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Experimental Investigations on Applications of Laser Processing on Ultra Hard Metals

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ABSTRACT: Laser processing of ultra-hard materials is a relatively new field that have the potential to improve variety of products and different industries. This dissertation explores specific new development in this field through three main subjects: laser machining, laser deposition of thin film, and laser treatment. In laser machining of ultra-hard material, controlled crack propagation mechanism -as opposed to the typical ablation mechanism was investigated, and micromachining of ultra-hard thin film was also observed. For the laser deposition of ultra-hard thin film, designing new microstructured materials was explored, and the utilization of the inherent particulate formation associated with the pulsed laser deposition process was proposed for the first time. After that, a novel laser/waterjet treatment process to increase the hardness of certain ceramic materials was studied. Also, laser shock processing was investigated. Analytical and experimental approaches was conducted through all of these studies, and different analysis techniques were applied. The results indicate the feasibility of these processes when applied on ultra-hard materials, and provide a better understanding of the governing mechanisms.

Key Words: Mechanisms, Hard materials, Analysis, Technics, Feasibility

1.0 INTRODUCTION:

Ultra-Hard Materials : New materials facilitate the development of new technologies. Engineering systems and products are required to perform more complex tasks than ever before as well as to function under more severe operational conditions. In many fields, engineering ceramics are emerging as the most desirable alternative for various high performance applications such as cutting tools in manufacturing applications, heat resistance shield in aerospace applications, and anti-oxidant in refractories. The desirability comes from the superior properties such as low density, wear resistance, hardness, stiffness, chemical inertness, and thermal stability. These characteristics make shaping these materials for their applications difficult, and limit the ability to shape them for more applications. Engineering ceramics can be divided to two groups: 1) hard ceramics with Vickers hardness less than 35 GPa such as alumina, zirconia, and silicon nitride; 2) ultra-hard ceramics with Vickers hardness greater than 35 GPa such as diamond and boron nitride. Generally, hard ceramics substitute metals when high wear resistance parts are needed or extreme operational conditions are applied (high temperature or corrosive environment). Ultra-hard ceramics are used as abrasives, cutting and drilling tools, and protective layers. For many engineering ceramics, conventional processes such as drilling, milling, turning, and honing can be used. On the other hand, ultra-hard ceramics cannot be shaped effectively using conventional processes. This drawback had limit the machining of ultra-hard ceramics to unconventional processes such as electro discharge machining (EDM), lasers processing, and water-jet machining. Even though these processes are currently being used in industries to machine the ultra-hard ceramics, they still face variety of limitations such as low process efficiency and high cost. As an example for some of these limitations: not all ultra hard ceramics are electrically conductive to utilize EDM, nor can be efficiently machined with lasers or water-jet since they require high power and long machining time. More often, these materials are either produced in their final shape directly from powdered materials using high pressure high temperature process (HP-HT) or are applied as thin film on other materials using chemical or physical vapor deposition techniques.

1.1 Laser processing and Ultra-Hard Materials

Among all the current processes of ultra- hard materials, laser processing is in unique position for the future of these materials. It is the only process that can be applied as cutting process, thin film deposition process, and treatment process. Therefore, the utilization and machinability of ultra-hard ceramics will be addressed in this dissertation with emphasis on laser processing through these three main topics: machining, thin film deposition, and treatment of ultra-hard materials. The emphasis of laser processing in each of these topicscomes from the unique advantages of lasers in dealing with ultra-hard materials as described in each of these topics below.

1.2 Laser Machining of Ultra-hard Material

Laser-alone and laser-based hybrid processes show more potential in processing ceramics because the machining efficiency is primarily dependent on the thermal and optical properties instead of the mechanical properties of the work piece material. Lasers have been used in conjunction with other conventional processes to cut ceramics and produce better quality cut surfaces. For example, in laser-assisted turning; the laser is focused on the workpiece in front of the cutting tool to heat up the workpiece locally. The heated material just in front of the cutting tool becomes softer and can be easily removed. This increases the performance of the process since it allows the turning process to cut hard to machine brittle materials. Laser-assisted turning also requires lower magnitude of cutting forces leading to high workpiece surface quality and dimensions accuracy with low energy and cost .According to Dubey et al laser-assisted turning of silicon nitride and alumina ceramics is economically effective since it reduces the surface roughness, cutting forces, and tool wear.

