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AN INVESTIGATION INTO CHARACTERIZING AND OPTIMIZING LASER CUTTING QUALITY—A REVIEW

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Abstract—The quality of a laser-made cut is of the utmost importance in laser processing. Any improvements in this area would be of considerable significance, in that it would lead to an elimination of post-machining operations. As laser systems are becoming progressively more unmanned, the need for improvements in the fields of monitoring, diagnosis, regulation and modelling becomes essential for achieving and maintaining high quality cutting. Although there have been numerous techniques developed over the years, currently there are few appropriate strategies implemented in industry for improving laser cutting quality, partially due to the fact that laser cutting is a highly complex thermal process. The mechanisms governing the laser cutting process are not fully understood. It is the aim of the author therefore to critically investigate and review the current status of laser cutting and associated quality improvement techniques, including research efforts undertaken in the fields of modelling, regulation, diagnosis and monitoring. Present trends and future directions are then presented.

1. INTRODUCTION

1.1. *Significance and difficulties encountered in improving quality*

Laser cutting has made significant headway into the well established area of metal cutting, and has done so for a number of reasons. These are well documented. Amongst these reasons is the ability of lasers to produce high quality cuts at reasonable production rates. Laser cutting has become automated in the same way as many other processes, due to the explosion in the availability of computer technology. This eliminates the need for operators to man these systems, and hence the whole notion of effective monitoring becomes apparent. This does not mean that laser cutting systems are unstable but rather that the high degree of quality they are forced to conform to, in addition to high production rates, means that any decrease in acceptability levels need to be detected and rectified quickly. "Since the capital and operating costs for laser systems are large, high material removal rates, high dimensional accuracy, good surface quality and a high degree of repeatability must be achieved to make these processes economically viable" [1].

Currently, there are some problems with the process which require immediate attention. Process parameters are adjusted and tuned to provide the quality of cut desired, but this consumes exhaustive amounts of time and effort, and still the optimal cutting conditions may not be found. If a different type of material is to be cut, then this procedure has to be repeated. This has been recognized as a major shortcoming, and this issue of optimized process planning or parameter selection is currently being addressed.

Cutting quality deviations can be attributable to slow process drifts and disturbances. There are many reasons for such drifts, but workpiece property variations, assist gas fluctuations, velocity fluctuations, power and spatial–density distribution fluctuations, and optical integrity perturbations are all known to cause such variability in cut quality. So monitoring schemes are necessary.

As just mentioned, the cause of a process producing poorer quality than can be tolerated can be due to many various interlinked reasons. In order for any changes to

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be made then, the relationships between process (and workpiece) variables and cut quality need to be investigated. Diagnosis therefore becomes important though difficult to establish. Once it is known what parameters to vary then, it is necessary to determine by how much, so modelling becomes essential.

So the need for research into laser cut quality is apparent, as it ultimately determines if subsequent finishing operations are necessary. The difficulties and concerns mentioned above make it obvious that addressing these issues is important if laser cutting systems truly wish to become unmanned.

In an attempt to address the overall concern of achieving high quality, the need for such a review became evident, as no existing survey comprehensively encapsulated this entire area, with particular reference to the brevity of information on phenomena occurring within the laser–material interaction zone and the importance of modelling.

1.2. *Definition of quality in laser cutting*

The quality of a laser made cut can be defined in many different ways. Some such criteria are

kerf width
cut edge squareness
inner side slope of the kerf
heat affected zone extent
dross appearance
surface roughness (striations)—the wavelength
—the depth.

It can be seen that some of these quality characteristics are for macroscopic evaluation, such as kerf width, dross appearance and kerf taper, whilst others such as surface roughness and heat affected zone are for microscopic evaluation.

Depending on the ultimate use of the manufactured part, one or more of these definitions may apply. It is important to note that both laser and work material parameters affect the quality of a cut.

2. CLASSIFICATION OF QUALITY IMPROVEMENT

There have been basically four areas undertaken in the past for improving cut quality. Refer to Fig. 1. The first such approach is associated with improvements in laser beam monitoring and control. There are numerous real-time monitoring techniques for regulating power and spatial–density distributions. Definitely, improvements in the stability and quality of the laser beam and optics will improve the material processing quality.

This approach is often termed the indirect method as opposed to the method of actually improving cut quality by monitoring and controlling the material–laser interaction zone directly. This has been the newer approach because although laser beam

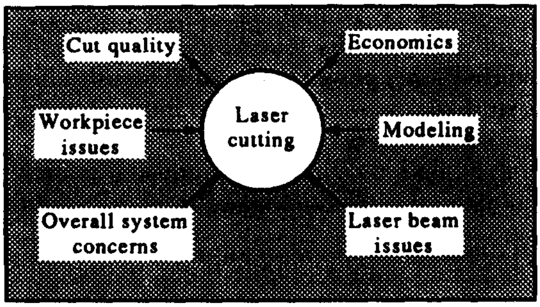

Fig. 1. Concerns and issues affecting laser cutting.

monitoring can bring about improvements, it does not account for workpiece material variations, plasma formation and other phenomena occurring within the interaction zone.

The third such approach for improving cut quality can be classified as modelling. Modelling is seen as an important tool for the pursuit of knowledge in the area of cut quality. There have been many attempts at modelling the laser cutting process. Those who have undertaken this task have almost exclusively looked at the steady state behaviour of the process. Laser cutting is both dynamic and stochastic, with fluctuations in absorbed power, material composition and optical integrity, amongst other perturbations as already mentioned. Steady state modelling has been beneficial for obtaining approximate order of magnitudes for various parameters, but is clearly limited when such models are used for control. In these cases, dynamic models need to be developed and improved, and this is seen as an important area of concern for improving quality. Modelling is also seen to be important to gain a firm grasp of the complex issues occurring within the interaction zone. If the laser cutting process can be more closely characterized, then this should bring about quality improvements.

