Laser Material Processing

-- Some Applications in Welding Research Institute

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Abstract

Laser material processing technology has started taking deep roots in our country and no more it is a mystery. Though the technology started penetrating in our country for nuclear applications[1], no doubt, it has deepened into other industrial sectors like defence, transport, electronics, space, energy, etc..

Welding Research Institute (WRI) has a 575 Watts capacity CO_2 Laser supplied by M/s. Coherent, USA. In WRI, the following laser material processing feasibility investigations were carried out for the applications of

- Laser welding of battery can hermetic sealing,
- Laser welding of stainless steel spindle assembly,
- Laser cutting of silicon wafers,
- Laser scribing of silicon steel transformer laminations, and
- Laser scribing of solar cells.

The details of the investigations are brought out in this paper, which will give more explanations about the advantages of Laser material processing compared to conventional material processing techniques. A comparison of performance between Laser and EBW is brought out in the paper for the benefit of the readers.

1.0 Introduction

1.1 Application fields of high energy density beam processes

Applications of high energy density beam processes viz Laser and Electron Beam Welding (EBW) cover today a whole range of industries such as automobile, aeronautics, energy, electrical appliance, nuclear etc..

These advanced technologies are applied[2]

- in joining very expensive components (jet engines) as well as in very cheap ones (gears),
- in welding small sized parts (pressure transducers) as well as very large components (bodies of aeroplanes),
- in welding thin components (saw blades) as well as very heavy sections (pressure vessels),
- in welding ordinary metals (structural steel) as well as exotic metals (titanium).

Today, there are around one thousand industrial multikilowatt Laser equipments, of which 1/3 are used in welding. Available beam powers range from 1 to 10 KW, but the large majority (1 to 5 KW) are found in the automobile industry for assembling gear components[2]. Laser beam welding has taken advantage of the experience already acquired by the users of EBW; indeed, joint design and the preparation of parts are almost similar for the two processes[2]. In U.S.A there are about 7500 units below 100 Watts of power, 1400 in the 100 to 999 Watts range and 300 exceeding the 1 KW with about 10% of these in the 5 KW and above range. Among Lasers exceeding 100 Watts of power, it is estimated that 52% are used in drilling, cutting and metal removal, 42% of these are used in welding and 6% in surface treatment tasks[3]. Today in industry, Lasers outnumber electron beams virtually by a factor of 8.

1.2 Comparison of performance of Laser and EBW

Laser and EBW, the ultra high power density processes (106 $Watts/cm^2$) have many unique features compared to conventional processes. Among these two processes, Laser presents the following advantages over EBW[2]:

- Laser beam (LB) does not need a vacuum, it can be transmitted over a long distance without attenuation
- LB is not disturbed or affected by electromagnetic and electrostatic fields ; also, it is possible to use vacuum and magnetic chucks for job handling unlike in EBW
- LB can be employed in areas of difficult access by means of suitably placed mirrors

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- LB does not produce X-rays, as does EBW
- LB can be used on a time sharing basis to supply several work stations, thus resulting in effective utilisation of the equipment
- LB can be divided into several subsidiary beams of lower power (beam splitting), which can be used simultaneously for different functions. In a similar way, a high power beam can be employed as subsidiary beams of lower power[4].
- LB can be used for nonmetallic material processing

However, LB presents the following disadvantages when compared with EBW :-

- Energy efficiency of LB is low (10 to 20%) compared to EBW (90 to 98%). This is also true with equipment efficiency.
- LB entails a considerable consumption of gas and electricity. So running cost is high.
- Oscillation of LB is made by mechanical means, thus limiting the sweep frequency.
- Lack of flexibility in varying focal distance.
- Need of protection screens against incidence of direct and indirect Laser beams
- High investment costs for power greater than 5 KW.

Considering the technical performances of EBW and LB, in welding stainless steel at 1 m/min. welding speed, as an example,[2] thicknesses

- upto 4 to 5 mm, EB and LB produce similar penetrations when the operating conditions are similar (similar power and focal spots), and
- beyond 5 to 6 mm, the increase in penetration with LB is less than for EBW.