For ultra-hard ceramics, lasers are used to perform machining and micromachining through ablation, melting, and evaporation. Since ultra-hard ceramics are often needed in high precision applications, these mechanisms of material removal do not meet some of the high industries requirements. In laser machining using these mechanisms, heat affected zone,low speed, and high energy are some of the main limitations. However, due to the unique mechanical properties of ultra-hard materials an alternative cutting mechanism can be used.The novel controlled crack propagation mechanism would minimize heat and energy required for laser machining and increase the cutting speed. The work done on investigating this cutting mechanism is reported in four scientific peer reviewed papers (Chapter 2, 3, 4 and 5). These investigations addressed the role of the fluid medium in Laser/Water-Jet (LWJ) process with respect to controlled crack propagation mechanism, and modeling the mechanism to optimize for the process parameters. Also, a change of the crack direction was investigated.

As in laser machining, laser micromachining of ultra-hard materials face the same problems of low precision and large heat affected zone; however, controlled crack propagation mechanism cannot be applied due to the high precision requirement. We addressed these limitations through the investigation of material removal through ablation mechanism, but using smaller wavelength laser and smaller pulse duration to minimize the heat and the area affected by laser.

2.0 LITERATURE REVIEW

This paper details the importance of brightness in relation to laser beams.

The 'brightness' of lasers is a term that is generally not given much attention in laser applications or in any published literature. With this said, it is theoretically and practically an important parameter in laser-material processing. This study is first of a kind which emphasizes in-depth, the concept of brightness of lasers by firstly reviewing the existing literature and the progress with high brightness laser-material processes. Secondly, the techniques used to enhance the laser beam brightness are also reviewed. In addition, we review the brightness fundamentals and rationalize why brightness of lasers is an important concept. Moreover, an update on the analytical technique to determine brightness using the current empirical equations is also provided. A modified equation to determine the laser beam brightness is introduced thereafter. work The modified equation in turn is a new parameter called "Radiance Density". Furthermore, research studies previously conducted to modify laser design to affect laser beam brightness are also discussed. The paper not only involves a review of the techniques used to improve laser beam brightness but also reviews how bright lasers can be employed to enhance/improve laser process capabilities leading to cost reduction of the laser assisted processes in areas such as manufacturing.

Polycrystalline cubic boron nitride (PCBN) is the second hardest known material, diamond being the hardest. Unlike diamond, PCBN is not found in nature, but is a man-made material. It is hailed as the best performance cutting tool material for machining hard cast iron, high chrome alloy steels, high-strength nickel super alloys and powder metal alloys because of its advantages over diamond in terms of thermal and chemical stability. PCBN is manufactured by sintering fine particles of c-BN with the aid of ceramic matrix typically TiN or AlN under high pressure and high temperature conditions. PCBN not only possesses the outstanding mechanical properties such as extreme hardness and wear resistance but also exhibits high thermal conductivity, high Young's Modulus, low coefficient of friction, and chemical inertness (less reactive to metals like titanium). In recent years, PCBN tools are increasingly used in micro-manufacturing of a variety of precision components because PCBN is able to keep its nature when scaling down the end mills from conventional to microscopic sizes. In addition, PCBN meets the high demands of form accuracy, surface quality and low subsurface damage in ductile machining of brittle materials. Thus, PCBN is currently employed in the industry for cutting 'difficult-to-machine' materials because of its superior characteristics. However the same properties limit the ability to shape the PCBN tools for various geometries.

Many machining techniques have been developed to shape PCBN that ranged from water-jet to electric discharge machining (EDM), and pulsed Nd:YAG laser. Due to the shortcomings in the water-jet process such as time consumption, wide kerf, poor surface finish and taper water-jet was not acceptable. In EDM, the process has been used to fabricate all insert shapes with good quality, but the material removal rates remained low. Lasers, on the other hand, have excellent prospects for machining PCBN. However, the central issues like formation of recast layer, phase transition, and kerf geometry require a secondary process like honing. Also, the material removal rate is low. Thus the existing processes for the fabrication of PCBN tools are inefficient with respect to cost, time, and energy consumption.

3.0 Experimental Details

Equilateral triangular inserts of PCBN without carbide backup, prepared by EDM, were offered by Diamond Innovations, Worthington, Ohio, USA for the experiments. The triangles have 7 mm side length and 1.6 mm thickness. The average particle size is 4 µm with a composition of 75% of c-BN and 25% of Ti based matrix containing carbon, by volume (BZN 9000 of Diamond Innovations). Surface roughness (Ra) of the top (polished) and the side(EDM machined) were 0.3 and 3 µm respectively.

