Laser-assisted machining of compacted graphite iron

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Received 5 January 2005; accepted 7 April 2005
Available online 13 June 2005

Abstract

Compacted graphite iron (CGI) is a material currently under study for the new generation of engines, including blocks, cylinder liners, and cylinder heads. Its unique graphite structure yields desirable high strength, but makes it difficult to machine, thus resulting in a machining cost. Laser-assisted machining (LAM) is adopted to improve its machinability and hence machining economics. The machinability of CGI is studied by varying depth of cut, feed, and material removal temperature and then evaluating resultant cutting forces, specific cutting energy, surface roughness, and tool wear. At a material removal temperature of 400°C and a feed of 0.150 mm/rev at a cutting speed of 1.7 m/s, it is shown that tool life is 60% greater than conventional conditions at a feed of 0.100 mm/rev. Surface roughness is improved 5% as compared to conventional machining at a feed of 0.150 mm/rev. CGI microstructure evaluated post machining by sectioning and polishing shows no change. An economic analysis shows that LAM can offer an approximately 20% cost savings for the machining of an engine cylinder liner.

Keywords: Compacted graphite iron; Laser-assisted machining; Machining; Machinability

1. Introduction

Current engine block design is limited by material limits, while higher performance, such as improved fuel economy and lowered emissions, demands stricter design requirements. The limitations are increasingly seen in diesel engines, where the performance demands have increased bore pressure to around 135 bar with peak pressures of 160 bar and the next generation of diesel engines is expected to operate at pressures greater than 160 bar [1]. Increased pressure requires an increase in wall thickness for current materials, which in turn increases block weight and decreases overall efficiency. Current materials, such as gray iron, are unable to satisfy economic, environmental, and performance objectives that have been set forth for new engine block designs [2]. A promising option for next generation engine blocks is compacted graphite iron (CGI), which has also been used in cylinder heads and liners.

With the microstructure and mechanical properties that are between those of gray and ductile irons, CGI offers a material that is stronger and stiffer than gray iron while having better castability, machinability, and thermal conductivity than ductile iron. The properties of CGI lend themselves to components that undergo both mechanical and thermal loading [3]. The disadvantage of CGI is that, due to its higher strength, stiffness, and hardness, it is not as machinable as gray iron. At high speeds (800 m/min) with polycrystalline cubic boron nitride (PCBN) tools, the tool life for machining CGI is reduced to 1/20th when compared to machining gray iron [4]. At slower cutting speeds, such as 100 m/min, the tool life of CGI is only 50% that of gray iron. Laser-assisted machining (LAM) offers an opportunity to cost-efficiently machine CGI, as intense, localized heating reduces the workpiece strength and lowers cutting forces, thereby increasing tool life. By utilizing LAM to increase tool life and material removal rates of the machining process, the overall part cost could be lowered, making CGI more attractive to engine designers.

Typically, the graphite present in gray cast irons is in the form of randomly oriented, elongated flakes, while the graphite in ductile iron exists as individual spheres [5]. The graphite in CGI is characterized by randomly oriented particles that are elongated as in gray cast irons, but they are shorter, thicker, and have rounded edges. The rounded edges of the graphite particles stem crack initiation, while the strong adhesion slows crack propagation [6]. The graphite...
Nomenclature

\begin{itemize}
  \item \( c_p \) specific heat at constant pressure (K/kgK)
  \item \( d \) depth of cut (mm)
  \item \( D_l \) laser beam diameter (mm)
  \item \( D_w \) workpiece diameter (mm)
  \item \( f \) feed (mm/rev)
  \item \( F_c \) measured cutting force (N)
  \item \( F_f \) measured feed force (N)
  \item \( F_t \) measured thrust force (N)
  \item \( h \) enthalpy (J/kg)
  \item \( h^* \) previous value of enthalpy (J/kg)
  \item \( k \) thermal conductivity (W/mK)
  \item \( L_t \) laser tool lead (mm)
  \item \( N \) rotational speed (rpm)
  \item \( P_l \) laser power (W)
  \item \( r \) radial coordinate (m)
  \item \( R_a \) surface roughness (µm)
  \item \( T \) temperature (C or K)
  \item \( T^* \) previous temperature value (C or K)
  \item \( T_{init} \) initial workpiece temperature (C)
  \item \( T_{max} \) maximum temperature under the laser spot (C)
  \item \( T_{mr} \) material removal temperature (C)
  \item \( t_p \) preheat time (s)
  \item \( U_c \) specific cutting energy (J/mm³)
  \item \( v \) cutting speed (m/s)
  \item \( z \) axial coordinate (m)
  \item \( \alpha \) absorptivity of the unmachined workpiece
  \item \( \varepsilon_{IR} \) emissivity as seen by the infrared camera
  \item \( \phi \) cylindrical coordinate (m)
  \item \( \rho \) density (kg/m³)
  \item \( \omega \) workpiece rotational speed (rad/s)
\end{itemize}

Particles are in a three-dimensional matrix, which has been described as a carbon coral reef [7], so that there is strong adhesion between the graphite and iron matrices, which may be ferritic or pearlitic as demanded by the application.