The fourth such area of concern deals with the improving of the workstation or overall system behaviour. This includes the areas of contour programming and the changing of process parameters at points of profile change, dynamics in the motion system and adaptive focusing capabilities for allowing thickness changes. These are generally of a very high standard today and do not pose as many problems as some of the other issues.

It should be remembered that many of the strategies employed for monitoring and controlling the laser cutting process are often not only specific for laser cutting, but can be readily employed for general laser material processing including marking, welding and heat treatment. In addition, although much of the work presented has been for metal cutting, it is also relevant for cutting polymers, composites, ceramics and wood. Table 1 summarizes the references given, grouped under the four classification areas.

3. LASER BEAM MONITORING AND CONTROL

Real-time monitoring and regulation of laser beams have received much attention over the years. Some schemes have been very simple in nature, whilst others have been very elaborate. The simplest methods record the overall laser power fluctuation. One such study was the development of diverting a portion of incident CO_2 laser power to a pryoelectric detector [2]. This is achieved by the use of a beam splitter. The beam is sampled by a simple chopper, and the resulting intermittent signal is then focused onto the detector, the output signal from which can be easily recorded by a computer.

As most lasers are fitted with standard beam dumps, this can also be used as a calorimeter [3, 4]. Power is measured as the rise in temperature of water flowing through a cone. Thermocouples measure this temperature difference. A lens focuses the beam into a black coated spherical chamber which absorbs the power incident on it. This device is portable and can be used to measure power just before the point of material processing. The flowing cone calorimeter beam dump does unfortunately suffer from a slow response time and is insensitive to small, but important power changes [5]. A commercially available one is the Power Meter Calorimeter System (PMCS) [6].

The method above clearly interferes with the incident laser beam. A recent development circumvents this problem by measuring acoustic signals which are detectable from the mirrors in the beam delivery system. Due to reflected laser radiation from the mirrors, it was found that the high frequency acoustic signal varied with beam power, diameter, position of the beam on the mirror, and even gas mixture and state of tuning of the cavity. The mechanisms governing the acoustic signal are still not fully understood, and several theories exist [3, 7–9].

If a more complete picture of the incident laser beam is desired, then there are

TABLE 1. PRINCIPAL CLASSIFICATION FOR QUALITY IMPROVEMENTS

Laser beam analysis	Pyroelectric detector [2] Calorimeter (thermocouples) [3–6] Acoustic mirror [3, 7–9] Laser beam analyser [3, 5, 8–11] Spoke wheel instrument [12, 13] Needle wheel instrument [12, 14] Rotating wand (thermistor array) [15] Sweeping hollow needle [12, 16–18] Spinning drilled cylinder [19] Beam propagation analysers [13, 20–29] Video imaging (CCD cameras) [30, 31] Photodiode arrays [32, 33] Plastic burn analysis (PBA) [34] Laser beam position sensing [15, 35–37]
Material processing analysis	Spark–shower observation [38–43] Acoustic mirror [3, 7–9, 44, 45] Acoustic microphone [1, 46] Kerf width scanner [47] Video imaging/pyrometers [2, 48–55] Roughness sensing [56, 58–65] Photodiode sensors [66–68] Plasma sensing [70–73]
Modelling	Moving sources of heat [74–87] Fresnel absorption models [93, 94] Inert gas jet model [95] Striation issues [38, 40, 81, 82, 88–92, 96–98] Finite difference models [99–103] Blind cutting model [104] Energy coupling issues [70–72, 105–117]
Overall system performance	Geometric adaptive control [122, 123] Focal positioning [3, 124–128] Information systems [129]

several options which have been investigated. One such development was the Laser Beam Analyser (LBA) [3, 8–11], from which a clear intensity distribution can be easily obtained in about 1/100th of a second. A circular, reflecting molybdenum rod is swept through a laser beam from which a portion of it is reflected into two pyroelectric detectors. This method does not interfere with the laser beam as much as some other methods developed, and claims only an estimated 0.25% power loss. The LBA can also be used to derive the beam diameter, relative central power and overall power level, all of which are valuable in-process characteristics.

The LBA can be used for power feedback control [5]. Using a servo controller, power was stabilized to +/−0.2% as compared to 0.75% with no controller, start up time was reduced to less than 1 min as compared to a usual warm up period of 45 min for most lasers, and its response to a step change in power was an order of magnitude faster than that usually possible.

Other similar devices are the spoke wheel instrument and the needle wheel instrument, both of which can directly measure the intensity distribution in the unfocused beam [12–14].

In another attempt at power control of a laser, a mirror was fitted with motor-driven micrometers to allow resonator alignment along two orthogonal axes under electrical control [15]. The laser power was monitored using a rotating wand which reflected a portion of the beam at 90° onto an array of thermistors. The array was electrically divided into four quadrants, allowing four signals to be obtained (which were representative of the quadrants of the laser beam sampled) and hence a measure of the beam asymmetry was possible. Control of the motors can then allow the reduction of this error. The controller was able to stabilize drift to within 2% per quadrant.

The sum of the quadrant voltages also gave a measure of total average power output, and power stabilization was possible by varying the laser's power supply. The controller was able to maintain the output to within 3% of the desired value. The controller did suffer from slow response time though, but this was thought to be due to the large thermal time constant of the thermistor array. It was envisaged that if pyroelectric detectors were used, this problem could be alleviated.

A variation of the LBA is the use of a sweeping hollow needle [16–18]. Refer to Fig. 2. This method allows the intensity distribution to be measured both in the unfocused and the focused beam [12]. Another similar version is that of a spinning drilled cylinder [19].

