## T.3 Applications of Nd:YAG lasers in Indian nuclear power programme

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Over the last two decades, lamp pumped Nd:YAG laser have proven to be the workhorse in industrial environment. High power Nd:YAG lasers with fiber optic beam delivery have been exploited commercially for various material processing applications such as cutting, welding, drilling etc. in harsh environments. In order to enhance the quality and range of material processing applications, it is desirable to deliver the beam through an optical fiber with core diameter and numerical aperture as low as possible. Thus, to cope up with the demands of material processing applications, higher and higher power Nd:YAG lasers with improved beam quality are being developed world wide. The basic configuration of a lamp pumped Nd:YAG laser consists of a pump cavity containing a flash lamp and a Nd:YAG rod within a gold coated elliptical reflector or a close coupled diffuse reflector and an optical resonator suitably designed to achieve high output power and better beam quality. Assessing the advantages of fiber coupled Nd:YAG laser in applications related to Department of Atomic Energy, an industrial laser system of 250watt average power, 2-20ms pulse duration and 1-100Hz repetition rate having 5kW peak power and 100J maximum pulse energy was developed. This system is pumped with 5kW input electrical power and provides an electrical to laser conversion efficiency of about 5%, which, to the best of our knowledge, is the highest as compared to any commercially available lamp pumped Nd:YAG laser. This fiber-coupled Nd:YAG laser system has four time-shared fiber ports, each of them has a fiber having 400m core diameter, 0.2 numerical aperture (NA) and 150m length. Specially designed material processing nozzles of diameter in the range 13 mm to 25 mm with gas flow through the same tube containing optical fiber were developed for applications having space restrictions in nuclear power installations. Using this, cutting of stainless steel sheets up to 14 mm and welding up to depth 2 mm were established. This remotely operable laser system has been engineered for its robustness with proper fixtures and toolings for various material processing operations on industrial scale. High power CW lasers have also been developed with an output power of 400watt having 4% electrical to laser conversion efficiency. CW laser with higher powers using multi-cavity design and modulation is useful in deep penetration welding and laser rapid manufacturing. Fig.T.3.1. is a photograph of the industrial Nd:YAG laser developed at Solid State Laser Division, Raja Ramanna Centre for Advanced Technology.

In material processing, laser acts as a point source of thermal energy, which heats the material to reach its melting temperature and a high-pressure gas is used to remove the molten material for cutting. During laser material processing temperature drops from melting temperature to almost room temperature beyond the thermal diffusion length, $2\sqrt{\kappa\tau}$, where $\kappa$ is thermal diffusivity and $\tau=l/v$ is the dwell-time of the beam in traveling across its diameter. The beam diameter is typically 0.8mm and typical cutting speed for 14mm stainless steel is ~40mm/minute, resulting in a dwell time of about 1.19s. Thermal diffusion length corresponding to these values is ~10mm and with 250watt laser it is impossible to reach melting temperature of SS at 1400°C. However, in the pulsed mode laser cutting the scenario is different. There is a negligible movement of the laser beam within its pulse duration of 15ms and the dwell time can be taken as 15ms. This results in a diffusion length of ~1mm and with 70J of pulse energy, it is enough to melt up to a depth of 7mm, and with repetitive pulses and exothermic reaction with high pressure oxygen gas, it becomes feasible to cut up to a depth of about 14mm. To work in nuclear environment there are stringent requirements in the design of tool & fixtures for laser processing because of limited operating space and radioactivity. Often the approach to the area where laser cutting is to be done is very restricted and the cutting nozzle needs to have either linear movement or circumferential movement and sometimes a combination of both as per the processing requirements. Fixture to hold and move cutting nozzle should be designed such that it requires minimum time and effort for it's fixing at the desired location to minimize exposure to radiation.