This is attributed to the presence of plasma at the impact point, which prevents the Laser energy from penetrating inside the material. Recent experiments carried out in vacuum[4] showed that much higher penetrations were obtained with LB, approaching those of EBW. Thus the incidence of plasma is completely neutralised when LB welding is carried out in vacuum; it can be said that the best welding conditions and the best Laser performance are achieved when welding is done in vacuum !

Reflection and plasma plume formation are the two major factors that limit CO_2 Laser heat input during Laser welding. Pulsed CO_2 Laser welding has the advantage of a power spike at the beginning of each pulse that can be tailored to overcome the reflectivity barrier[5]. The plasma plumes created when Argon is used as a shielding gas can cause decoupling of the Laser light from the metal surface limiting heat input efficiencies to about 15%. By using Helium as a shielding gas and focusing slightly below the metal surface, heat input efficiencies in excess of 30% can be achieved[5]. The Welding Institute, UK, has proved that Nitrogen, which is approximately one tenth the cost of Helium, can produce almost as good results as Helium. The weld hardness produced with N_2 gas is slightly higher than that achieved with Helium, but the weld size and strength is very similar[6].

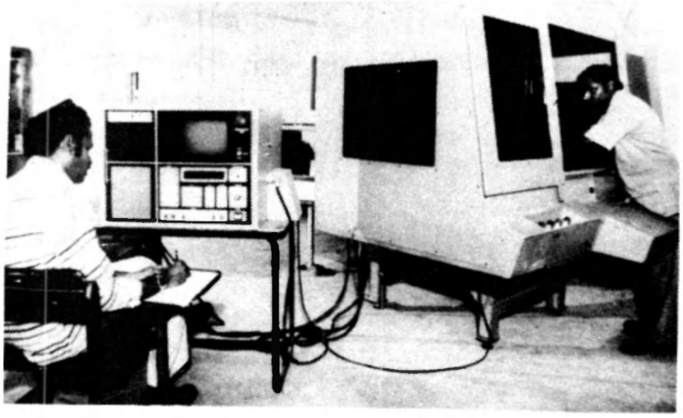

Fig. 1. *CO_2 Laser Equipment at WRI*

2.0 Laser Equipment

Welding Research Institute has a 575 Watts capacity CO_2 gas laser, which can be operated both in continuous wave (CW) mode and enhanced pulse mode (single and repetitive pulse) (Fig. 1). During enhanced pulsing mode, the maximum peak power can reach upto 3.5 KW (at very low duty cycle) and the maximum pulsing frequency of 2.5 KHz. The mode structure of the beam is TEM_{00}, Gaussian mode structure, so the power concentration and hence the heat concentration at the beam centre is very high. The equipment has got a three axis CNC facility to have a programmed movement of any profile apart from the rotary table circular movement. A He-Ne pilot Laser of red colour origin is mounted in the same axis of main CO_2 Laser beam to find out the trajectory of the beam on the component before actual material processing, as the CO_2 Laser beam is invisible radiation. The equipment is provided with 3 sets of focal length Zn-Se lenses viz 1.5" lens, 2.5" lens and 5.0" lens. The focus adjustment is possible to the micro level by adjusting a micrometer on the focus head, which results in up and down movement of the lens with respect to component surface. A CCTV camera with monitor is provided for closer look into Laser material processing.

3.0 Applications in Welding Research Institute

3.1 Laser Welding of Battery Can Hermetic Sealing

A battery company in India is manufacturing Ni-Cd and lithium batteries with stringent quality requirements. At present, these battery cans and the lids are joined by mechanical swaging at their works, which is a slow process consuming 15 minutes time for each can. Also, when these cans were subjected for a quality check, such as keeping the cans in the tilted position for about 24 hours time and checking for any leakage of electrolyte through the joint, they have encountered about 30% rejection. The problem was referred to WRI as a consultancy job for welding and WRI took it up as a challenge. Thus, the objective of the present work was to improve upon the consistency in quality of hermetic sealing and to improve upon the productivity.

Before welding, the battery can is loaded inside with non-woven nylon separator as a roll for the insulation between positive and negative electrodes occupying almost the entire volume along with the electrolyte. The melting temperature of the above nylon separator is 160°C. The most critical requirement of this experimental work is that, when welding is carried out between the can and the lid, there should be no thermal damage to the nylon separator inside the battery can. So, very high heat concentration is required at the weld joint and also the process speed should be much faster, which can be easily met by Laser welding. The hermetic sealing requirement is mandatory in this application, because the battery is loaded with potassium hydroxide electrolyte, which is also highly corrosive.