A complex beam analysing system was developed to record not only power fluctuations, polarization states and intensity distributions, but also the focusability of the laser beam during material processing [20]. The system was developed to investigate changes in laser beam quality whilst cutting highly reflective materials such as aluminium. Cutting such materials results in light back scattering, which can degrade laser performance.

In an attempt to describe focusability, it is necessary to express the beam in terms of far field divergence angle, beam waist width and beam location. A beam quality factor has been derived in an attempt to compare an actual beam to that of an ideal Gaussian beam [21–25]. Others have also tried to characterize real laser beam profiles [26–28].

It was shown that power level changes, polarization changes, spot size and focal length changes did occur during processing. Such a system is useful for the detection and prevention of such changes, as they can result in damage to the optical elements in the beam delivery system and the laser resonator.

A similar instrument developed and now marketed, is the ModeMaster™ beam propagation analyser [24]. Refer to Fig. 3. It is capable of measuring most of the fundamental parameters describing the propagation of laser beams. These include waist location, divergence, intensity profiles, beam axis location and angle, waist diameter, times-diffraction-limit (M^2), principal axes and beam axis stability. The ability of this instrument to allow real-time access to this information makes it extremely useful for in-process control. Rofin-Sinar, Inc., and others have also developed a beam propagation analyser, similar to those mentioned above [13, 29].

Beam profiling can also be done by using solid state array cameras [30, 31]. Once a portion of the beam is focused onto the array, a video image can be captured, digitized and then stored by a frame grabber. Today this process can be done in real-

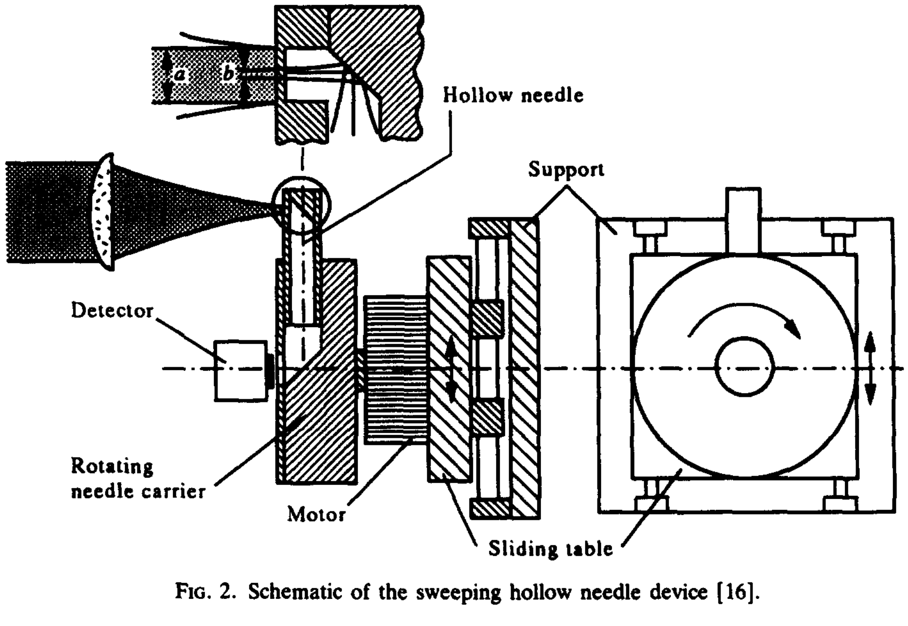

FIG. 2. Schematic of the sweeping hollow needle device [16].

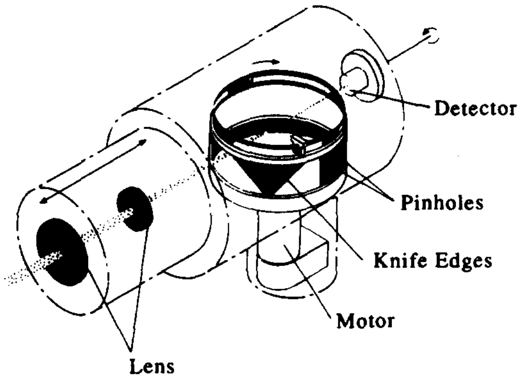

Fig. 3. Schematic diagram of the ModeMaster™ [24].

time at rates of 60 Hz. They offer many advantages over some of the other more conventional methods. The beam profile image is two-dimensional, and therefore integrating a profile along one axis is not needed. These cameras are also very small and robust; therefore, they find many applications in harsh test environments.

These cameras can easily detect the thermal distortion of lenses, optical damage, beam misalignment and stability, and are therefore an excellent diagnostic tool. Many solid state cameras have been developed over the years, with the most popular being the Charge-Coupled Device (CCD) camera for laser diagnostics.

Measuring beam profiles of diameter less than 0.5 mm are not recommended as accuracy is substantially reduced because of the detector arrays used in these solid state cameras. They are light sensitive and therefore require a large amount of attenuation.

Photodiode arrays have also been used in the same manner for characterizing XeCl lasers [32]. High speed photography techniques employing streak cameras with reflex optics have also been used to obtain time and spatial distributions of CO and CO_2 pulsed laser radiation [33]. Plastic Burn Analysis (PBA) has been used for obtaining a simple qualitative measurement of CO_2 laser beam profiles [34]. Burning or pyrolysis of plastics, especially polymethylmethacrylate or PMMA, has been well established over the years to characterize laser beams. This qualitative diagnostic tool can be used to analyse and measure beam profiles, diameter, divergence, resonator mode and alignment of the delivery system. There are variations of the traditional PBA techniques which are currently used, but they all suffer from the problem of being solely qualitative.