The material properties of CGI offer better strength and stiffness than gray iron, and better castability, machinability, and thermal conductivity than ductile iron, making it ideal for components that undergo both mechanical and thermal loading [7]. There is almost always some spheroidal nodularity, which is ideally between 0 and 10%, although 20% is allowable depending on the application [8]. Compact graphite iron (CGI) tends to hold its strength and elongation properties well until approximately 400 °C [9]. The reduction in strength at elevated temperatures was found to correspond to the transformation of pearlite to ferrite and graphite at intermediate temperatures and the further change to austenite at high temperatures. When the elevated temperature properties are compared to those of gray iron, CGI shows 1.5–2 times the strength throughout the whole temperature range [10].

Because CGI has a higher tensile strength and higher stiffness than gray iron, it is more difficult to machine. Additionally, the pearlitic CGI structure is more difficult to machine than ferritic CGI. Hughes et al. [9] state that the tool life for pearlitic CGI is equal to that of nodular cast iron. The properties of CGI necessitate that high torque and stiffness machine tools be used and Dawson [11] notes that 20–30% higher spindle power is required. The greatest losses in tool life occur during turning and cylinder boring [12]. Dawson et al. [13] state that during low speed cutting using carbide tooling, a 50% reduction in tool life is seen as compared to gray iron. Abele et al. [6] report there is no difference in tool life between cutting speeds of 10 and 100 m/min. At lowered cutting speeds, DeBendictis [14] reports that CGI is prone to built up edge (BUE) and flank wear, while positive insert geometries help alleviate this problem.

The loss of tool life is particularly important because the automotive industry requires rapid machining to keep productivity high. Abele et al. [6] and Gastel et al. [4] have studied the machinability of CGI in comparison with gray cast iron using PCBN inserts. At high cutting speeds (800 m/min), diffusion and oxidation wear become important in both systems. At high temperatures (above 700 °C), the binder phases in the tools begin to break down, thus increasing wear considerably. By investigating the residue material on the surface, it was found that a layer of Manganese Sulfide (MnS) forms on the gray cast iron, which acts as a lubricant and a protective layer, resulting in longer tool life during machining of gray cast iron. Because the sulfur content of CGI is lower than that of gray cast iron, no MnS layer can form, leading to short tool life at high speeds.

The machinability of CGI was studied by Phillips [15] using tungsten carbide (WC), hot pressed aluminum oxide (Al₂O₃), and Al₂O₃ coated tungsten carbide. The machinability of ferritic and pearlitic CGI was compared against ferritic and pearlitic gray and ductile irons using a constant feed of 0.011 in./rev and a depth of cut of 0.060 in. Ferritic CGI was found to have greater machinability than the pearlitic CGI. In general, the WC inserts were found to have greater tool life than the Al₂O₃ inserts with the tool life greater than 10 min for most cutting speeds.

Laser-assisted machining was first tried in the late 1970s as a method of increasing productivity in machining difficult-to-machine materials, such as nickel-based superalloys, titanium alloys, and hardened steels [16–18]. LAM is based upon the idea that at elevated temperatures, the yield strength of a material would decrease, lowering the required cutting force and increasing the ease of material removal. Bass et al. [16] and Jau et al. [17] conducted research to
explore LAM of Inconel 718, stainless steels, and Udiment 700. A cutting speed that is too slow could lead to melting or hardening of the material such that machining became more difficult, while too fast a cutting speed caused the laser heating to be ineffectual due to the short heating time. Basic modeling of the process was undertaken, including laser and shear plane heating, to determine the power required to reach a desired shear plane temperature, and it was found that a minimum power of 7 kW needed to be required to double the material removal rate of Inconel 718. Rajagopal et al. [18] used a 15 kW CO₂ laser in their investigations of Inconel 718 and Ti-6Al-4V and found the beam location was an important factor in optimizing the thermal gradients and maximizing tool life. Low beam efficiency was cited as a major problem and several coatings, including black ink, graphite, and phosphates were tested with phosphates yielding the best absorptivity. No systematic analysis was performed to measure or model the temperature fields in order to optimize the process. Overall LAM was found to be feasible, but could not be justified economically due to the low absorptivity of metals. No economic benefits could be established, which caused further studies in LAM to become dormant.