The material of the battery can body and the lid is low carbon steel and the thickness is 0.4 mm for both. The joint design is the close gap edge weld (Fig.2) and the penetration required is 0.5 mm. Both battery can and the lid are electroless coated with nickel of minimum thickness 2 microns to prevent corrosion. In this application, the surface coating of nickel has improved the absorbtion of CO_2 -Laser beam energy by the component. It is observed that in some cases, the energy absorption in metal is very low since more than 85% of the impinged beam is reflected out. This makes the CO_2 -Laser processing of metal inefficient, sometimes even impossible. The absorption, however, can be markedly improved by the surface condition like surface coating[7].

3.1.1 Welding Experiments and Results

The experimental set up is shown in Fig.3. A copper jig for holding the can was employed without water cooling, which acted as a heat sink preventing the thermal damage to the nylon separator.

During the welding experiments, it was observed that the plasma plume was present due to metal vapour at the weld zone. Laser plume is a subsonic metallic vapour jet of target material, which absorbs and scatters a part of the incident energy. Considerable amount of thermal energy upto 40% of the incident energy is carried away by the plume, which obstructs the effective transfer of beam energy to the component[8]. A plasma disruption gas jet has already been successfully employed, which has allowed an increase in penetration upto 40%[9,10]. In this experiment, argon gas jet was passed across the weld zone to blow out the plasma plume.

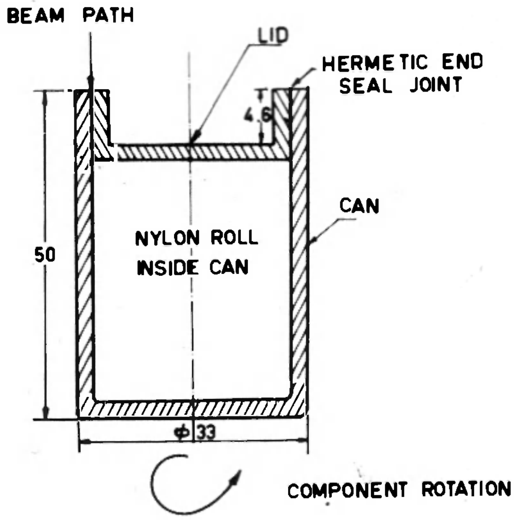

Fig. 2 *Cross sectional view of the joint design - Battery Can*

Laser welding was carried out on the battery cans using both CW and pulsing modes at beam power of 600 Watts. The parameters employed during pulsing mode were pulsing frequency of 100 c/s and pulsing width or time of 6 milliseconds. Though satisfactory welds could be made by both CW and repetitive pulsing modes, the weld bead appearance by CW mode was better, when compared to pulsing mode (Fig.4).

In this experiment, three welding speeds were employed viz 500 mm/min, 1000 mm/min and 1400 mm/min. The beam focus (2.5" focal length lens) was kept 5 mm above the surface, as the application does not call for deeper penetration, but calls for good bead appearance and also to accommodate the imperfect joint gap. About 120° overlap was given during circular welding of the component to take into account the inherent upslope nature of the beam power. With 500 mm/min welding speed, the nylon seperator did not have thermal damage, but the weld bead was inconsistent. The welding speed of 1000 mm/min was found to the optimum, which satisfied all the requirements of good weld bead, no thermal damage to the nylon seperator and minimum damage to the nickel coating near the weld area (Fig.4).

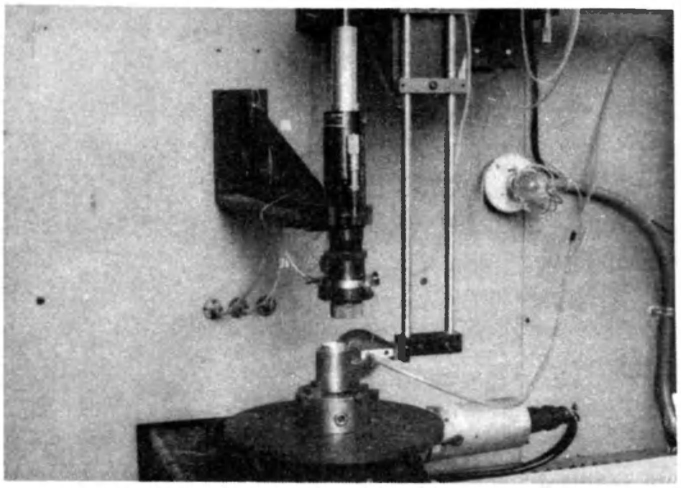

Fig. 3 *The experimental set-up of a copper jig for holding the battery can for CO_2-Laser beam welding.*