Laser beam position sensing is important as it affects cut quality. A few methods have been developed for this purpose. One such device reflects a small portion of incident laser beam down past a rotating disk (which contains a slot in it) and onto a photosensor [35, 36], the signal from which is amplified and recorded on a computer. The signal generated depends on beam power, location and diameter, as well as on the width of the slit. Automatic or adaptive beam alignment is therefore possible to alleviate beam wander and instability. Others have looked at this problem [15] and the problem of guiding laser beams over long distances whilst trying to maintain a given beam diameter [37].

4. DIRECT QUALITY MONITORING AND CONTROL

There have been a few different sensing techniques developed in the past for optimizing the laser cutting process. Attempts have been hampered because of space restrictions and high temperatures in the vicinity of the cut. Splattering of molten material makes the environment even harsher, therefore non-contact sensors are strongly favoured.

One such method proposed was the viewing of the main angle of the spark–shower from beneath the cut kerf [38–40]. This was achieved by taking photographic snapshots during cutting, and was found to correlate well to the angle of striations formed. Striation angle has been shown to be an important factor affecting the resulting cut quality, and can be used as an effective indicator of quality for on-line monitoring purposes.

Although this sensing technique can provide certain information for quality assessment, modifications to current laser systems would be necessary if it were implemented in industry. It has also been shown that striations can, on occasion, differ greatly on opposing sides of a cut and hence the reliability of this technique can be questioned.

Another system has also been developed for viewing the spark–shower cone blown out of the kerf in an attempt to assess cut quality [41–43]. A TV camera observes the spark–shower and this is then processed using real-time imaging techniques. A rule based decision system then initiates the control of the processing velocity, gas supply and power level if necessary.

This decision system was chosen because there exist many parameters in laser cutting which are difficult to identify, measure and control. In addition to this, models which relate cone shape and workpiece characteristics to laser power, feed rate and gas flow are not readily available. So the use of a rule based system in this case was justified.

The acoustic emissions detectable from the mirrors in the beam delivery system can also be used to obtain in-process signals suitable for laser welding quality monitoring [3, 7–9]. If the transducer is mounted on the last mirror, and is less than about a metre away from the interaction zone, a back reflected signal is detectable [44]. This is because any high power radiation incident on the mirror will produce a signal, regardless of where it has come from. This concept was extended to the case of quality monitoring for laser cutting [45]. The experimental set-up used is shown in Fig. 4.

This methodology has several advantages over some of the other proposed sensing techniques. It does not interfere with the incident laser beam and is independent of the processing direction. It was found that an overall increase in signal strength was associated with a decrease in kerf width and smoother cut faces. This sensing technique does provide a general overall guideline for monitoring cut quality, but because the information is purely qualitative and difficult to analyse, it is not appropriate for real-time implementation.

Another acoustic sensing technique developed, obtains the acoustic emission detectable when the assist gas jet impinges upon the cutting front [1, 46]. These emissions are in the audible range from 5 to 20 kHz and are due to gas vibration. An acoustic microphone obtains the signal from which the frequency spectrum can be analysed by use of Fast Fourier Transformation. It was found that the resonant frequency detectable varied with cutting front geometry changes. A theoretical analysis has determined what the natural frequency for laser cutting is in relation to the kerf width and depth of cut. This corresponded well with the experimentally obtained results. With thicker materials though, the theoretical analysis over-predicts the kerf depth quite substantially. This is thought to be due to turbulence because of flow separation occurring at the underside of the kerf as the gas jet exits.

This sensing technique can be used for control purposes. Once the microphone picks

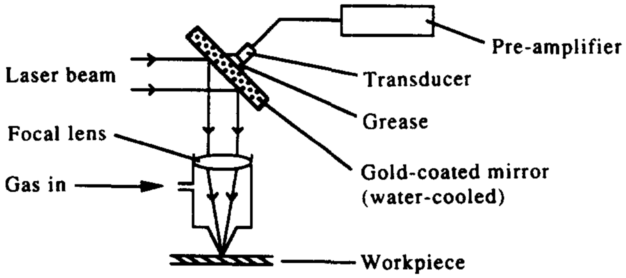

FIG. 4. Experimental set-up used for monitoring acoustic signals [45].

up the signal, it can then be used to obtain the resonant frequency, and through the theoretical model, the width of the kerf can be calculated if the depth of cut is known. If this value deviates to unacceptable levels, then process parameters can be controlled to bring the kerf width back to its desired value. Accurate process models need to be developed though to bring about the necessary control actions.

Attempts have also been made at obtaining a signal by attaching an acoustic emission sensor to the workpiece. This has several drawbacks including the variability in contact between workpiece and sensor every time a new workpiece is used, which greatly affects the signal obtained. Therefore non-contact measurement of the signal is preferred [44].

A system of scanning a He–Ne laser beam across a laser cut was developed to measure the kerf width and also to detect the presence of dross adhesion on the lower cut edges [47]. This was achieved by obtaining a signal from a photodiode which detects the reflected scanning laser beam. The typical signal contains two peaks, which correspond to the laser cut edges. The kerf width can then be easily calculated through the use of simple relationships. It is suggested that the width of the heat affected zone (HAZ) can also be determined by this system.

This technique works well when linear cuts are performed, but complexities arise when profile cutting. These can be overcome though. Filtering the visible light emitted from the cutting process is also necessary because it will affect the photodiode signal obtained.

Direct observation of the cutting and welding process can be achieved by use of filtered CCD-camera systems [48–50], or pyrometers can be used for temperature sensing [2, 51, 52]. Radiation emission of the cutting zone can be a useful parameter to examine for diagnostic purposes from which, the workpiece temperature distribution can be calculated [53], but it is necessary to realize that inaccuracies in its determination are present. Emissivity is not a constant but a function of both wavelength and temperature, and is therefore very difficult to account for [54]. Thermal imaging systems have also been developed for laser welding and surface hardening by using infra-red cameras. It was reported that in practice, temperature measurements in the range 500 to 1500°C (with an expected emissivity dispersion) have an estimated precision of 50°C [55].