The interest in LAM has been resurrected with its application to ceramics in the 1990s. Ceramics are inherently hard and brittle, thus making grinding the only industrially viable material removal method [19,20]. LAM was applied to silicon nitride and it was found that good quality surfaces could be produced with low forces, however, no thermal modeling was done in order to optimize the process [21,22]. Rozzi et al. [23,24], Lei et al. [25], Rebro et al. [26], and Pfefferkorn et al. [27] all studied the application of LAM to various ceramics, including silicon nitride (Si₃N₄), mullite, and partially stabilized zirconia (PSZ). In all the cases, LAM was successful in machining ceramics with tool lives comparable to those of metal cutting and achieving much greater material removal rates than grinding with surfaces free of cracking. Rozzi et al. [23,24] developed a transient, 3-dimensional thermal model to predict temperatures of ceramic workpieces during LAM. By utilizing the model, they were able to perform parametric studies in terms of various operating conditions and provided insight into successful LAM. Their model was subsequently validated for LAM of various ceramics using in-process infrared temperature measurements [23,24,26,27].

The overall goal of the present study is to explore LAM capabilities for machining of CGI. To achieve this goal, the previously validated thermal model was applied to LAM of CGI and used to optimize machining conditions. The thermal model with temperature-dependent properties of the material was again validated by experiments, thereby establishing confidence in its use. Machinability tests were conducted and the resulting data were analyzed, including tool wear mechanisms and tool wear rates, so that machining parameters which can extend tool life could be identified. Throughout this process, a key requirement was to maintain the underlying microstructure of CGI, as the unique graphite morphology provides the desirable physical properties that make CGI an attractive choice for future engine designs. To this end, microstructural analysis was performed after the tests under various LAM operating conditions and a suitable operating condition was determined so as not to alter the microstructure.

2. Experimental setup and emissivity calibration

2.1. Experimental facilities

A Convergent Energy Everlase S51 1.5 kW CO₂ laser provides optical energy that is focused upon the workpiece in a Jones and Lanson 60 hp turret lathe, which is integrated with a NUM 1060 controller. Water cooled mirrors and enclosed beam ducts contain and direct the laser energy until it reaches the focusing optics, which is a spherical concave mirror with a 25 mm effective focal length. A specially designed output nozzle ensures that any stray reflections are reflected back into the nozzle where they are absorbed in black paint and water cooling dissipates the heat.

Prior to machining, the workpieces were sandblasted to obtain better surfaces for painting. Pelikan Plaka #70 black was used as the absorptive coating. Kennametal SPG 422 K313 uncoated carbide inserts with a nose radius of 0.8 mm were used in a Kennametal CSRPL-164D tool holder, of which back rake, side rake, clearance, and side-cutting edge angles were 0, 5, 11, and 15°, respectively.

A Kistler 9121 three component dynamometer and Kistler Model 5184B1 amplifier were used to measure cutting forces. Force data was collected at 1 kHz, with an average taken at every 100 data points, resulting in a data point every 0.1 s. Surface temperatures were measured with a FLIR ThermoCAM SC300 infrared camera. The camera remained stationary during tests and was focused on a line along the workpiece axis and 80° downstream from the laser spot. Emissivity was set in the software to a value of 0.96 based upon calibration tests described in Section 2.2. Temperature data was collected at 60 Hz and averaged every fifth point, so that a data point was recorded every 1/12 s.

After each trial the surface roughness was measured using either a Surtronic Duo or Surtronic 3+ profilometer with a 5 μm diamond pick-up and a 0.8 mm cut-off length. Five readings were taken at random points on the machined surface and averaged after each test. Tool wear was measured on the primary flank, rake, and secondary flank faces using a Zeiss optical microscope. Average and maximum tool wear values were measured on each flank.

Several samples from each test were sectioned using an Al₂O₃ abrasive wheel with a flood coolant and then mounted in Bakelite for polishing. Three different grits of 320, 400, and 600 were used in the initial fine grinding and water
cooling was used throughout to avoid overheating and damaging the microstructure. A six micron nylon cloth wheel was used with a 1 μm diamond abrasive and red oil lubricant for final polishing. Two percent Nital (2% nitric acid and 98% ethanol) was applied for 10 s, followed by an ethanol rinse in order to etch the samples. Again, the Zeiss optical microscope was used to inspect the microstructure.

