and LAM surface when Phi angle is 90° degree

In the Insertion loss analysis by changing the Phi angle, it is seen that the LAM ceramic surface provides about 0.5% more efficient communication. Also, in the Insertion loss analysis by changing theta angle, the difference between CM and LAM ceramic surface was found to be approximately 0.06%. The reason for this is that the electromagnetic waves coming from theta angle should always get through the same amount of unit material due to the 2-dimensional surface roughness model.

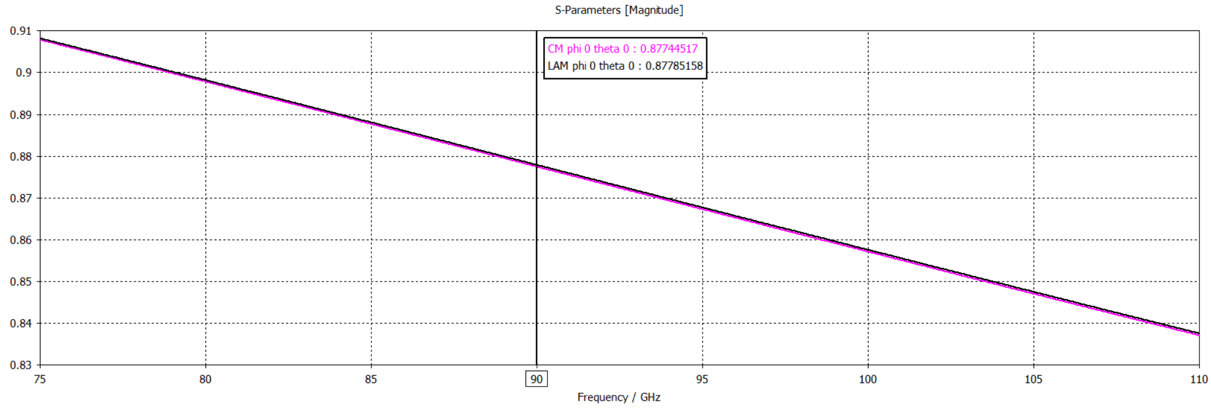

Figure 6. Insertion loss analysis of CM and LAM surface when Theta angle is 0° degree

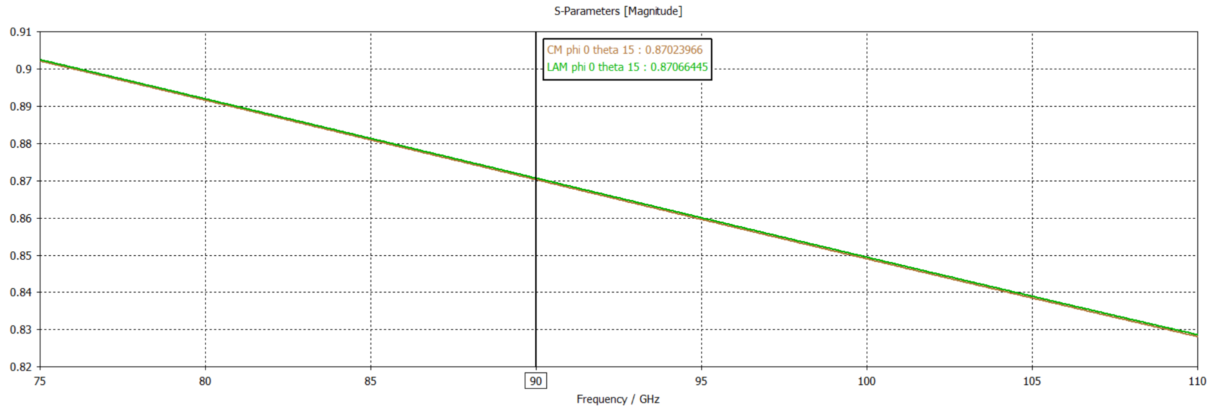

Figure 7. Insertion loss analysis of CM and LAM surface when Theta angle is 15° degree