Quality assurance of laser cutting has been achieved by obtaining a direct roughness profile of the inner kerf by using a laser beam as a stylus [56]. This has the advantage of being non-contact. It was realized, for control purposes, that from a roughness profile, it is very difficult to establish the significant parameters affecting it, and often it is a complex combination of many different laser and material characteristics. Pattern recognition methods were therefore used to group similar profiles into clusters whose characteristics were distinct from other groups.

It was found that the arithmetic average roughness parameter R_a was a reliable parameter for characterizing the profile, as some were overly sensitive. A limitation, though, was that a roughness profile can only be done at a particular depth of interest, and therefore there is reliance on this one profile to be indicative of the characteristics of the complete cut surface. In addition, this methodology can only be used off-line, and at best, the results can only be analysed soon after performing the cut. Other attempts at characterizing laser-cut surface profiles have been carried out [57].

Numerous surface monitoring techniques have been developed over the years [58–65], although not specifically developed for monitoring laser cutting. These may find applications in off-line inspection and diagnosis of laser cutting quality.

A clever method developed was based on the detection of the emitted light from the cut front by using a photodiode [66–68] (Fig. 5). A CCD camera can also replace the photodiode to analyse the shape of the cutting front. A photodiode sensor has also been successfully used in the field of laser clad quality monitoring [69].

The final bending mirror in the beam delivery system was replaced with a beam splitter. This allowed emitted visible light from the cutting front to pass through it,

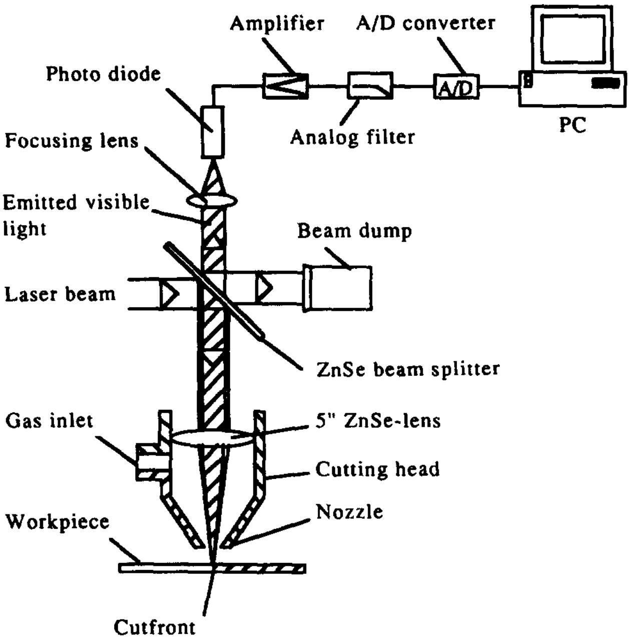

FIG. 5. Emitted light sensing using a photodiode [66].

and then be focused onto a photodiode. This non-contact sensor is neatly fitted above and away from the cutting zone, and hence is unintrusive and independent of the processing direction taken. With minor modifications, this system is compatible with present industrial laser cutting machines, and is independent of the type of material cut. The signal obtained is not contaminated by any of the reflected CO_2 laser radiation, as CO_2 laser radiation does not lie within the visible range.

Although the signal is comparatively easy to obtain in real-time, the analysis is somewhat more complex. Although successful in physically interpreting characteristics from the signals to phenomena occurring within the cut kerf, the signal is purely qualitative and not quantitative, making efficient monitoring difficult.

The importance of processing temperature changes occurring during cutting on cut quality has also been stressed. It was found that the temperature increased with increasing cutting speed [68]. This was done by dividing the emitted radiation into a visible and infra-red range, which are detectable by two photodiodes. A growth in this ratio corresponds to an increase in temperature. This correlated well with theoretical and experimental investigations previously undertaken.

In laser material processing, plasma often forms above the interaction zone. It has been shown that it fluctuates characteristically and its emission can be measured with both a photodiode and an acoustic microphone [70–72]. The reason for the plasma fluctuation was shown to correlate well to the surface movement of the melt, which obviously affects the resulting quality. An Ar laser beam was focused onto the melt, which was then reflected up to a detector able to sense the melt movement. It has been argued that on-line control of the welding process is possible using this technique. Although it applies to laser welding, possibly it could also be applicable to the laser cutting case.

An alternative method senses the charged particles in the plasma. These particles are randomly distributed over the interaction zone, which therefore cause a potential difference to exist. This voltage can be measured in a variety of ways, and this signal can then be used for on-line quality control. It has been reported that the detection of weld penetration, craters, holes, humping, mis-tracking, keyhole formation and end notches are possible [73].

5. MODELLING THE LASER CUTTING PROCESS

There have been many models developed over the years for the laser cutting process. These are necessary so that process models can relate the operating variables and characteristics of the laser, CNC system and gas jet to the parameters affecting cut quality, namely the temperature distribution and the geometry of the cut kerf. In addition to this pursuit, modelling provides considerable insight into understanding this complex process, involving both fluid dynamics and heat transfer considerations.

Possibly the origins of many authors' work on laser modelling stemmed from early attempts by others to characterize the now well established fields of metal treatment, including welding, oxy-acetylene cutting, casting, flame-hardening and quenching. Although many years have passed since the fundamentals were first developed, the theory of moving point, line and plane sources of heat [74, 75] is one such famous area now receiving wide attention in general [76, 77] and in the field of laser modelling [78–87].