2.2. Emissivity calibration

Spectral emissivity of the workpiece, which is highly influenced by the coating used, must be known to accurately measure surface temperature during LAM. The specimen was a piece of 4140 steel cut using a band saw and then ground to produce two flat, parallel surfaces. The upper surface was then sandblasted to mimic the conditions under which the CGI workpieces are painted and to improve paint adhesion. K-type thermocouples were spot welded to the sample and then the upper surface was painted with Pelikan Plaka #70 black paint.

A wire gauge was set on fiber flex insulation and then the sample was placed upon the wire gauge. A piece of fiber flex insulation was placed over the sample with a small hole cut to allow for radiation measurement. The insulation minimizes heat loss and prevents large thermal gradients from forming during heating with a propane torch. A piece of cardboard with a hole cut in it was used to block any stray radiation from the IR camera’s field of view, which will prevent damage to the internal sensor of the FLIR SC3000 Infrared Camera.

Several trials were run with the infrared camera, by heating the specimen to 350, 400, and 475 °C. Fig. 1, the emissivity calculated using the Planck and Wien relation vs. the measured thermocouple temperature [28]. An emissivity of 0.96 makes the IR camera data match well with thermocouple readings in all cases.

3. Thermal modeling

3.1. Thermal model description

As mentioned above, Rozzi et al. [21,24] developed a thermal model to predict temperatures throughout a workpiece during LAM of an opaque homogeneous ceramic workpiece, as shown in Fig. 2. A low-pressure gas assist jet is used to protect the CO₂ laser’s focusing optics and impinges on the workpiece surface in the area of jet interaction of Fig. 2. The laser itself is offset from the tool by the laser tool lead distance, normally between 0.5 and 2 mm. Eq. (1) shows the governing heat transfer equation, assuming isotropic thermal conductivity, where $\rho$ is density in kg/m³, $\omega$ is the rotational speed in rad/s, $h$ is enthalpy in J/kg, and $k$ is the thermal conductivity in W/mK, while $r$, $\phi$, and $z$ are cylindrical coordinates in m.

$$\rho \omega \frac{\partial h}{\partial \phi} + \rho V_z \frac{\partial h}{\partial z} + \rho \frac{\partial h}{\partial t} = \frac{1}{r} \frac{\partial}{\partial \phi} \left[ r k \frac{\partial T}{\partial \phi} \right] + \frac{1}{r^2} \frac{\partial}{\partial \phi} \left[ k \frac{\partial T}{\partial \phi} \right] + \frac{\partial}{\partial z} \left[ k \frac{\partial T}{\partial z} \right] + q''$$

The axial advection term is included due to the fact that the coordinates are fixed relative to the laser heating and/or machining, while circumferential advection arises from the rotation of the workpiece. Eq. (1) can be rewritten to account for variation of specific heat with temperature, as shown in Eq. (2) [29], where $T^*$ and $h^*$ are the values of $T$ and $h$ from the previous iteration that are used to find $T$ in the current iteration. The numerical solution is considered converged once $T^*$ and $h^*$ are equal to $T$ and $h$. Once convergence is achieved, Eq. (2) reverts to the form of Eq. (1), as the $c_p T$ terms cancel out on both sides of Eq. (2).
and the maximum temperature. Among the parameters varied were cutting speed ($v$), depth of cut ($d$), feed ($f$), initial temperature ($T_{\text{init}}$), laser power ($P_l$), rotational speed ($N$), and workpiece diameter ($D_w$). Several other parameters were held constant, including absorptivity ($a$), emissivity ($\varepsilon_{\text{IR}}$), laser beam diameter ($D_l$), laser tool lead ($L_l$), and preheat time ($t_p$). Table 1 shows the overall test matrix for this parametric study.

Fig. 3 shows the variation in the maximum temperature and material removal temperature with laser power. The maximum temperature denotes the workpiece temperature directly under the laser heating spot, while the average bulk workpiece temperature entering the shear zone is represented by the material removal temperature. As can be seen, for every 100 W increase in laser power, there is an approximately 500°C rise in the material removal temperature and 900°C increase in the maximum temperature. Similarly, Fig. 4 shows the effect of changing feed. In this case, for each 0.025 mm/rev increase in feed, the maximum temperature decreases by 50°C, while the material removal temperature decreases by 45°C. Fig. 5 depicts how the temperatures change with cutting speed by changing the spindle speed. Each 0.35 m/s increase in cutting speed causes a 50°C decrease in maximum

