The Third Generation of Disk Lasers: A New Benchmark for Industrial Solid State Lasers

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1. Introduction

The disk laser technology has been the subject of debate when compared with other types of high power fiber delivered technologies (e.g. fiber laser). However, a new day has dawned, and it's apparent that disk laser technology has earned its stripes. In order to illustrate the metamorphosis of disk laser technology, we'll be referencing TRUMPF's research, which has resulted in the new TruDisk series. Conceptualized in the early 1990's, introduced at the Munich Laser Fair in 1998, and with over 500 installed for industrial fabrication, TRUMPF's multi-kilowatt disk laser combines high brightness and production worthiness, an already-successful marriage that has become even stronger with the introduction of a new generation of en- hancements. The new generation of TRUMPF's disk laser offer an output power of up to 16 kW and a beam quality of 2 to 8 mm*mrad.

Fig. 1 TRUMPF's new generation 4 kW disk laser, TruDisk 4002

2. Disk Laser Concept

The disk laser design benefits from five unique properties[1-3]:

1. Virtually no thermal lensing due to axial heat flow enables high brightness of the disk laser.
2. Low brightness requirements of the pump diodes enable cost effective lasers with high electrical to optical conversion efficiency – especially in the high average power regime.
3. Area scaling of the beam cross section enables power scaling while keeping constant internal intensities.
4. Deep gain saturation eliminates harmful back reflection problems which are commonly encountered in fiber laser systems[4]
5. The modal cross sections are generally large compared with the longitudinal ex- tension of the gain medium. Therefore high peak power sources are possible without facing problems due to non- linearities.

The disk laser's output can be scaled in two ways. First, the output power per disk scales directly with the power of the pump source. The pump source of a disk laser consists of discrete modules. The number of pump modules can be adjusted to fit the desired output power per disk, which enables easy field upgradability. Secondly, several disks can be arranged optically in series, further increasing the possible output power at constant beam quality. Serial combining within a single resonator is the preferable approach because simpler optical layouts can be used. Up to four disks have been connected in series. Commercial systems with 4 disks achieve an output power of 16 kW, which is equivalent to 4 kW per disk. All TruDisk lasers have integrated switches (up to 6) for beam distribution to different work stations.

Until now, experimental investigations have not reached any fundamental limitations of maximum output power per disk. Calculations from the University of Stuttgart indicate that 30 kW from one disk are, in principle, possible[5]. The most brilliant disk laser so far has been built by Boeing[6,7]. A nearly diffraction limited beam quality "suitable for tactical laser weapons" has been achieved at an remarkable output power of more than 27 kW. Until now, these parameters have never been reached with other laser concepts, which shows the unique capability of the disk concept.

Figure 2 shows the option to adapt the pump spot on the disk, which is advantageous for the scalability of the output power per disk. The output power from a single disk can be increased while still keeping the pump power density constant. Only the pump spot diameter increases with the square root of the desired output power. If the pump spot diameter is doubled, one can increase the pump power by a factor of 4 without changing either the power density nor the thermal conditions inside the disk. Contrary to other concepts, such as the rod or fiber laser, the output power density on the disk itself is uncritical, even at the highest output power.

With this concept it was very easy to increase the output power of one disk without changing the beam quality. Figure 4 shows very clearly, that a change in beam quality has virtually no effect on the obtainable output power of the beam source. Therefore the beam quality of the disk laser can be adapted to the needs of the targeted applications.

In addition, figure 3 shows a maximum output power out of one disk of about 5.5 kW. This is the basis of the new TruDisk 4002, which guaranties 4 kW at work piece. The reserves of the laser can be used to realize a power feedback control. As the achieved welding depth is directly related to the laser power, the end user can not accept any variation of this parameter. Unlike other laser concepts, neither the environmental conditions nor internal parameters like cooling water temperature of the laser have any influence on the output power, which remains constant at all times in case of the TruDisk.