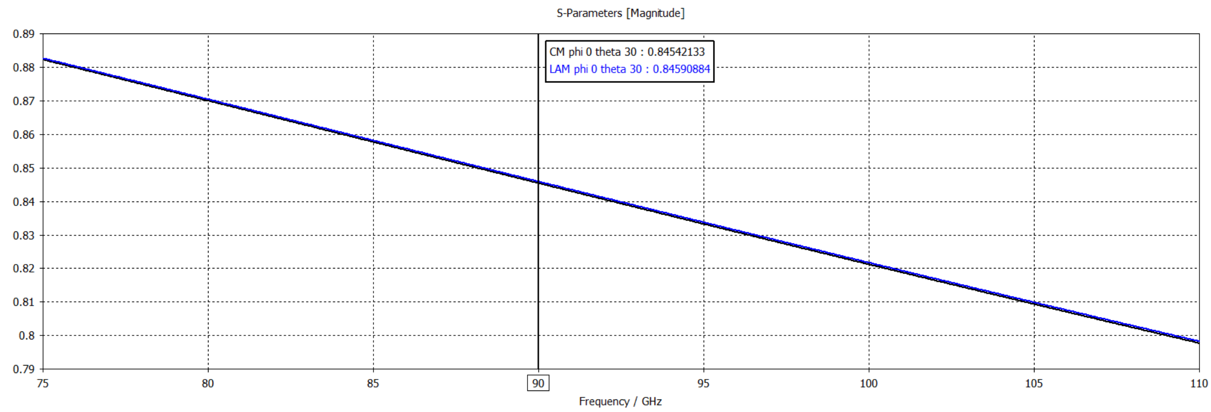

Figure 8. Insertion loss analysis of CM and LAM surface when Theta angle is 30° degree

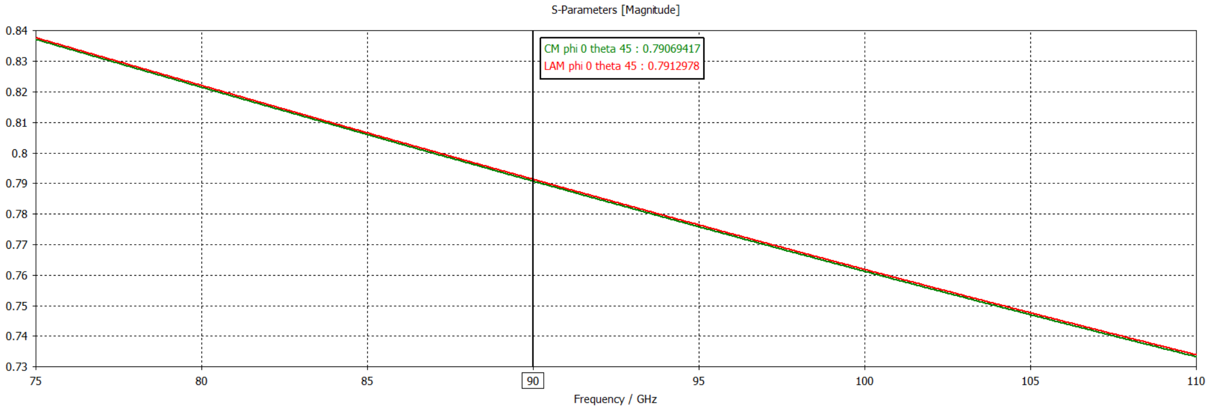

Figure 9. Insertion loss analysis of CM and LAM surface when Theta angle is 45° degree

Based on these graphs, in the case of 3-dimensional modeling of surface roughness, it is concluded that the electromagnetic waves coming from the Phi angle will cause a difference in CM and LAM ceramic surfaces.

4. Conclusion

Considering the results of different angle of incidence, the change of theta angle and incoming electromagnetic waves in the spherical coordinate system showed that there was no difference between the RF performances of the surface roughness geometries modeled for both production methods. Because even if the angle from which the electromagnetic wave changes, after passing through each surface roughness (for CM and LAM models), the amount of unit material that the beam travels in the ceramic material model remains the same.

However, the variation of the electromagnetic waves with the phi angle showed that there was a slight difference between the RF performance of the geometries modeled for both production methods. The reason for this is that with the change of the angle phi, the shape changes due to the surface roughness seen by the electromagnetic wave vector. It has shown that the beams corresponding to the valleys on the surface pass through the amount of less unit material in the ceramic material model than those corresponding to the peaks. From this point of view, we can comment on the effect of the difference between the peaks and valley points on the surface on RF performance. Even surface roughness values developed by laser assisted machining in micron range have a positive effect on RF performance in W band communication frequency.

