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High-power diode laser assisted hard turning of AISI D2 tool steel

P. Dumitrescu, P. Koshy*, J. Stenekes, M.A. Elbestawi

McMaster Manufacturing Research Institute, and Department of Mechanical Engineering, McMaster University, Hamilton, Canada

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Abstract

Difficulties with the integration of CO_2 and Nd-YAG lasers into a machining centre have hitherto impeded industrial implementation of laser assisted machining technologies. The rapidly emerging new technology of high-power diode lasers holds potential in this regard, on account of the laser being compact and the feasibility of fiber optic beam transport. In comparison to other commercial systems, high-power diode lasers combine higher efficiency and metal absorption with lower capital and operating costs; however, their current metal processing applications are confined largely to surface hardening and joining, due to their lower power density. With a view to expanding their application envelope, the work presented in this paper explores high-power diode laser assisted turning of fully hardened AISI D2 tool steel, a material that is difficult to machine. Laser assist is shown to inhibit saw tooth chip formation, suppress chatter, deter catastrophic tool fracture and bring about a substantial reduction in tool wear and cutting forces, with minimal affect on the integrity of the machined surface.

Keywords: Hard cutting; Laser assisted machining; Machinability

1. Introduction

Enhanced flexibility, higher material removal rates, reduced lead times associated with better logistics, and environmental benefits of dry cutting have accelerated the widespread industrial adoption of hard part machining technology in the last decade. Hard cutting of AISI D2, which is a high-carbon, high-chromium tool steel widely employed in the manufacture of cold-forming tools for its excellent wear resistance and hardenability, presents major problems with respect to the current state of machining technology. A perspective of its extremely poor machinability can be realized with reference to typical tool life obtained when hard machining this material being an order of magnitude lower than that corresponding to AISI H13 tool steel [1]. In this context, this paper presents an enabling technology for hard turning D2 tool steel.

Considering that machining by cutting entails shearing of the work material, one plausible avenue to improving the machinability of a difficult-to-cut material is to reduce its shear strength selectively in the immediate vicinity of the shear zone by thermal softening. This technique known as hot machining could be accomplished through the use of an external heat source such as a laser, the role of which in this instance is to merely assist the cutting process, but not to be directly engaged in material removal as in laser machining. The work reported herein explores laser assisted turning of hardened D2 tool steel. The novel aspect of this work is the application of a High-Power Diode Laser (HPDL), the technological characteristics of which are quite different from CO_2 and Nd-YAG lasers hitherto used elsewhere for Laser Assisted Machining (LAM).

2. LAM: A brief overview

The technology of hot machining is not new: the first patent on hot machining was issued before the introduction of high speed steel. Previous generations of this technology employed low-grade heat sources such as flame, electrical resistance, induction and plasma arcs. With the advent of several advanced difficult-to-cut materials, and with the availability of heat resistant tool materials and

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*Corresponding author. Tel.: +1 905 525 9140; fax: +1 905 572 7944.
E-mail address: koshy@mcmaster.ca (P. Koshy).

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cost-effective lasers, there has been a renewed interest in this technology. Successful application of LAM relates to the following advantages: increase in material removal rates, reduction in the occurrence of chatter and catastrophic tool failure, decrease in cutting forces and tool wear, and the capability to cut brittle work materials without extensive cracking [2]. In profile machining applications, the ability to cut rather than grind a material is further advantageous with regard to process flexibility.

The challenge in realizing an ideal LAM process is to ensure that the rate of heating is commensurate with the kinematic cutting parameters such that the bulk of the input heat is transported in the chip, with the least thermal detriment to the machined surface/sub-surface. Work material classes that are well suited to the application of LAM technology include: (i) hard and brittle materials such as engineering ceramics that can otherwise be subject only to cost-prohibitive abrasive processing, (ii) heat resistant materials like nickel alloys, (iii) materials with abrasive constituents such as high silicon content aluminum alloys, and (iv) materials with a propensity to significant strain hardening like austenitic stainless steels.