### Table 1: Parametric thermal model test matrix

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Parameter varied</th>
<th>$P_l$ (W)</th>
<th>$d$ (mm)</th>
<th>$N$ (rpm)</th>
<th>$F$ (mm/rev)</th>
<th>$D_w$ (mm)</th>
<th>$T_{\text{init}}$ (°C)</th>
<th>$v$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nominal</td>
<td>650</td>
<td>0.5</td>
<td>2500</td>
<td>0.100</td>
<td>13</td>
<td>26.85</td>
<td>1.7</td>
</tr>
<tr>
<td>2</td>
<td>Power</td>
<td>550</td>
<td>0.5</td>
<td>2500</td>
<td>0.100</td>
<td>13</td>
<td>26.85</td>
<td>1.7</td>
</tr>
<tr>
<td>3</td>
<td>Power</td>
<td>750</td>
<td>0.5</td>
<td>2500</td>
<td>0.075</td>
<td>13</td>
<td>26.85</td>
<td>1.7</td>
</tr>
<tr>
<td>4</td>
<td>Feed</td>
<td>650</td>
<td>0.5</td>
<td>2500</td>
<td>0.125</td>
<td>13</td>
<td>26.85</td>
<td>1.7</td>
</tr>
<tr>
<td>5</td>
<td>Feed</td>
<td>650</td>
<td>0.5</td>
<td>2500</td>
<td>0.100</td>
<td>13</td>
<td>26.85</td>
<td>1.7</td>
</tr>
<tr>
<td>6</td>
<td>RPM</td>
<td>650</td>
<td>0.5</td>
<td>2000</td>
<td>0.100</td>
<td>13</td>
<td>26.85</td>
<td>1.7</td>
</tr>
<tr>
<td>7</td>
<td>RPM</td>
<td>650</td>
<td>0.5</td>
<td>3000</td>
<td>0.100</td>
<td>13</td>
<td>26.85</td>
<td>2.04</td>
</tr>
<tr>
<td>8</td>
<td>DOC</td>
<td>650</td>
<td>0.75</td>
<td>2500</td>
<td>0.100</td>
<td>13</td>
<td>26.85</td>
<td>1.7</td>
</tr>
<tr>
<td>9</td>
<td>DOC</td>
<td>650</td>
<td>1</td>
<td>2500</td>
<td>0.100</td>
<td>13</td>
<td>26.85</td>
<td>1.7</td>
</tr>
<tr>
<td>10</td>
<td>Work Dia</td>
<td>650</td>
<td>0.5</td>
<td>2500</td>
<td>0.100</td>
<td>13</td>
<td>26.85</td>
<td>1.7</td>
</tr>
<tr>
<td>11</td>
<td>Init Temp</td>
<td>650</td>
<td>0.5</td>
<td>2500</td>
<td>0.100</td>
<td>13</td>
<td>76.85</td>
<td>1.7</td>
</tr>
</tbody>
</table>

$D_i=4.5$ mm, $L_i=1.7$ mm, $t_p=1$ s, $\alpha=0.9$, $\varepsilon_{\text{IR}}=0.95$.

$3.2. \text{Parametric testing of CGI thermal model}$

Prior to running any tests, the various parameters in the thermal model were varied to see the effect on the material removal temperature (average, minimum, and maximum)
temperature, with a 45 °C decrease in material removal temperature.

Fig. 6 shows how the temperatures react to changes in the depth of cut. As can be seen, there is little difference between 0.5 and 1.0 mm. The workpiece diameter was changed only once, because only two cuts can be made on a workpiece while maintaining a cutting speed of 1.7 m/s with the current lathe. Fig. 7 shows its effect on the material removal temperature and maximum temperature since the larger diameter will have a higher capacity. The initial bulk temperature of the workpiece could be raised by utilizing a heat gun. Hot air is blown onto the workpiece, which is slowly rotating in the lathe, to produce uniform heating by convection. Fig. 8 shows the effect of raising the temperature by 50 °C. As expected, both the material removal and maximum temperatures increase by 50 °C with the preheating.

Of the variable process parameters, power has the largest effect on the material removal and maximum temperatures. Increasing feed and cutting speed both cause decreases in the temperatures, meaning that for a given material removal temperature, the power must be increased. On the other hand, during the second cut on a workpiece, the temperatures would increase because the diameter is smaller. Thus, to compensate for this rise laser power needs to be decreased to maintain the same material removal temperature. Changing the depth of cut causes minimal changes in the temperatures, especially between 0.50 and 0.75 mm.

### 3.3. Thermal model validation

The thermal model has been validated for several materials, in both the axial and circumferential directions: Rozzi et al. [30] for Silicon Nitride, Rebroy et al. [26] for Mullite, Pfefferkorn et al. [27] for partially stabilized zirconia. Prior to running machining experiments, the thermal properties of CGI and the thermal model were validated experimentally under the conditions: a rotational speed of 900 rpm, feed of 0.05 mm/rev, 4.5 mm laser diameter, a preheat time of 4 s, following laser powers of 300 and 500 W.