Five triangular inserts were used, one for each fluid medium. Laser machining was accomplished at two different cutting speeds 42.3 and 84.6 mm/sec (100 and 200 in/min) for each insert. All fluid media pressure was kept at 140 kPa (20 psi) except for the water-jet. Since the abrasive-free water-jet was used in the work, the pressure was kept higher at 5.5 MPa (800psi).

A continuous wave CO2 Laser (Model 820 Spectra Physics) of 10.6 µm wavelength and 500 W power was used in all experiments. The laser beam was focused to a spot size of 0.2 mm on the sample surface using a 127 mm focal length lens. For the laser/water-jet experiment, the water-jet followed the laser beam with a spacing of 4 mm to avoid the absorption of laser power by direct contact with water. See Figure 1 for laser head description. It may be noted that water absorbs about 70% of CO2 laser energy. Details of laser-water-jet setup are described else where.

Laser Treatment of Ultra-hard Material Laser treatment of metals is a very well established field, and it has been used in many industries for precise controlled surface treatment. On the other hand, laser treatment of ceramic materials has been established recently and especially with some certain ceramic materials - Boron Nitride (BN) - this process was never addressed. Based on our work on BN in the laser machining and PLD of ultra-hard materials, we noticed the potential of laser treatment of BN. Improving the hardness of BN using lasertreatment would open the door for unlimited opportunities in many industries. Especially in the tooling industry, this opportunity would have a huge impact. Diamond is the hardest material but suffers from low thermal and chemical stability when used in machining of ferrous materials, and cubic boron nitride is thermally and chemically stable but has half the hardness of Diamond. We addressed this issue through investigating hardness improvement of cubic boron nitride material through two approaches: 1) Laser shock processing (LSP), and 2) Laser waterjet (LWJ) heat treatment. The first approach used shock waves to embed nano diamond particles on the surface of PCBN tools in order to increase the hardness of the tool. The second approach used LWJ surface heat treatment to increase the hardness of BN tools. The approaches in both projects were initiated for the first time in the field of ultra-hard ceramics to the best of my knowledge.

4.0 RATIONALE OF THE STUDY

Cubic Boron Nitride (CBN) is the second hardest material on earth, inferior only to diamond. It is not found in nature but can be synthesized by application of high temperature and pressure [1]. Polycrystalline cubic boron nitride (PCBN) blank are produced through sintering of CBN powders with ceramic matrix such as titanium nitride (TiN) or aluminium nitride (AlN). Since its discovery, PCBN has been used in industry as a substitute for diamond due to the superior thermal and chemical stability. The advantages that PCBN does not react with ferrous metals and has a high resistance to oxidation makes it ideal tool material for machining hard cast iron, high chrome alloy steels, high-strength nickel super alloys, powder metal alloys and metal matrix composites.

CBN Tool inserts are traditionally cut from the compact blanks by either diamond sawing, electric discharge machining (EDM) or Nd:YAG laser cutting and finished by diamond grinding, lapping, and polishing. A variety of tool geometries such as square, triangle, circle and rhombus are fabricated for use in various machining operations. The main requirements of a manufacturing process in cutting the desired geometry of tool inserts are:capabilities to generate smooth surface, parallel and narrow kerf, minimal heat affected zone and excellent dimensional tolerance enabling precision; and high cutting speed. In tool production, high speed, low cost and fine resolution are the main consideration for industrial productivity. However, none of the current machining processes perform the combination of these features due to the extreme hardness of PCBN materials. Traditional manufacturing methods for producing tool inserts in PCBN are slow and cost-inefficient.

Given the limitations of conventional

material removal mechanisms, a number of recent reports have focused on non-conventional mechanisms for cutting and machining of pCBN. Hidai and Tokura investigated the hydrothermal-reaction assisted laser drilling of pCBN in steam environment based on measurements of mass loss at high temperatures. CBN film deposited on copper substrate, binder-containing sintered pCBN, and binderless sintered pCBN were irradiated with an Ar-ion laser in water and steam as well as in different gas atmospheres. Single-crystal and binderless sintered CBN reacted very well with steam and thus hydrothermal-reaction-assisted laser machining was effective. However the technique failed in machining the binder-containing sintered CBN.