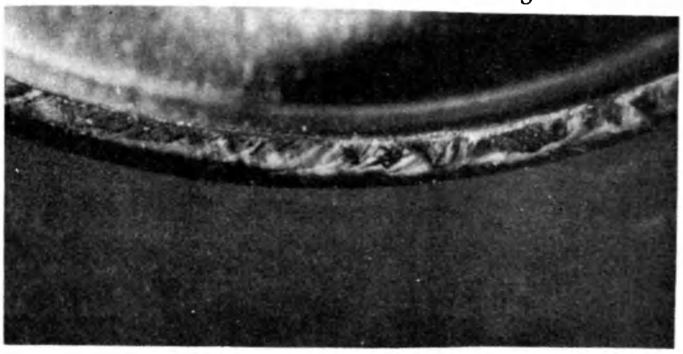

Fig. 4 *The close-up view of the circular weld on the battery can at optimum welding parameters.*

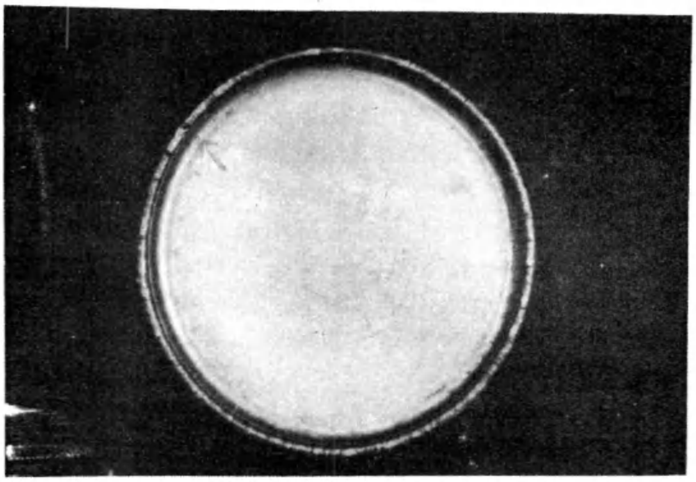

Fig. 5 *Plan view of the circular weld showing the unfilled key-hole at the point of 'weld off'.*

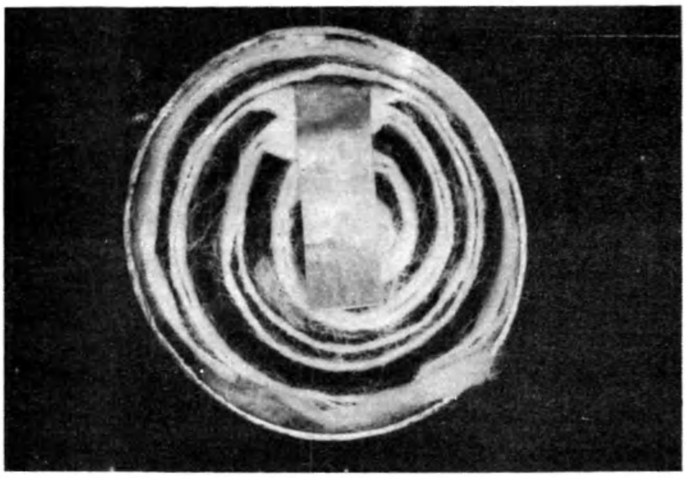

Fig. 6 *Cut open view of the underside of the welded can lid showing the nylon separator.*

Another problem encountered with this experimental work was that the key-hole was left unfilled, where the welding was stopped at the final point in the course of circular weld, because of lack of down-slope facility in the equipment (Fig.5). Laser spot welding was carried out to fill the key-hole with single pulse mode of pulse width 100 milliseconds and further defocused beam of 10 mm above the surface.