The formation of striations has received much attention because it strongly affects the quality of laser cutting. But the mechanisms affecting the forming of stria are not well understood. Striations will result to some extent due to the non-steady nature of laser cutting. There have existed for a long time several different explanations for stria occurrence, but there is still no general consensus on this dynamic effect.

One explanation given for this phenomena is that at cutting speeds less than the speed of the moving molten layer, caused by oxidation, sideways burning occurs and results in the forming of a stria [88]. This effect was observed using high speed photography techniques. But at high cutting speeds, this model cannot explain why striations exist.

Others have dismissed this phenomena as the blowing out of the melt from the kerf, leaving a stria on the cut edge. But the fact that on opposing sides of a cut kerf, striations can vary greatly, and can vary during cutting, means that stria formation cannot be so simply accounted for. It has been suggested that striations could form as waves in the thin molten layer behind the moving cutting front [38–40]. Often, two striation patterns are also observable, with a regular pattern near the upper surface and an indistinct pattern nearer the lower surface, increasing the complexity of accounting for their appearance [38, 40, 89, 90].

It has been shown that pulsations in the molten layer prior to it being blown out of the kerf cause periodic striations to form. It was suggested that fluctuations in absorbed laser power could cause both the thickness and temperature of the liquid layer to oscillate. Absorbed power fluctuations can be caused by plasma formation, incident power variations or material absorptivity variations. But it was also shown that in special cases, even without absorbed power fluctuations occurring, the liquid layer can oscillate with a natural frequency. This explanation for the forming of striations during reactive gas assisted laser cutting has been well documented [81, 82, 89, 91], and would seem to be more correct than some of the other explanations. The results obtained with these models have correlated very well with experimental investigations undertaken by others.

It was also shown that pulsing the laser beam at the same frequency as the natural striation pattern can eliminate these striations completely [92]. This has the effect of greatly improving quality.

A cutting model was developed for high speed laser fusion cutting, based on the simplified assumption that a two-dimensional geometry exists and light absorption is characterized by the Fresnel laws [93]. An equation was developed over the cutting front which allowed the maximum cutting depth and absorption coefficient to be readily calculated.

A more complex three-dimensional geometry model was then investigated, again light absorption was characterized by the Fresnel laws [94]. The influence of various laser beam parameters was theoretically examined for their effect on the absorption in the cutting front. This model was necessary as the two-dimensional model neglected kerf width, the circular nature of the laser beam, heat conduction losses and polarization effects.

An energy balance was then derived from which the shape of the cutting front can be determined. As with all modelling, simplifications were still made. In this case, it was assumed that the width of cut was the same as the diameter of the laser beam, the kerf did not taper in size, the contour lines on the cutting front were semi-circular of radius equal to that of the laser beam, the front inclination was linear over the cut depth and could be determined experimentally.

In an attempt to investigate the forces exerted by an inert gas jet on the thin molten layer, the equations of motion of the gas flow were solved [95]. The dominant mechanisms governing the ejection of the melt were found to be the pressure gradient that exists within the cut kerf and the frictional forces also present. Conformal mapping methods and boundary layer theory were used to obtain these, respectively. The gas flow was assumed to be laminar and subsonic, in addition the cutting front was assumed to have a linear inclination. It was also shown that the cooling of the melt due to the gas jet (approx. 2.5 W), was insignificant to typical incident laser beam powers.

Work has been undertaken for the purpose of predicting possible workpiece thicknesses that can be cut during reactive gas cutting, depending on cutting speed and incident laser power [78–80]. The model assumes that the cutting front is vertical and covered by a molten layer. It is assumed that heating occurs through absorbed beam power and reactive gas burning, and heat losses occur by vaporization, melt ejection, conduction and melting of solid material (see Fig. 6). It was shown numerically that heat loss by melting of the solid material and melt ejection of the molten layer is negligible in comparison to the other terms.

It was also importantly shown that the contribution of evaporation to cutting speed is large for thin materials, whilst liquid melt ejection dominates for thicker materials. Cut quality is known to decrease with thickness increases, and therefore can be attributed to the large melt ejection contribution to cutting speed.

A model of melt ejection showed that hydrodynamical instabilities existed, and it was argued that these instabilities correlated with periodic striations [96]. It was proven that if the driving mechanism for melt removal was due to the pressure gradient, then the removal was unstable. This tended to vanish when the pressure gradient was small compared to the shear force.

In another investigation, a simple model for reactive gas cutting exhibited limit cycles [97]. It was suggested that these instabilities could be sources for the formation of striations. Heat losses due to the melt ejection and heat conduction losses were not taken into account, both of which play important roles in the real laser cutting process.

In an attempt to accommodate different laser beam distributions, a model was

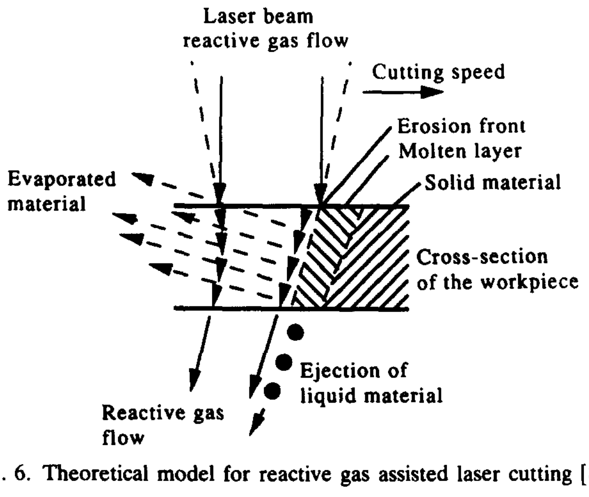

Fig. 6. Theoretical model for reactive gas assisted laser cutting [80].

developed, from which a three-dimensional cutting front geometry can be calculated [98]. The model allows the parameters which affect periodic striations to be established. The self-adjusting kerf width and melt film thickness are iteratively found by calculation of the gas flow, melt flow, heat conduction and local energy balance (see Fig. 7).