As a result of the increased output power per disk, the number of components and therefore the size of the laser and the cost of the system were

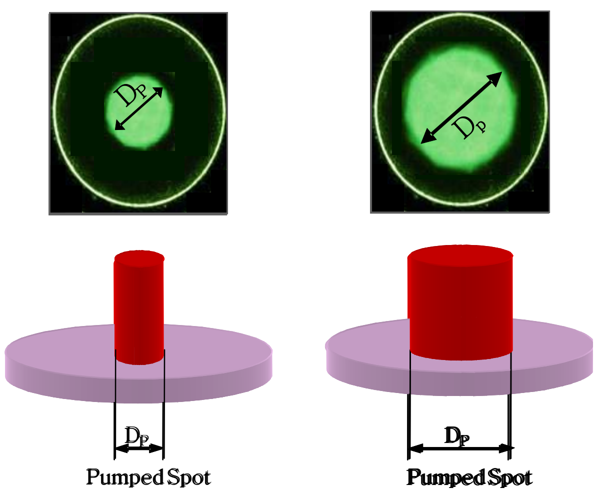

Fig. 2 A certain laser power can be extracted per unit of area → $P_L \sim D_p^2$

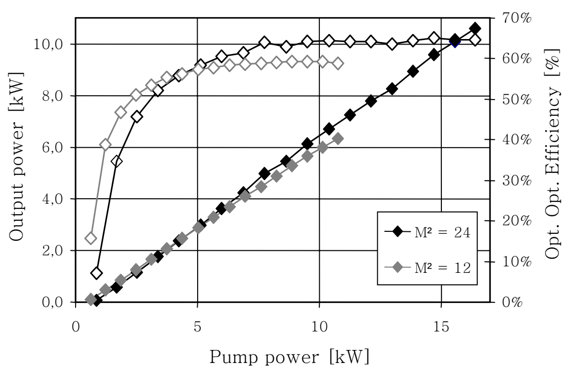

Fig. 3 Output power and efficiency of a typical high power single disk laser oscillator for two beam qualities, M^2 = 50 and M^2 = 24. This corresponds to a beam parameter product of 16 mm mrad and 8 mm mrad respectively

dramatically reduced.

3. Cost efficiency

The cost of the disk laser has continued to decrease since first introduced back in 1998. However, the third generation disk laser has brought significant reductions in both capital investment and operating costs for several reasons. First, and as already mentioned, the diode modules for the new TruDisk are more powerful than any prior. Greater diode power means more laser power per disk. More laser power per disk means less disks per unit power, and fewer disks means a reduced number of pump units, pump modules, laser cavities, resonator optics, etc., and a reduced cabinet size. All this adds up to much reduced manufacturing costs and less floor space, which decreases operating cost.

Secondly, the new more powerful diodes are a product of TRUMPF. Manufactured at TRUMPF in the United States, these new diode modules are more cost effective than any prior modules purchased via external suppliers. It is also important to note that since the pump spot on the disk is relatively large, the diodes used to pump disk lasers can have a relatively poor beam quality (500-600 mm-mrad). Whereas the diodes used for fiber lasers, since they are launched into very small diameter fibers and spliced to a small diameter fiber laser, require very good beam quality. This means that the disk laser architecture has an inherent advantage over the fiber laser when it comes to the quality and price of the pump source. TRUMPF has used this economic advantage to add value to the integrated laser package (e.g. real time power feedback control, meaningful tele-presence, hot plug fiber capability, up to six fiber outputs, etc.), while achieving price parity with high power fiber laser resonators. Finally, not only are the diode modules less expensive, enabling much reduced investment costs, but the diodes have a significantly increased life expectancy leading to greatly reduced running cost.

4. Diode life expectancy

This is a subject packed with debate and controversy. One leading laser manufacturer has decreased diode life expectancy estimates from 500,000 hours to just 50,000 hours within the last three years. With the disk laser, the trend is in the opposite direction, with it's first generation having an estimated diode life of about 25,000 >hours. In reality, it is not the diodes themselves that fail, but rather the cooling of them that might break down. The cooling is via micro-channels that might erode over time due to the relatively high water flow through them. When erosion degrades the micro-channels to the point of a water leak, the diode module reaches the end of it's life. With the new generation TruDisk, the diodes are passively cooled. Simply stated, the micro-channel failure mechanism goes away. In fact, the failure mechanism shifts to the bulk semi-conductor material, which is fundamentally the same as that of the single emitters used in other laser concepts - leading to the same diode life expectancies.