After completion of welding, every can was cut and opened at the top side to inspect the thermal damage of the nylon seperator. With optimum parameters established in this experiment, no thermal damage was observed, which is shown as the plan view of the can after cutting (Fig.6).

The penetration requirement of 0.5 mm was satisfied, the weld bead width was measured to be 1 mm, and the welding ime taken was 8 seconds. The leak check and hydraulic pressure testing was carried out on these battery cans by the battery company. Though the design testing pressure was 35 psi, the cans withstood upto 75 psi under the leak test. The hydraulic pressure testing was carried out upto 160 psi and found satisfactory. The quality of the battery cans has been accepted in totality by the battery company.

Laser welding technology has been successfully established for the hermetic seal welding of battery can and this work has been presented at International Conference on Laser Advanced Materials Processing, Osaka, Japan[11] The same application has been developed in USA[12] using pulsing mode of CO_2-Laser, but the details are confined only to the optimised parameters. It is worth to state here that the same application can be carried out by solid state Nd-YAG Laser with much reduced running cost. The critical requirements of this application can not be met by conventional welding processes. Though the same application can be carried out in EBW, beyond any doubt, considering the small size of the component, very low power requirement and flexibility in processing, Laser has got an edge over the EBW process.

3.2 Laser Welding of Stainless Steel Spindle Assembly

At present, stainless steel spindle assembly bellow components are imported in BHEL for power generation equipment. As an import substitution, the component welding was taken up in WRI Laser equipment. The type of weld joint is lap/lap butt; 2 weld joints are to be done with dissimilar thicknesses of 0.1 mm + 0.4 mm (1:4) and 2 more weld joints of 1.2 mm + 3.7 mm (1:3). Partial penetration circumferential welding is the requirement and steam leak tightness is the quality of the joint expected.

Such a low thickness welding requirement is not possible by conventional welding techniques, as very controlled heat input is required with faster welding speed to avoid burn-through or puncturing at the joint. Laser has been successfully demonstrated at higher welding speed of 425 mm/min to meet the quality demands of the component. Before taking up the actual component, mock up pieces were made to represent the dissimilar thicknesses and Laser welding was carried out. After welding was completed, the mock up pieces were subjected to dye penetrant testing and the welds were found free from defects. The actual component after Laser welding is shown in Fig.7. For this application, the parameters optimised are shown in Table-1.

TABLE - 1 Optimised Parameters for Laser Welding of Stainless Steel Spindle Assembly

Laser Power	:	250 Watts
Mode	:	Continuous-Wave
Focal Length of Lens	:	2.5"
Focal Position	:	1.25 mm below surface
Shielding Gas	:	Argon (coaxial)
Gas Pressure	:	0.7 Kg/cm^2
Welding Speed	:	425 mm/min.

3.3 Laser Cutting of Silicon Wafers

In BHEL, solid state thyristors are manufactured for electronics applications. In thyristors, the mojor raw material is silicon circular wafers and they are imported in thickness range of 0.47 mm. Many circular wafers of diameter 57 mm are procured as standard available sizes and the requirement is to cut these wafers into 3 small size circles of 25 mm diameters. Silicon being very brittle material, conventional cutting techniques are impossible. So, Laser profile cutting of these wafers was successfully carried out in WRI. The quality of cut requirement was that the cut surface finish should be very good without any cracking in the wafer. A suitable vacuum holder was employed for this application to avoid any cracking due to clamping itself and also to avoid flying off of the small size wafer after cutting is over, under the dynamic gas pressure from the cutting nozzle.