The FLIR SC3000 infrared camera was used to take temperature measurements. The surface temperature distribution along the axis of the workpiece centerline was recorded and compared to the thermal model. The tests show good agreement with the thermal model, as can be seen in Fig. 9, where test H1 and test H2 denote the measured temperatures with laser powers of 300 and 500 W, respectively.
4. Experimental results

4.1. LAM of CGI

An experimental matrix was designed to test the effects of depth of cut, feed, and material removal temperature, as shown in Table 2. The cutting speed was held constant at 1.7 m/s (100 m/min); this was determined by the maximum available rotational speed of the lathe of 2600 rpm and the initial workpiece diameter of 13 mm. A rotational speed of 2500 rpm was used with the 13 mm diameter workpieces, so that a second cut could be taken at 2600 rpm and a diameter of 11.9 mm. The workpieces were approximately 45 mm in length, of which 33 mm was available to machine. In order to provide clearance for the laser optics during LAM, only 19.05 mm was machined. During conventional machining, the laser optics were positioned out of the way and protected with a sheet metal guard so that a length of 25.4 mm was machined.

Except for tests LAM_2 and LAM_3, the material removal temperature has been held constant in order to ensure an even comparison between the different conditions. With no way to measure the temperature under the laser spot due to a lack of optical access, the validated thermal model has been used to find appropriate operating conditions for the cases of Table 2. Fig. 10 shows the results from the thermal model for the material removal and maximum temperatures for case LAM_1. As can be seen, a quasi steady state condition is reached very quickly.

As the workpiece diameter needed to be held constant for the CGI workpieces, laser power was varied to produce conditions, shown in Table 3, to meet the requirements of the experimental matrix. Test LAM_8 was added after the other seven cases had been run and the workpieces had all been machined once. Therefore, the starting diameter was set to 11.9 mm in the thermal model. Besides cutting speed, several other parameters were held constant, including laser beam diameter, \( D_l = 4.5 \) mm, laser-tool lead, \( L_l = 1.7 \) mm, \( t_p = 1 \) s, workpiece absorptivity, \( \alpha = 0.90 \), and emissivity, \( \varepsilon = 0.96 \).

A minimum of four trials were run for each of the tests in the experimental matrix to determine average cutting forces and surface finishes. Cutting force data was collected at 1 kHz and averaged every 100 points, so that a reading was taken every 0.1 s. The machining data from the first 12 s were used to compare conditions.

Fig. 11 shows the effect of feed on specific cutting energy and surface roughness, while maintaining all other parameters constant. As can be seen, increasing the feed from 0.10 to 0.15 mm/rev decreases the specific cutting energy approximately by 25%. Overall increasing feed generally decreases specific cutting energy in metals, so that this decrease is not all together unexpected. Increasing the feed shows only a minor degradation in surface finish, as there is only a 2% difference between the nominal feed of 0.100 and 0.150 mm/rev.

Similarly, Fig. 12 shows the effect of material removal temperature on specific cutting energy and surface roughness. A slight decrease is noted between the 400 and 500 °C material removal temperatures. This decrease corresponds to the decrease in tensile strength at higher temperatures; at 500 °C the pearlitic matrix begins transformation to ferrite and graphite [19]. The surface roughness is roughly constant.

Table 2
Experimental matrix for LAM of CGI

<table>
<thead>
<tr>
<th>Test</th>
<th>Variable tested</th>
<th>Desired ( T_{mr} ) °C</th>
<th>( d ) (mm)</th>
<th>( f ) (mm/rev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conv_1</td>
<td>Conventional machining room temp</td>
<td>0.5</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>LAM_1</td>
<td>Datum LAM conditions</td>
<td>400</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>LAM_2</td>
<td>( T_{mr} )</td>
<td>450</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>LAM_3</td>
<td>( T_{mr} )</td>
<td>500</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>LAM_4</td>
<td>DOC</td>
<td>400</td>
<td>0.76</td>
<td>0.1</td>
</tr>
<tr>
<td>LAM_5</td>
<td>DOC</td>
<td>400</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>LAM_6</td>
<td>Feed</td>
<td>400</td>
<td>0.5</td>
<td>0.075</td>
</tr>
<tr>
<td>LAM_7</td>
<td>Feed</td>
<td>400</td>
<td>0.5</td>
<td>0.125</td>
</tr>
<tr>
<td>LAM_8</td>
<td>Feed</td>
<td>400</td>
<td>0.5</td>
<td>0.15</td>
</tr>
</tbody>
</table>
for the temperatures tested, with a difference of 0.15 μm between the max and the min values.