5. Integrated footprint

Wouldn't it be much simpler to just use the word "footprint"? Well, perhaps simpler, but likely misleading. What is meant by integrated is that the footprint includes everything necessary for an industrial laser tool. Instead of just the beam generation, the TruDisk includes the heat exchanger, fiber incouplers, the space required

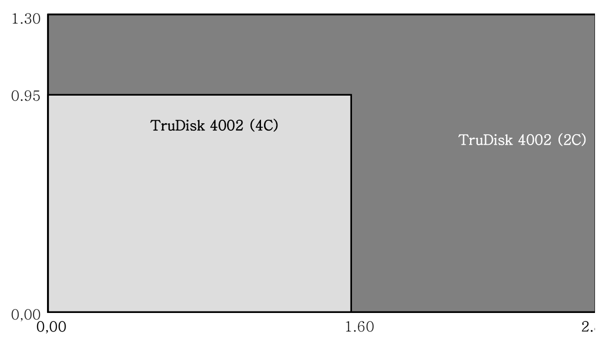

Fig. 4 Integrated footprint comparison for 4 kW laser, 1st generation disk laser vs. new generation TruDisk (4C)

for multiple outputs, a fiber access compartment and the integrated power feedback control. In other words, the integrated footprint includes everything the user needs, with no "extra" surprises at installation. So then, how much smaller is the new generation of lasers compared to the first generation? The new generation 4 kW disk laser has an integrated footprint of about 1.6 m x 0.95 m, a whopping 61% smaller than the first generation 4 kW (see Figure 4). Apples to apples, the new 4 kW disk laser, complete with integrated chiller, 4 beam switches and fiber incouplers, is truly the smallest 4 kW laser on the market. The new 8 kW laser is about 50% smaller than the prior generation.

6. Applications of the TruDisk laser

The disk laser concept enables a multitude of different applications. The range begins with Microprocessing and extends to (but does not end with) multi-kW applications in the thick plate range. With an installed base of about 500 lasers, the TruDisk series has grown to one of the most reliable and important laser tools today. The following examples of different applications is just a small sampling of the broad base of disk laser applications.

7. High speed cutting of thin sheets

Especially in the thin sheet area, the 1 μm wavelength of the disk laser enables higher cutting speeds compared to the 10 μm wave-length of CO_2-lasers. Since years, 1 μm lasers are used for cutting foils and thin sheets with a thickness of up to 2 mm. Due to the improved brightness of the cw disk laser, cutting speeds were increased significantly. Although the fundamental cutting speed was increased, cutting of small contours and edges is an issue. The speed of the handling system (robot, gantry) for small features has to be reduced. An increased heat input follows, which can lead to excessive burning and poor cut quality. One strategy to reduce this effect is to lower the cw output power proportional to the cutting speed. However, this technique is often not enough to realize excellent cut quality for these features.

To avoid such problems and to optimize the synergy between maximum cutting speed of a cw laser with best cutting results of a pulsed laser, TRUMPF has developed an new software feature called "cut assist". The laser receives an analogue signal, which is proportional to the speed of the handling system and processes this signal internally. At programmable velocity thresholds, the behavior of the TruDisk laser changes from a cw laser to a laser which is operated in pulsed mode. Pulse peak power, pulse duration and frequency are controlled based on the in situ process and adapted to the current system speed. The variable and programmable laser parameters are stored inside the laser control and can be assigned to both material type and thickness, enabling the appropriate laser parameters to be automatically selected.

There are multiple advantages for the user. It is the first time that both the maximum cutting speed of a cw cut and the accuracy of a pulsed cut can be achieved with a single laser device. Shorter production times and higher quality of the laser cut parts result. Typical reduction of the cutting time in the range of up to 50% were achieved in industrial applications already, which increased the economics of this process significantly.