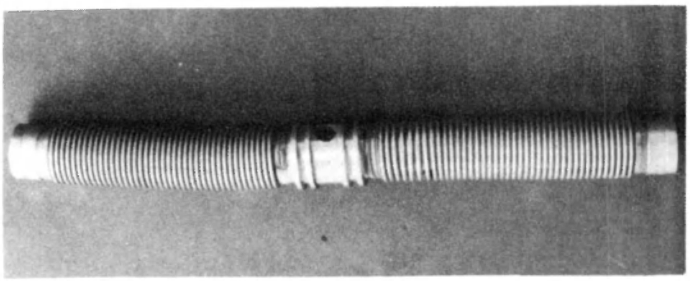

Fig. 7 *Laser beam welded spindle assembly made of stainless steel.*

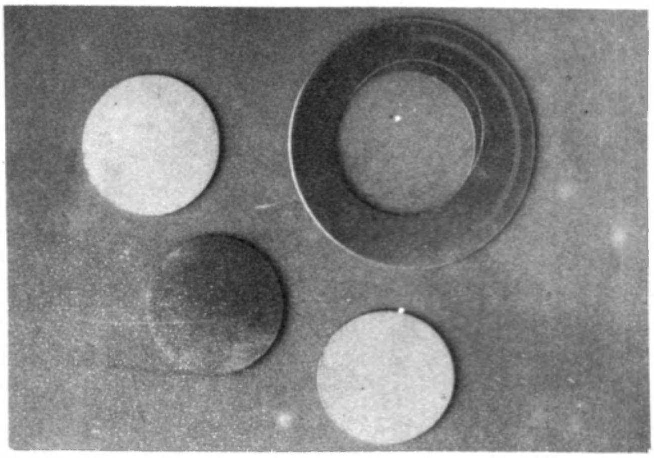

Fig. 8 *Laser cut silicon wafers*

Fifty numbers of 25 mm diameter silicon wafers were cut with good cutting finish and they arc used in regular manufacturing of thyristors and test results have proved that the components with Laser cut silicon wafers have passed the acceptance tests. The parameters optimised for this application are shown in Table-2. The silicon wafers cut by Laser are shown in Fig.8.

TABLE - 2 Optimised Parameters for Laser Cutting of Silicon Wafers

Laser Power	:	220 Watts (Average)
Mode	:	Repetitive Pulsing
Pulsing Frequency	:	300 Hz
Pulse Width	:	0.5 millisecond
Cutting Speed	:	1500 mm/min.
Focal Length of Lens	:	1.5"
Focal Position	:	On the surface
Assist Gas	:	Nitrogen (coaxial)
Gas Pressure	:	2.0 Kg/cm^2

3.4 Laser Scribing of Silicon Steel Sheets

In BHEL, R&D Project was taken up to improve the high power transformers' efficiency by reducing the magnetic losses in the transformer core laminations. These transformer laminations are silicon steel material of thickness 0.3 mm. It has been proved in the developed countries that by Laser scribing of these lamination sheets,

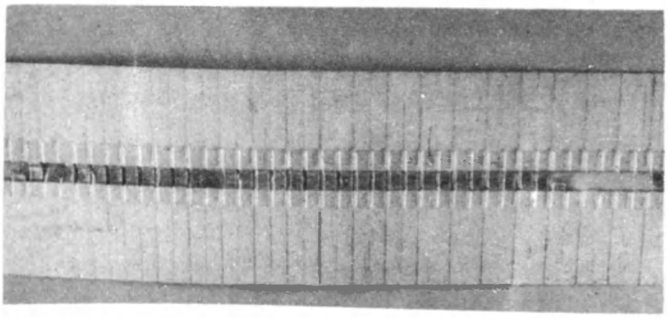

Fig. 9 *Laser beam scribing was done on silicon steel sheet at 6000 mm/min. scribing speed with pitch distance 5-10 mm and depth around 50 microns.*

the magnetic properties of the transformer core are altered and thereby the iron loss is considerably reduced and results in increased transformer efficiency.

These silicon steel sheets were first attempted by mechanical scribing method using carbide tips. But the problems encountered were slow speed, less accuracy and frequent change of tips. So, Laser scribing of these sheets were taken up in WRI. The length of the sheets was of 700 mm/300 mm and the width of the sheets was of 100 mm/50 mm. The depth of scribing was in the range of 50 microns and the pitch distance was of 10 mm/5 mm.

Laser scribing was carried out on 80 sheets. Laser being, a noncontact process, the accuracy and repeatability is very good with high productivity. The scribing speed established was 6000 mm/min, resulting in less distortion of the sheets. The parameters optimised for this application are shown in Table-3. The photograph of Laser scribed silicon steel sheet is shown in Fig.9.