Klocke and Zaboklicki [3] presented several demonstrator components that confirmed the feasibility of cutting sintered silicon nitride through LAM. For workpiece temperatures in the range of 1000–1400 °C, chip formation was observed to be realized predominantly through ductile plastic deformation, resulting in machined surfaces of a quality similar to that obtained in diamond grinding. Based on electron microscopic analysis of chips obtained, Lei et al. [4] inferred that plastic deformation of silicon nitride in the shear zone was sustained by the enhanced mobility of the rod-like silicon nitride grains, facilitated by a reduction in the viscosity of the intergranular glassy phase at elevated workpiece temperatures. Rebro et al. [5] developed a double-ramp laser profile protocol for LAM of a mullite ceramic to preclude thermal fracture of the workpiece, the incidence of which is exacerbated by the lower thermal diffusivity, fracture toughness and tensile strength of this porous material, in comparison to silicon nitride. LAM was further employed by Pfefferkorn et al. [6] to cut a partially opaque zirconia, and achieved a forty-fold improvement in the life of the polycrystalline cubic boron nitride tools (PCBN) in an operating workpiece temperature window of 900–1100 °C.

LAM of an alumina reinforced aluminum metal matrix composite was studied by Wang et al. [7] who reported that laser assist reduced cutting forces and wear of the carbide tool by 30–50% and 20–30%, respectively. The machined surface was further observed to exhibit enhanced wear resistance, due to the higher concentration of alumina particles in and immediately beneath the generated surface, evidently due to the tool nose displacing the particles into the thermally softened aluminum matrix. Gratias et al. [8] characterized the effect of laser power and beam-tool lead distance in the machining of hardened XC42 steel (equivalent to AISI 1042) and found the cutting forces to be reduced by 80%. During the course of an investigation on LAM of aerospace alloys, Lesourd et al. [9] observed laser heating to inhibit catastrophic shear instability in the cutting of titanium alloys, and facilitate machining of Inconel at speeds as high as 400 m/min, which represents an order of magnitude productivity enhancement. LAM applications detailed above predominantly pertain to turning processes, although schemes have been outlined [10] for milling. Westkaemper [11] has further reported a laser assisted grinding process wherein the stock removal rate in continuous dress grinding of hot pressed silicon nitride was increased by a factor of six with no adverse effects on the machined surface quality.

Despite having been introduced more than two decades ago and the large body of research literature that has accrued over this period, there seems to be no large scale industrial implementation of LAM technology at present. This is predominantly due to issues referring to safe and seamless integration of the laser into the machine tool. The relatively new and emerging technology of HPDL [12,13] holds significant potential in this regard.

3. HPDL in the context of LAM

Individual diode lasers are a few hundred micrometers in size, and have a limitation on their output power. Depending on the total power and beam quality required, HPDL therefore constitute several diode laser stacks comprising a number of diodes. Although the output is therefore multimodal, and incoherent, the beam is of high temporal stability, which is critical for the robustness of a manufacturing process. The output radiation of the diode diverges 2–6 times higher in a plane perpendicular to the plane of the p–n junction known as the fast axis, in comparison to the parallel plane identified as the slow axis. Due to fast and slow axis collimations, the laser beam footprint of commercial direct diode systems are generally rectangular, which influences the design and response of the process that the laser is used for. In reference to the application of HPDL for LAM, its characteristics vis-à-vis CO_2 and Nd-YAG lasers are summarized in Table 1.

Compared to CO_2 lasers, HPDL operate at a much lower wavelength band, resulting in better metal absorption and smaller absorption length, both of which have significant process implications. Application of an absorption enhancing coating is an option in laser processing, however, this represents an additional operation and is not quite practicable for multi-pass LAM processes. To this end, HPDL hold a definite advantage over CO_2 lasers. The shorter absorption length is also beneficial for LAM applications in terms of minimizing thermal damage to the generated surface. HPDL further possess higher electrical to optical conversion efficiency, resulting in less severe cooling requirements, which reflects favorably on the size of the laser head and the peripheral equipment. Compactness is critical to integrating the laser into the machine tool; so is the feasibility of conveying the laser