8. Fine welding of thin foils

Besides high beam quality, it is the high dynamics of the laser source which is most important for welding of thin foils with high accuracy. The following example shows the coupling of a 1 kW disk laser (TruDisk 1000) with a programmable focusing optics (PFO). Due to perfect matching of the TRUMPF focusing heads and the disk laser, the problem of thermal lensing is avoided. Therefore processing results are absolutely reliable. The integrated feedback power control enables reproducible welding depth under all conditions. Although other laser sources might be influenced by environment conditions (e.g. water temperature), the output power of the disk laser is absolutely stable.

The advantages of such a combination shows the following example, where some specific needs have to be fulfilled:

- Thermal influence or heat marks cannot be visible on the back side of the welded parts
- Welding speed of 60 m/min
- Simultaneous welding of two parallel tracks should be possible

Figure 5 shows the top side of two welded foils with a thickness of 0,1 mm (top) and 0,2 mm. An energy sharing of 50:50 % was used to enable the simultaneous welding of two tracks. Such energy sharing options have been applied since many years with Trumpf's laser sources.

The welding time is less than 1 ms, therefore the welding is completed while the melt pool is still fluid. (see figure 6)

9. Welding in powertrain

Laser welding of power train components has been done with CO_2-lasers for many years. The disk laser is a new alternative beam source for such applications, due to its high beam power and excellent beam quality. A typical shape of a TruDisk- weld is shown

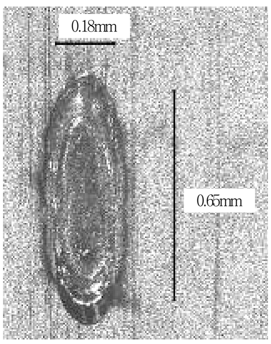

Fig. 5 Welding of thin foils (0,1 mm to 0,2 mm) with TruDisk 1000 and 50:50 % energy sharing option

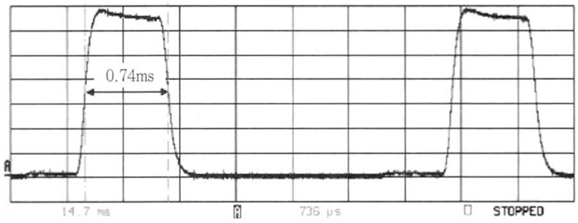

Fig. 6 Time dependent behavior of the laser pulse of a cw TruDisk 1000 (here: two sequential laser welds). The extremely high dynamics of the laser source TruDisk 1000 enables this time critical application. The digital power feedback control ensures reliability of the process under all conditions!

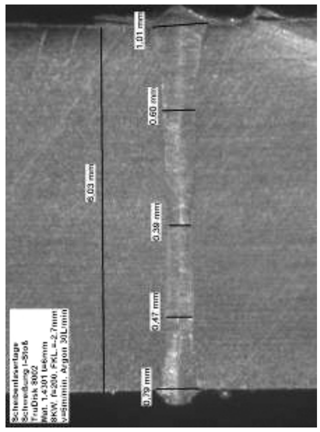

Fig. 7 Typical disk laser welding seam geometry with a high aspect ratio (stainless steel, thickness 6 mm, welding speed of 6 m/min)

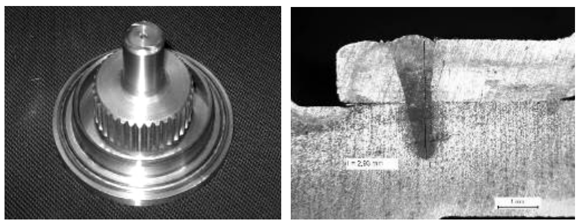

Fig. 8 Shaft to collar joint

in figure 7, which displays a very high aspect ratio of the welding seam.

Typical joints, which can be made with the disk laser, are found in numerous applications in gear manufacturing. Figure 8 shows a joint of shaft to collar. The welding depth of 3 mm was achieved with a 3 kW disk laser and a welding speed of 3 m/min.