***Fig. T.3.1:*** *Industrial Nd:YAG laser with time-shared fiber-optic Beam delivery.*

To introduce nuclear applications, we begin with the design of pressurized heavy water reactors (PHWR), which is characterized by natural uranium fuel, heavy water as moderator, pressure tube containment of primary coolant, fuel bundles and ON POWER refueling. Each reactor has typically 306 coolant channels, which are mounted horizontally within a horizontal cylindrical vessel, called Calandria and surrounded by low pressure, low temperature heavy water moderator. Fig. T.3.2 shows a simplified diagram of PHWR together with side-view of Calendria & coolant channels. A single coolant channel is a composite structure of end fittings, liner tube and a pressure tube. These pressure tubes, which contains fuel bundles, is made up of Zr-2 or Zr-2.5% Nb alloy and is attached with SS-403 liner tube and end fitting by means of rolled joints. Further, each end fitting is connected to a coolant pipe (feeder) by hub joint with a seal ring and High-pressure feeder coupling (HPFC) studs. Annular space around the coolant channel is sealed by a metallic bellow and $CO_2$ is circulated in it (see Fig.T.3.3). It is essential to replace the pressure tubes in PHWR type of nuclear reactors after a period of 10-15years and this replacement is performed during en-masse coolant channel replacement (EMCCR) campaign of such reactors. This is a complicated process due to space restrictions and high MANREM involvement. The 306 coolant channels placed in a matrix are very close to each other and bounded to the core of the reactor by means of two shrink fit welded bellow attachment rings, made up of carbon steel, one on each face of reactor core located at a distance of about 945mm from E-face of end fittings i.e., from end point of coolant channel. These coolant channels can be replaced, if the welded bellow rings are detached at the welding point on each end. This requires grooving at the welding point up to the depth of welding (~3-4mm) and then pulling the channel. Although, single point mechanical cutters can be utilized for this operation, but these mechanical cutters are bulky, require their frequent replacement and take long time to cut, which results in higher MANREM involvement.

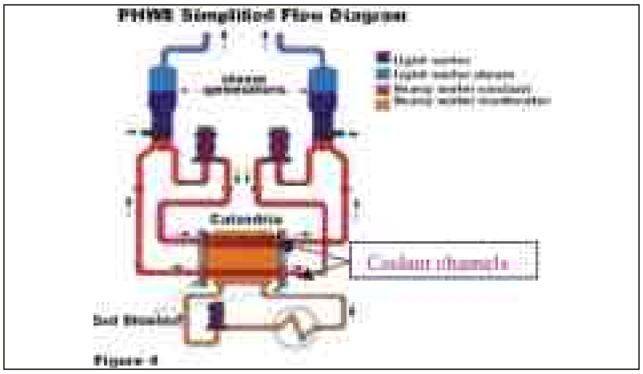

*Fig. T.3.2: Simplified flow diagram of PHWR with calendria and coolant channels (Source:http//www.npcil.co.in).*

The mechanism for laser cutting of bellow lip developed at RRCAT consists of a motorized circumferential rotary arrangement, which can be mounted on the E-face of coolant channel and can be fixed on it just by tightening of a single bolt. The laser based bellow lip laser cutting fixture/tool has been designed to work on motorized single backless spur gear train mechanism. The motor used in the fixture is a DC planetary geared with optical encoder. The tool is designed to fit on E-face of end fitting taking support on its bore. Locking of this tool is based on tapered ball locking grip at the sealing plug position of end fitting. Tightening of a box nut of size M32x2.5 can lock the fixture on E-face. This fixture is accompanied by an arm, which holds the laser cutting head and nozzle. For accurate positioning of the laser-cutting nozzle, it is guided by three bearings touching the end-fitting surface in front of the neck position of bellow lip. The arm holding the laser cutting nozzle has been provided a radial torque towards the center of end fitting, so that it rotates all along the circumference with bearings touching the end fitting surface and does not allow the nozzle to walk off the lip position at any location. The laser cutting head/nozzle is provided with spring-loaded rollers, which guide for accurate positioning in diameter as well as nozzle distance from bellow lip. The positional accuracy in diameter is within 0.1mm and axially the distance of nozzle tip from lip neck is maintained within 0.1mm. Fig.T.3.3 shows a schematic diagram of bellow lip cutting fixture mounted on the coolant channel. A miniature fiber coupled laser cutting head with 1/2" diameter is mounted on the fixture in such a way that it takes care of position tolerance of bellow lip and diameter of coolant channel. It is desired to separate the bellow rings in such a way that the outer ring can be reused for welding at the time of re-commissioning. This requires grooving of the ring at weld location up to a depth of ~4mm. It is easy to cut through and through using laser beam while it is very difficult to make precise grooves in a material. The laser grooving technique for carbon steel was established specially for this purpose.

Two industrial Nd:YAG lasers with time-shared four-port fiber optic beam delivery and 150m long fiber optic cables were deployed for cutting of bellow lip, one on each north and south vaults of NAPS#1 220MW reactor. In-situ bellow-lip cutting was performed and separation was ensured for all the 612 bellow-lips. The fixing of tool on any of the coolant channels required about one minute and the cutting process took ten minutes for each bellow lip, and total operation was completed within a few days of laser operation. Laser cutting of 50Nos. of high-pressure feeder coupling studs (16mm mild-steel bolt) was also performed within an hour of laser operation. Fig. T.3.4 shows the fixture mounted on coolant channel for laser cutting of HPFC studs. Laser cutting of bolts was found to be very effective in such EMCCR operations. Overall operation time was considerably less than what was estimated with the conventional techniques. This resulted in a large MANREM saving as compared to conventional technique and also time saving of at least two months with enormous cost saving. Total MANREM consumption was ten MANREM during the entire operation and there was further scope to reduce it by a factor of two in future operations. The photograph in Fig.T.3.5 shows the fixture mounted on a coolant channel performing the cutting process in mock-setup. Fig.T.3.6 shows the fixture mounted on E-face of coolant channel in NAPS#1 reactor. The same fixture was utilized for re-welding of bellow lip during re-installation of coolant channels. This fixture is able to hold laser welding nozzle as well as TIG welding torch. Welding mock-ups were tried with both the techniques i.e., TIG as well as laser. Fig.T.3.7 shows a laser welded bellow ring.