Swiss Federal Institute of Technology in Lausanne, Switzerland has developed Laser Microjet®, a hybrid technology based on waterjet-guided Nd:YAG laser for machining of pCBN. In this unique laser cutting technique, a free laminar waterjet is used as an optical waveguide to direct the Nd:YAG laser beam onto the sample. The Laser-Microjet® allows precise cutting of pCBN materials with smaller kerf and better surface finish. A Q-switched pulse laser (up to 300 W) of 532 nm wavelength and water pressure of 2-10 MPa was employed for the process. The

5.0 SCOPE OF THE STUDY

waterjet prevented any thermal damage and permitted parallel beam transmission through the sample leading to taper-free and narrow kerf features. The tolerances are much smaller than those obtained with conventional laser and EDM processes. However the process suffers from very slow cutting speeds as it reports 70 passes with each pass at a speed of 7 mm/min to cut 3.25 mm thick pCBN sample.

Crack propagation provides an energy and cost efficient method for cutting of ceramics because hardness and brittleness of ceramics lead to low material removal rates and slow cutting speeds during conventional machining processes. In low thermal conductivity ceramics such as alumina thermal shock induced fracture has been successfully utilized for energy efficient cutting [6, 7]. However in high thermal conductivity ceramics such as polycrystalline cubic boron nitride (pCBN), thermal shock is not feasible. In this paper, we investigate fracture based material separation of pCBN due to synergistic interactions between laser heating and subsequent waterjet quenching through “score and snap” mechanism — laser heating leads to localized damage and oxidation of surface layers; and subsequently stress fields developed due to the variable constrained.

Laser processing systems offer accurate processes at low costs as compared to conventional methods such as waterjet cutting, flame cutting and other processing methods. In addition, laser technology also offers permanent marking on consumer goods, electronic equipment and other products. Due to government regulations regarding clear marking on consumer products such as food, pharmaceuticals and others, laser technology is expected to be widely adopted for marking and engraving purpose. Furthermore, advanced laser products such as fiber lasers are expected to boost the demand for laser processing in manufacturing operations. These lasers offer large number of applications and are highly cost effective as compared to other laser products.

It's equally important to be keenly aware of the project's scope. The value of laser scanning is not limited to complex mechanical systems. While building the Community of Christ Church in Independence, Mo., our company used scanning to guide a complex concrete paver layout installed on pedestals. This made it possible for two crews to start work at opposite ends with the confidence that they would meet in the middle, which they did. Providing a clear definition of the scope and flexibility with the format of the deliverable can produce opportunities and value at all stages of the project.

6.0 OBJECTIVES OF THE STUDY

Advantages of laser technology for material processing over other conventional techniques are fueling the adoption of laser technology in industrial processes. Laser technology is used for processing wide range of materials including metals, non-metals, polymers, glass, rubber and others. This encourages manufacturers to adopt laser technology in their manufacturing operations. Growing automobile and aerospace industry across Europe and Asia Pacific regions is expected to drive demand for laser processing systems during the forecast period. Furthermore, laser processing systems are expected to witness high demand during the forecast period owing to the rising consumer electronics industry in countries such as China, South Korea and others. Laser processing systems offer accurate processes at low costs as compared to conventional methods such as waterjet cutting, flame cutting and other processing methods. In addition, laser technology also offers permanent marking on consumer goods, electronic equipment and other products. Due to government regulations regarding clear marking on consumer products such as food, pharmaceuticals and others, laser technology is expected to be widely adopted for marking and engraving purpose. Furthermore, advanced laser products such as fiber lasers are expected to boost the demand for laser processing in manufacturing operations. These lasers offer large number of applications and are highly cost effective as compared to other laser products. Material processing using laser technology led the global laser processing market with highest revenue share in 2013. This was mainly due to large number of applications offered by laser technology. Laser technology provides high precision cutting, welding, drilling and marking and engraving without damaging the material. Additionally, laser technology enables clean processes and minimal human intervention which helps in minimizing errors.

7.0RESEARCH METHODOLOGY

Industry Insights

Growing demand for wireless devices as well as telecommunication is expected to drive the laser processing market growth. Material processing needs laser processing which is expected to have speedy adoption leading towards the rise in the growth of the laser processing market over the forecast period. Owing to precise and speedy industrial processes comparing to traditional techniques, laser enabled manufacturing processes are expected to augment the laser process market growth. Mandatory applied government regulations are going to impact the market growth positively in coming years.