Comparisons of the average cutting force, average feed force, and average thrust force between conventional machining (test Conv_1) and LAM (test LAM_1) are shown in Fig. 13. The conventional machining tests were run for a total of 120 s, while LAM was limited to 90 s because it became clear that tool life for this particular condition would be worse than the conventional machining.

As can be seen there is an approximately 15% drop in the cutting and feed forces for LAM, while the thrust force increases by about the same amount for LAM.

In order to compare surface roughness, five samples were machined conventionally using the conditions of test Conv_2, for a total of 20 s machining time. Fig. 14 shows a comparison of average surface finish for the conventional trial and test LAM_8, which was run for 90 s. An approximately 5% improvement is seen with LAM, even though machining time was longer for LAM.

Tool wear on the primary and secondary flanks and rake face was measured at the end of each trial, which varied from 3 to 6 s depending on feed. Due to the small size of the workpieces, tools could not be run to failure; instead a linear curve fit was used to project tool life for a flank wear value of 0.300 mm. Tests were run for a minimum of 90 s unless projected tool wear showed a lower tool life than the conventional baseline. For all tests, crater and primary flank notch wear were not observed, and primary flank wear dominated secondary flank wear.

Table 4 shows the results for the tool life tests conducted. A baseline of 19.2 min was established for the conventional machining conditions of Table 2. The nominal LAM conditions (LAM_1) and an increased material removal temperature (LAM_2) both led to decreased tool life. This is most likely due to excess heat entering the tool and causing

| Table 3  |
| Conditions used to meet experimental matrix requirements |
| Test Variable | D (mm) | V (m/s) | N (rpm) | f (mm/rev) | dnom (mm) | P (W) | Tmr (°C) |
| Conv_1 | Conventional | 13 | 1.7 | 2500 | 0.1 | 0.5 | 0 | RT |
| Conv_2 | Conventional | 13 | 1.7 | 2500 | 0.15 | 0.5 | 0 | RT |
| LAM_1 | Dat LAM | 13 | 1.7 | 2500 | 0.1 | 0.5 | 650 | 400 |
| LAM_2 | Tmr | 13 | 1.7 | 2500 | 0.1 | 0.5 | 750 | 450 |
| LAM_3 | Tmr | 13 | 1.7 | 2500 | 0.1 | 0.5 | 850 | 500 |
| LAM_4 | DOC | 13 | 1.7 | 2500 | 0.1 | 0.75 | 650 | 400 |
| LAM_5 | DOC | 13 | 1.7 | 2500 | 0.1 | 1 | 670 | 400 |
| LAM_6 | Feed | 13 | 1.7 | 2500 | 0.075 | 0.5 | 590 | 400 |
| LAM_7 | Feed | 13 | 1.7 | 2500 | 0.125 | 0.5 | 750 | 400 |
| LAM_8 | Feed | 11.9 | 1.7 | 2500 | 0.15 | 0.5 | 750 | 400 |

Fig. 11. Variation of specific cutting energy and surface roughness as a function of feed during LAM.

Fig. 12. Variation of specific cutting energy and surface roughness as a function of material removal temperature during LAM.
breakdown of the carbide tooling. An extrapolation that can be made from this data is that for the uncoated carbide inserts used, increasing material removal temperature causes greater tool wear. Other tool types, such as coated carbide or ceramic inserts, may not be as affected at these temperatures.

When feed was increased, however, LAM yielded improved tool life. Test LAM_8 offers a 60% increase in tool life over the conventional conditions. A comparison of tool wear is shown in Fig. 15. As can be seen, initial tool wear is slightly higher for LAM, but then the wear rate is slower, leading to the increased tool life.

The graphite morphology of CGI must remain intact after a LAM trial to preserve its unique properties. The microstructure was examined throughout each sample, paying particular attention near the machined surfaces of the workpiece and the workpiece center, which should be relatively undisturbed from the laser heating. In most cases the microstructure is unchanged, as shown in Table 5. However, changes are observed in tests LAM_3 and LAM_7, where material removal temperature and the depth of cut were both increased over the nominal case. In the case of LAM_3, the additional laser heating most likely caused carbon diffusion so that spherical graphite formed close to the surface, which is characteristic of ductile iron. Figs. 16 and 17 show the microstructure near the center and machined surface, respectively, for test LAM_3. Fig. 17 shows the spheroidal graphite that has formed. The heating due to the laser in LAM_7 was kept the same as in nominal case, however, with the additional depth of cut more heat is generated in the shear zone. This additional heat had the same effect as increasing the laser power and caused carbon diffusion so that the final microstructure is that of ductile iron rather than CGI, so that tool life testing was not carried out at these conditions.