Using finite difference techniques, a three-dimensional heat transfer model was developed for laser processing with a moving Gaussian beam [99]. The model does not account for variable thermal properties and latent heat effects. The model allows for heat losses on both upper and lower faces of the slab, of finite thickness and width infinite length. The model is useful for predicting primarily the temperature profile, maximum processing speed and the heat affected zone. The model is limited to prediction though, as it is a time consuming scheme, even on a computer.

Cutting front mobility was also investigated for the cases of neutral and oxygen gas jets, by the use of finite difference thermal modelling [100]. Variations in reflectivity with temperature [101] and understanding melt dynamics and unsteady heat transfer in laser heated materials have also been possible using this methodology [102, 103].

A theoretical model was developed for laser "blind" cutting as opposed to the more commonly investigated "through" cutting [104]. The model allowed for the prediction of the depth of cut kerf that can be achieved using a particular material at a given laser power. It was shown that dimensional accuracy of the cut was an important issue and that high velocity gas jets and high speed processing both greatly improved the quality of blind cuts.

Recently, the formation of plasmas and energy coupling issues have received much attention [70–72, 105–115]. In a small region of cutting conditions, this plasma actually helps increase the coupling of radiation into the cutting front. But if the laser beam intensity is increased above a certain threshold, then the dense plasma formed actually shields the incident radiation from the cutting front, resulting in an interrupted and poor quality cutting process [72, 116, 117]. It has been suggested that an optimal range of laser intensities exists for high quality cutting through enhanced energy coupling.

6. IMPROVING OVERALL SYSTEM PERFORMANCE

The geometry of the actual workpiece to be cut greatly influences the resulting cut quality possible, and often determines what laser cutting system should be used if a few plants are available [118, 119]. Often parts are redesigned to remove some of the difficulties found in laser cutting, which may or may not be present to other material processing techniques. Some of the problems particular to laser cutting are entry holes, sharp corners, thin webs, part nesting and ending of cuts [120, 121].

A simple, yet very effective, method developed adaptively controls laser power and laser mode according to processing speed [122, 123]. This was done to compensate for the fact that when performing a contoured profile cut, the actual speed at the corners

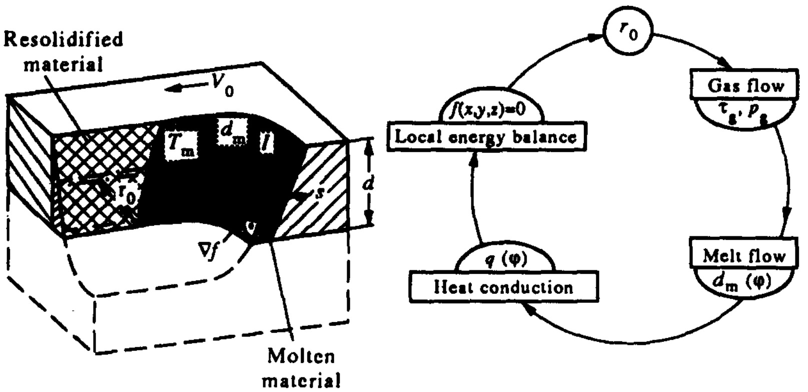

FIG. 7. Self-adjusting cutting Kerf model [98].

approaches zero due to direction changes. If the power remains a constant, then excessive over-heating results, and has the effect of melting off the corner. It was found that to cut the corners, a pulsed mode produced better quality cuts (less dross and melt off) than a continuous wave mode. It was also established that the roughness of a cut can be improved by pulsing at slow speeds, or by switching to continuous wave mode at high speeds.

Accurate focal positioning is detrimental to obtaining high cut quality. Shifts in the focal position can occur during processing, because of warping of materials as they heat up. This is especially true when cutting thin sheet metal. In addition, exhaustive CNC programming of the focal position to known thickness changes can be made obsolete if an in-process monitoring scheme is employed.

One such device is a capacitive clearance control device [124, 125] (Fig. 8). The workpiece makes up one electrode, therefore, a disadvantage of this type of clearance control is that the workpiece must be metallic. Capacitive sensors have not only found application in laser materials processing, but for decades have been used in flame and plasma cutting technologies. The other electrode is commonly the actual cutting nozzle, often copper cones or hemispherical tips are used. Regardless of the system's CNC programme being executed, the sensor will over-ride this to maintain clearance control and can do so very quickly by use of an accurate z-axis motor drive. It is reported that an accuracy of 0.1–0.2 mm is possible. Plasma, steam and splatter falling between the nozzle and workpiece, though, can cause the controller to react, even though the focal position may be correct [3, 124]. Edge cutting can also distort the signal produced.

Skid and feeler devices can also be used for clearance control. Since these types of sensors are contact types, the workpiece material does not have to be metallic and flying debris does not pose any problems. They also are very good at cutting near edges [124].