Demand of advanced processing tools, increasing applications in medical field, photo-biomodulation (an emerging area of medical science) and technological advancements & emerging trends in the industrial sector are some of the prominent key market drivers. However, diverging macroeconomic trends fuelled by euro crisis, lack of technical expertise to execute laser processing and high cost of ownership including initial investment, implementation & maintenance cost are expected to hamper the market growth. Furthermore, growing demand for automobiles & mobile electronic devices, different emerging applications of the laser technology, increasing adoption of disk lasers, green laser devices for projection applications and lassol (laser doping of solar cells) are expected to offer opportunities to global players to augment the market growth in coming five years.

Product Insights

Solid state laser, fiber laser and gas laser are the key products of laser processing market. Gas lasers include argon-ion laser, copper laser, carbon monoxide laser, helium-neon laser, carbon dioxide laser, nitrogen laser and ion laser. The introduction of commercial carbon dioxide lasers compared with conventional is anticipated to have a positive impact on the market of flexible food-packaging. Solid-state lasers majorly comprise chromium laser, F-center laser, neodymium laser, holmium laser and ruby laser. Fiber laser growth is expected enable manufacturers to benefit from this technology in their manufacturing solutions. This is going to expel the growth of the laser process market in coming years.

Process Insights

Marking & engraving, material processing and micro-processing are the key processes employed in laser process technology. Cutting non metal & metal and welding processes are other processes employed by laser technology. These are highly advantageous in drilling & mining execution, specifically in crude oil mining. Availability of numerous advantages over traditional techniques such as water-jet cutting technique is going to augment the market growth in processing of materials over the forecast period. High level of precision in small details which would otherwise be a difficult task is also going to impact the market growth positively.

Application insights

Aerospace, automotive, OEMs, medical treatment packaging & devices and electronics & micro-electronics are few of the applications of laser processing market. The micro-electronics and medical applications are going to drive the major growth of the market in coming years. Growing requirement for miniaturization is expected to drive the need for laser processing at nano scale which is going to expel the market growth. Furthermore, increasing demand for laser eye surgery is also expected to gain the significant market growth in coming years. Additionally, growing electronics demand, automotive products and increasing applications in oil & gas are going to lead towards the growth of the market over the forecast period.

Regional Insights

Asia Pacific countries such India, Japan, South Korea and China are going to witness the highest growth due to several factors such as growing number of OEMs & automotive industries and manufacturing cost-reduction. Applied regulations for stringent laser marking by the FDA are expected to increase the laser marking process in the U.S. European countries including Germany, Italy, France and U.K are also expected to witness significant growth due to increasing adoption of automotive industry in coming years.

Competitive Insights

Key players of laser processing market include Alltec GMBH, Eurolaser GMBH, Coherent Inc., Newport Corporation, Epilog Laser, Jenoptik AG, Ipg Photonics Corporation, Rofin-Sinar Technologies Inc., Laserstar Technologies and Trumpf Group. Players are expected to augment the market growth through new product development and customer relationship management.

8.0 CONCLUSIONS

The utilization of ultra-hard materials in more products and by more industries is held back by the difficulties to process and shape them. Though, unconventional machining techniques in general have more potential in processing ultra-hard materials since these processes do not rely solely on the mechanical properties of the material. Among all unconventional processes, laser processing hold a special advantage in dealing with ultra-hard materials due to the diversity of laser processing. It includes machining, thin film deposition, and treatment. The studies presented in this dissertation investigate some of the new developments in laser processing of ultra-hard materials, and initiate some new trends. In the process of laser machining of ultra-hard materials, the controlled crack propagation mechanism was investigated using LWJ system through: 1) studying the effect of different fluid mediums on the process; 2) optimizing the process parameters by modeling the governing mechanism of the process; 3) effectively changing the crack direction in controlled manner. Also, the micromachining of ultra-hard thin film using short pulse duration (picosecond) was investigated. In PLD of ultra-hard thin film, the feasibility to mimic the "brick-bridge-mortar" of Nacre's microstructure using PLD was explored. A comparative study of PLD using nano- and femto-second lasers initiated -for the first time- the utilization of the inherent problem of PLD; particulate formation. Controlling the density and the distribution of particulates on the film can be used to create the bridges in our design to mimic the microstructure as well as texture the film surface which can be used in other applications.

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