Kakrapar Atomic Power Station#2 is the first reactor in which Zr-2.5%Nb pressure tubes were used and it was required to generate data on this kind of pressure tubes. It was decided to take out one of the pressure tubes after about eight years of reactor operation. To extract pressure tube, it was required to cut 12mm thick end fitting and 4mm thick liner tubes from inside because of the space limitation. This was performed remotely by specially designed laser cutting innovative fixture. The tool fixing mechanism consisted of two disks of aluminum, one of them gets attached at E-face and the other disk is inserted inside the end fitting through a dual rod handle which comes out from two diametrically opposite holes in the first disk and holds the two disks together and can also fix the separation of the two disks. Fig.T.3.8 shows the developed fixture.

There is a third long screw, which passes through the first disk and is attached to the second disk. Tightening of this third screw pushes a button out of the disk diameter and

***Fig.T.3.4:*** *Fixture mounted on coolant channel for laser cutting of HPFC studs.*

***Fig.T.3.5:*** *Bellow lip cutting mock-up laser cutting of HPFC studs.*

***Fig.T.3.6:*** *A site view of laser based bellow lip cutting in NAPS#1 reactor.*

***Fig.T.3.7:*** *Welded bellow lip.*

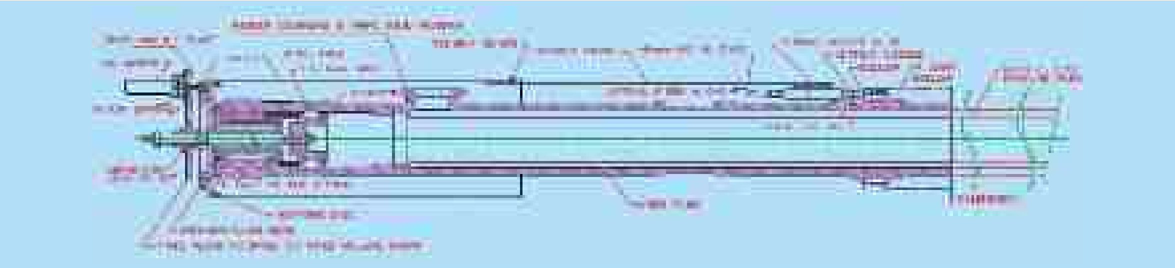

***Fig.T.3.3:*** *A sketch of bellow lip cutting fixture mounted on E-face of coolant channel.*

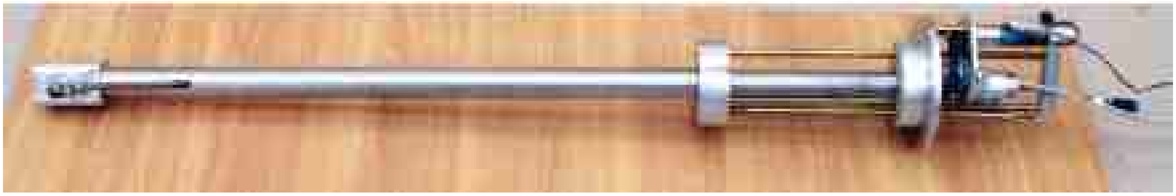

***Fig.T.3.8:*** *Coolant channel cutting fixture.*

helps in locking the disk and the whole fixture with the inner diameter of the end fitting. The motion of nozzle for circumferential cutting from inside of the tubes has been motorized by means of a DC motor and a geared coupling of fixture with the motor. Tool fixing time was about one minute and total cutting time was four minutes for liner tube and ten minutes for end fitting with enormous MANREM, time and cost savings. Fig.T.3.9 shows a mock up of coolant channel cutting from inner side of the channel.