Optical clearance control also has the advantage of insensitivity to flying debris and material edges. One such device developed was that fitted to the Melcut-3DCM laser cutting machine [126]. The sensor consists of a laser diode projected onto the workpiece, where the reflected beam is focused onto a position sensitive device. The height is independent of the reflected power but only depends on the position of the reflected

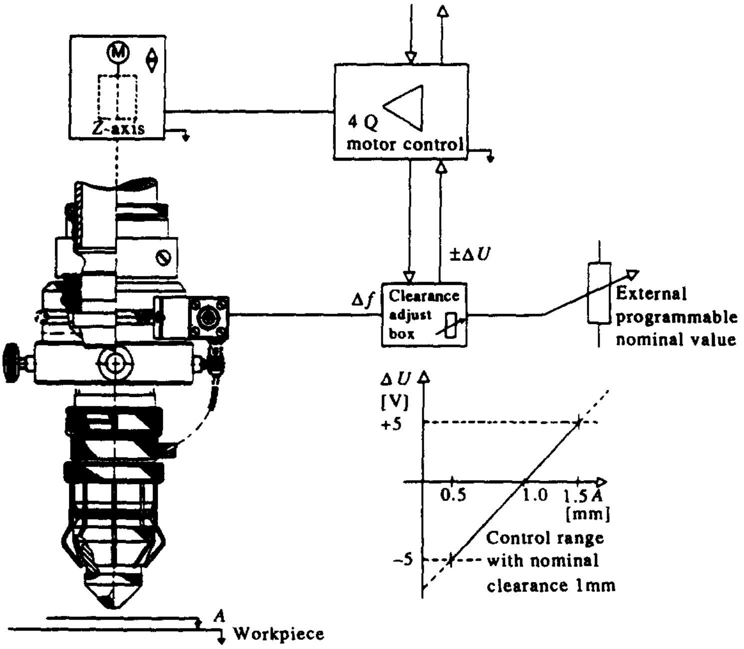

FIG. 8. Lasermatic™ capacitive clearance control [124].

beam. This method can adaptively control height to an accuracy of +/−0.5 mm. Similar optical devices have also been developed [127, 128].

The many different types of materials that can be cut with laser systems combined with the many inter-related process parameters that can affect cut quality, make the decisions faced by laser users very difficult to unravel. It has been recognized though that data bases and artificial intelligence techniques can ease this time consuming step. Information systems are leading the way in allowing users to predict process parameters, and hence arrive at a good set of starting conditions for the attainment of high quality, in reduced time [129].

7. PRESENT TRENDS AND FUTURE DIRECTIONS

It has been shown through the large compendium of references given, that quality improvement techniques through monitoring, diagnosis, control and modelling of the laser cutting process are becoming increasingly more important. Research efforts are being directed to this field in an attempt to provide industry with "smart" laser systems, capable of producing high quality work at high production rates. This is necessary if laser cutting systems are to continue to make an impact on an already well established field.

In the area of quality monitoring, it is clear that no one sensor can hope to "pick up" all the quality parameters at one time—this indicates the need for sensor fusion in the future. Until then, it is necessary for us to choose one or more quality definitions to apply sensor technology. This has the problem, therefore, of having to rely on particular quality parameters to provide an overall picture for quality assessment.

There are obvious problems also with trying to sense cut quality directly, namely, space restrictions and high temperatures in the vicinity of the cut. The splattering of molten material makes the environment even harsher, so reliable and robust sensing schemes are still a very real issue facing quality improvements in the future.

In laser beam control, the most important prerequisite is to have a highly stable and reliable source. In the future, the quality of laser beams will continue to improve, and this will see the shift in emphasis move from laser beam control to direct workpiece monitoring and control. The standard of laser beams and optics today are generally very high, and it is likely that the need to control laser beam parameters will diminish; needless to say that some form of monitoring will be needed for alerting operators of beam delivery failure in unmanned systems.

In the field of laser modelling, greater research efforts are necessary to characterize the dynamics in the cutting process. In particular, dynamic models need to be developed and improved for greater control of the process and for greater understanding of the mechanisms leading to striation formation. The complexity of the issues involved in the process have so far led to solutions with many underlying assumptions and inadequacies. This in turn, has hampered the progression of high quality industrial control, diagnostic and supervisory systems. Randomness inevitably exists in a laser process, such as laser power fluctuations, pressure and flow fluctuations of the assist gas, plasma formation and material property variations, all of which strongly suggest the need for stochastic modelling.

Artificial intelligence and the use of knowledge bases can be an effective way of circumventing the problem of not having adequate models for decision making [41–43]. Such an adaptive system is shown below in Fig. 9. It is likely that this trend will increase in popularity if modelling does not progress quickly enough in the future.

It is also obvious that the research efforts undertaken have often been material and laser parameter specific, so that loss of generality is prevalent. It is also apparent that present knowledge is scattered widely and that integration of the current research directions should occur in the future if indeed, we are to achieve the very best in total quality improvement. So not only can knowledge bases be useful in decision making in control schemes, but also for collating much of the information vital for optimizing the process planning step [129].

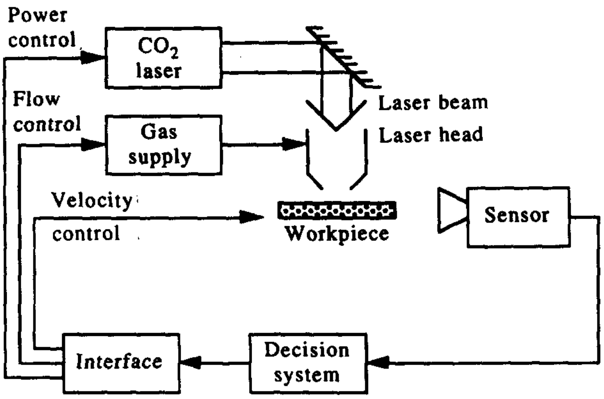

FIG. 9. An adaptive laser system.

8. CONCLUSION

The research efforts undertaken in this field have highlighted the need to guarantee quality, not prior to, but during the laser cutting process. It has also been shown that characterizing this operation is complex, and greater understanding of the mechanisms leading to striation formation is needed. An emerging trend has seen a shift in research from the field of beam monitoring and control to direct workpiece monitoring and control. There is also the reliance on using the dominant parameters affecting the process for quality assurance, and the dependence on particular quality indexes for quality assessment. The need for integration of research efforts in the future is also strongly stressed, possibly through the use of artificial intelligence techniques and knowledge bases.

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