4.2. Economic analysis

Cost was estimated for machining a generic engine cylinder liner with the dimensions of 305 mm and a diameter of 165 mm with a 0.5 mm depth of cut, so that 80,000 mm³ of material is being removed. Fig. 18 shows the total cost, broken down into machining cost, tool changing cost, tool cost, part loading cost, and laser operating cost. The machining cost uses the machining time plus 10% overhead. Assumed values used for calculation purposes were an operating rate of $120/hour, a tool cost of $2.50/edge ($10 per tool with four edges), and a laser operating cost of $20/hour.

The total cost for conventional machining is $50.60 while the total cost for LAM is $39.30, where both cases include machining and part loading costs. Even with the additional laser cost, LAM represents an approximately

### Table 4
Measured tool life for LAM of CGI

<table>
<thead>
<tr>
<th>Test</th>
<th>Projected tool life (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conv_1</td>
<td>19.2</td>
</tr>
<tr>
<td>LAM_1</td>
<td>15.8</td>
</tr>
<tr>
<td>LAM_2</td>
<td>12.8</td>
</tr>
<tr>
<td>LAM_7</td>
<td>27.6</td>
</tr>
<tr>
<td>LAM_8</td>
<td>30.3</td>
</tr>
</tbody>
</table>

### Table 5
Microstructure findings for CGI experimental matrix

<table>
<thead>
<tr>
<th>Test</th>
<th>Variable</th>
<th>Workpiece center</th>
<th>Machined surface</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conv_1</td>
<td>Conventional</td>
<td>CGI</td>
<td>CGI</td>
<td>No change</td>
</tr>
<tr>
<td>LAM_1</td>
<td>Dat LAM</td>
<td>CGI</td>
<td>CGI</td>
<td>No change</td>
</tr>
<tr>
<td>LAM_2</td>
<td>T_mr</td>
<td>CGI</td>
<td>CGI</td>
<td>No change</td>
</tr>
<tr>
<td>LAM_3</td>
<td>T_mr</td>
<td>CGI</td>
<td>High nodularity</td>
<td>Material affected</td>
</tr>
<tr>
<td>LAM_4</td>
<td>DOC</td>
<td>CGI</td>
<td>CGI</td>
<td>No change</td>
</tr>
<tr>
<td>LAM_5</td>
<td>DOC</td>
<td>CGI</td>
<td>High nodularity</td>
<td>Material affected</td>
</tr>
<tr>
<td>LAM_6</td>
<td>Feed</td>
<td>CGI</td>
<td>CGI</td>
<td>No change</td>
</tr>
<tr>
<td>LAM_7</td>
<td>Feed</td>
<td>CGI</td>
<td>CGI</td>
<td>No change</td>
</tr>
<tr>
<td>LAM_8</td>
<td>Feed</td>
<td>CGI</td>
<td>CGI</td>
<td>No change</td>
</tr>
</tbody>
</table>
20% cost saving per part, which is due mainly to the increased material removal rate and improved tool life. Neglected in this calculation is any cost for cutting fluids that may occur during conventional machining, so actual cost savings may be slightly greater.

5. Conclusions

Laser-assisted machining (LAM) of CGI has been studied to explore its ability to increase tool life and material removal rates by using a laser to heat a spot on a workpiece, lowering the localized strength and increasing ductility. The previously validated thermal model was adapted to CGI and a parametric study was undertaken to understand the effects of cutting speed, depth of cut, feed, initial workpiece diameter, initial workpiece temperature, laser, power, and rotational speed of the lathe on the material removal and maximum temperatures attained during LAM. After validating the thermal model as adapted to CGI, an experimental test matrix was designed to test the effects of depth of cut, feed, and material removal temperature. Laser power and feed were shown to have the largest effect on material removal temperature.

With the material removal temperature around 400°C, LAM was successful without affecting the microstructure of the finished surface. A 60% percent increase in tool life was achieved by increasing feed to 0.150 mm/rev. At the same time a 5% improvement in surface roughness was achieved as compared to conventional machining at the same feed. The increase in material removal rate and tool life allows for an approximately 20% reduction in the cost of machining a cylinder liner.

Acknowledgements

This research was conducted at the Center for Laser-Based Manufacturing and funded by the Indiana 21st Century R&T Fund. The authors wish to express special thanks to Caterpillar for their donation of workpieces.

References