Acknowledgements

Authors would like to express their gratitude to PROFEN Communication Technologies Inc. for providing all the hardware and software requirements throughout research.

References

[1] Konig, W. & Wagemann, A. (1990). Machining of Ceramic Components: Process-Technological Potentials, Machining of Advanced Materials, NIST Special Publication, 847, 3–16.
[2] Chryssolouris, G., Anifantis, N. & Karagiannis, S. (1997). Laser Assisted Machining: An Overview Laboratory for Manufacturing Systems, The Journal of Manufacturing Science and Engineering, 119, 766-769.
[3] Uehara, K. & Takeshita, H. (1986). Cutting ceramics with a technique of hot machining, Annals of the CIRP 35, 55–58.
[4] Konig, W. & Zaboklicki, U. (1993). Laser-Assisted Hot Machining of Ceramics and Composite Materials, Machining of Advanced Materials, NIST Special Publication, Volume 847, 455–463
[5] Banik, S. R. & Kalita, N. (2018). Recent trends in laser assisted machining of ceramic materials, Materials Today: Proceedings, 5(9), 18459-18467.

[6] Chang,C. & Kuo, C. (2007). Evaluation of surface roughness in laser-assisted machining of aluminum oxide ceramics with Taguchi method, International Journal of Machine Tools and Manufacture, 47(1), 141-147.
[7] Muženič, D., Dugar, J., Kramar, D., Jezeršek, M., & Pušavec, F. (2019). Improvements in Machinability of Zinc Oxide Ceramics by Laser-Assisted Milling. Strojniški vestnik - Journal of Mechanical Engineering, 65(10), 539-546.
[8] Yang, B., Shen, X., & Lei, S. (2009). Mechanisms of edge chipping in laser-assisted milling of silicon nitride ceramics, International Journal of Machine Tools and Manufacture, 49(3–4), 344-350.
[9] Li, Z., Zhang, F., Luo, X., Chang, W., Cai, Y., Zhong, W. & Ding, F. (2019). Material removal mechanism of laser-assisted grinding of RB-SiC ceramics and process optimization, Journal of the European Ceramic Society, 39(4), 705-717.
[10] Dong, X. & Shin, Y.C. (2014). Laser Machining and Laser-Assisted Machining of Ceramics, Comprehensive Materials Processing, 9, 219-234.
[11] Przestacki, D. & Jankowiak, M. (2014). Journal of Physics: Conference Series, 483, 012019, 1-7.
[12] Rozzi, J.C., Pfefferkorn, F.E., Shin, Y.C. & Incropera, F.P. (1999). Experimental Evaluation of the Laser Assisted Machining of Silicon Nitride Ceramics, ASME. J. Manuf. Sci. Eng., 122(4), 666–670.
[13] Song, H. & Dan, J. (2018). Experimental investigation of machinability in laser-assisted machining of fused silica, The International Journal of Advanced Manufacturing Technology, 97(1–4), 267–278.
[14] Chryssolouris, G. (1991). Laser Machining: Theory and Practice, Springer-Verlag, New York
[15] Rebro, P.A., Shin, Y.C. & Incropera, F.P. (2002). Laser-Assisted Machining of Reaction Sintered Mullite Ceramics, ASME. J. Manuf. Sci. Eng., 124(4), 875–885.
[16] Sharif Ullah, A.M.M. & Tamaki, J. (2010). Modeling and Simulation of 3D Surface Finish of Grinding, Advanced Materials Research, 126-128, 672-677.
[17] Felho, C. & Kundrak, J. (2014). CAD-Based Modelling of Surface Roughness in Face Milling, World Academy of Science, Engineering and Technology International Journal of Mechanical and Mechatronics Engineering, 8(5), 814-818.
[18] Fischer-Cripps, A.C. (2011). Nanoindentation, Mechanical Engineering Series, Third edition, Springer-Verlag New York, USA.
[19] Lukianova, O.A. & Sirota, V.V. (2017), Dielectric properties of silicon nitride ceramics produced by free sintering, Ceramics International, 43(11), 8284-8288.