TABLE - 3 Optimised Parameters for Laser Scribing of Silicon Steel Sheets

For 10 mm Pitch Distance

Laser Power	:	60 Watts
Mode	:	Continuous-Wave (CW)
Scribing Speed	:	6000 mm/min.
Lens Focal Length	:	2.5"
Focal Position	:	On the surface
Lens Protection Gas	:	Nitrogen: min pressure (coaxial)

For 5 mm Pitch Distance

Laser Power	:	30 Watts (Average)
Mode	:	Repetitive Pulsing
Pulsing Frequency	:	100 Hz
Pulse Width	:	5 Milliseconds
Lens Focal Length	:	2.5"
Focal Position	:	On the surface
Lens Protection Gas	:	Nitrogen: min pressure (coaxial)

3.5 *Laser Scribing of Solar Cells*

Another R&D Project in BHEL is on development of solar cells for exploiting the rich solar energy available in our country. These solar cells are manufactured with silicon wafer doped with 'p' type and 'n' type semiconductor layers one above the other. The size of the solar cell is 100 mm x 100 mm and thickness is 0.4 mm. The requirement of scribing on these solar cells' 4 edges is to have electrical isolation between semiconductor layers with outer periphery of solar cells. Laser scribing of 10 nos of solar cells was successfully carried out on all 4 sides in one stroke using CNC with scribing speed of 6000 mm/min. The optimised parameters are shown in Table-4. Though 2 microns depth of scribing is sufficient for this application, 10 microns depth was carried out for confirmation. A vacuum holder was engaged in this application also to hold the job without any jerk at faster scribing speed of 6 m/min. The photograph of Laser scribed solar cell is shown in Fig. 10.

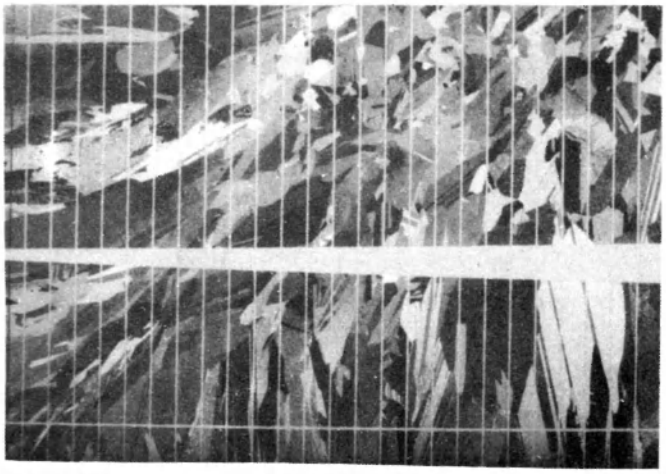

Fig. 10 *Laser beam scribed solar cell.*

TABLE - 4 Optimised Parameters for Laser Scribing of Solar Cells

Laser Power	:	200 Watts
Mode	:	Continuous-Wave (CW)
Scribing Speed	:	6000 mm/min.
Lens Focal Length	:	5"
Focal Position	:	On the surface
Assist Gas	:	Argon (coaxial)
Gas pressure	:	0.7 Kg/cm^2

4.0 Conclusion

Some Laser material processing applications carried out in WRI are brought out in this paper to disseminate information on possible applications of Laser for variety of jobs with very good accuracy, repeatability and consistent quality, which are the technology requirements of present days. Some more applications of Laser like profile cutting of odd shape components for BHEL requirements and Laser cutting of insulation materials like precom, epoxy, glass wool and asbestos are in progress in WRI. Though EBW and Laser are competitive processes in welding applications, Laser is proved to be an ideal tool for thin sheets applications due to flexibility and uniqueness in performing multifunctions both for metals and nonmetals.

5.0 Acknowledgement

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Perception of Quality

Quality cannot be realised fully through technological means only. Ultimately, it is the man behind each operation who determines the quality. With the best equipment and technique, he may not deliver the best quality and also he may deliver very high quality even though not equipped with the best facilities. A lot depends upon what is his perception of quality.

- Does he appreciate what the quality of his work will mean to the end customer ?
- What will it mean to the growth and prosperity of his company and his own self ?
- What does it mean to him in terms of self-actualization ?
- Does he realise that the final quality is an expression of the disciplined practice of his profession, which makes him contribute not only to his fellow workers and his company but also to the society atlarge ?

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