***Fig.T.3.9*** *shows a mock up of coolant channel cutting from inner side of the channel.*

Pressure tubes in PHWR's are about 5m in length and are highly radioactive. After EMCCR operations, if these tubes are stored as such this requires a large space. For initial exercise to reduce storage space, a laser based cutting fixture was designed and deployed for cutting of seven pressure tubes removed from Madras Atomic Power Station #1 in two halves and this was found to be very useful in reducing storage space. This will be further deployed in mass cutting of pressure tubes by slotting the pressure tube linearly in three pieces using three nozzles simultaneously at 120 with each other and then cutting it circumferentially after a certain length.

***Fig.T.3.10:*** *Pressure tube cutting fixture and mock-up.*

***Fig.T.3.11*** *shows cut samples from pressure tube.*

In this case the laser beam was rotated for the circumferential cutting, keeping the tube stationary and the tube was axially pulled under the focused laser beams for longitudinal cutting, keeping the laser beams stationary Rotation arrangement for laser cutting nozzle consists of a rotating disk (gear) supported by ball bearings on a vertical bracket (plate). It is having a central hole of 110mm diameter through which the tube is brought into the position by an existing ram. Tube is located and gripped by a V-block based pneumatically actuated two-piece gripper cum locator. The gripper is mounted on the backside of stationary bracket and the cutting head is mounted on a compact (rectangular piston) cylinder. Rotary encoder and proximity switches monitor the position of locating cylinders, cutting head cylinders and rotary disk. The actual cutting process has been performed by initial longitudinal cutting through an axial pulling of the tube up to a length of 2.7meter, then pulling was stopped, and cutting head started rotating in circumferential direction.

A miniature laser cutting head with diameter of 13.5mm was also developed for cutting or sampling of leaky steam generator (SG) tubes in nuclear power plants. Fig.T.3.12(a) shows the miniature cutting head inserted through SG tube and Fig. T.3.12(b) shows the cut sample.
Similar laser system was also commissioned at PIED, BARC for cutting of end plates of fuel bundles to collect data on PHWR fuel bundles. Fig.T.3.13 (a), (b), (c) shows the intact fuel bundle, laser cutting of fuel bundle and separated fuel pins respectively.

FBTR spent fuel bundles having hexagonal shape were also cut by laser system commissioned at IGCAR to extract fuel. This laser was also deployed at NFC to extract fuel from rejected fuel pins of PHWRs and fuel from about 65tons of storage was extracted within a period of one year.

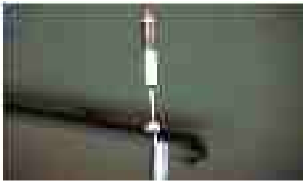

***Fig. T.3.12(a):****Miniature cutting head inserted through SG tube.*

***Fig.T.3.12(b):****Cut sample.*

***Fig.T.3. 13(b):*** *Laser cutting.*

***Fig.T.3.13(a):****Intact bundle.*

***Fig.T.3.13(c):****Dismantled fuel pins.*

Apart from cutting of various nuclear reactor components, several laser welding applications also were successfully done. Laser welding technique for Brachytherapy and Radiography capsules was developed and deployed at BRIT with about 97% acceptance, which is very high as compared to conventional TIG welding technique in which rejection rate was more than 70%. It is being regularly used at BRIT for production of such capsules. Fig.T.3. 14(a), (b) and (c) show the brachytherapy capsule welding fixture, welded sample and weld bead respectively.

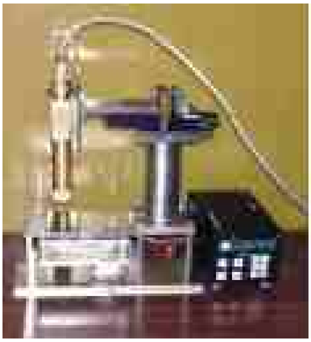

***Fig.T.3.14(a):*** *Brachytherapy capsule.*

***Fig.T.3.14(b):*** *welded sample.*

***Fig.T.3.14(c)*** *weld bead welding fixture.*

Development of high-performance materials is often needed in nuclear applications, which requires measurement of variation of thermal conductivity with temperature. It is very difficult and time consuming to measure thermal conductivity at high temperatures and it also requires large specimens for conventional methods. The method of laser flash to measure thermal diffusivity is relatively fast and requires very small amount of material, which is an important consideration in research on new experimental materials. A high energy short pulse duration Nd:YAG laser has been developed for thermal diffusivity measurement of high-performance materials. This lamp pumped Nd:YAG laser system provides a 1ms pulse with variable laser energy from 1Joule to 18.5Joule. Four such laser systems for thermal diffusivity measurement have been commissioned in IGCAR and BARC for regular use.

To summarize, about twenty lamp pumped Nd:YAG laser systems have been developed and commissioned by SSLD, RRCAT at various locations in DAE for different material processing applications. This has demonstrated that there is an enormous scope for deployment of laser-based material processing techniques in nuclear field and other industries with several advantages.