Due to the very slim joint geometry, it is also

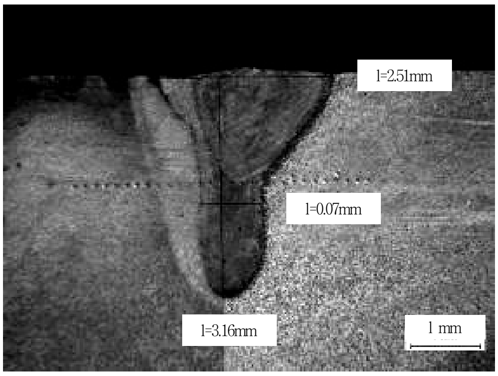

Fig. 9 Disk laser welded differential: Material combination 16MnCr5 and GGG 60

possible to weld material combinations. Figure 9 shows a cross section of a differential joint, where a tempered steel (16MnCr5) was laser welded to cast iron (GGG 60). Normally one would expect an extreme increase of hardness in the fusion zone, which would lead to cracks and would greatly compromise the weld. To avoid this, a filler wire (NiBAS 70/20) is used and the resulting hardness within the fusion zone is reduced and is more homogenized. Spikes of hardness and therefore cracks can be avoided. The differential was welded with a 3.5 kW disk laser power at a welding speed of 2 m/min, while the penet- ration depth is about 3.2 mm.

10. Hybrid laser welding with high laser power

Industrial applications of laser hybrid welding can be found since many years. While the lamp pumped solid state laser dominated in the low power applications, the high power applications were realized with CO_2- lasers so far. The entrance of the disk laser in the thick sheet area was enabled by the higher output powers, which have been available since 2007. Three years ago, the first 10 kW disk lasers were delivered and since then they are serving these applications:

- Laser hybrid welding of truck axles
- Laser hybrid welding of poles
- Laser hybrid welding of panels in shipyard area

The laser hybrid welding process offers a lot of advantages, like increased welding speed with high sheet thicknesses. On the one hand side, process efficiency is increased, on the other hand, the process enables less heat input into the material. Therefore, thermal distortion can be minimized. In addition, the combination of laser and arc increases the size of the fit-up gap that can be bridged compared to welding with the laser beam only.

The main advantage of the disk laser compared to CO_2-lasers is the capability to guide the laser beam with a flexible fiber. This enables a considerably simplified integration of the laser into a conventional MIG-/MAG-welding process. In addition the efficiency of the disk laser is increased and the need of process gas can be avoided due to the shorter wavelength.

Figure 10 shows a cross section of a hybrid weld of 12 mm thick ship panels. The T-joint was done in one pass. The welding speed was 1.3 m/min at a laser power of 8 kW. The left hand side of the picture shows the advantage of energy sharing the laser beam, which is used since years with the disk laser. A simultaneous weld from both sides (using an energy shared laser beam) decreases distortion of the welded part.

Laser hybrid welding is an application with high potential for future growth. Especially heavy machinery and shipyards can benefit from this approach. Within 2009 TRUMPF will release its

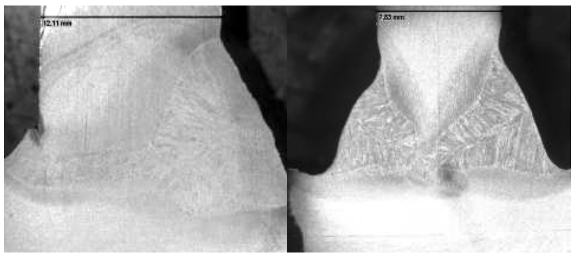

Fig. 10 left: Laser hybrid welded T-joint; 8 kW laser power, welding depth 12mm, welding speed 1,3 m/min right: double sided simultaneous welding of an 8 mm thick sheet (enabled due to energy sharing option of the disk laser)

16 kW disk laser, which is specifically developed for these thick sheet applications.

11. Laser Scanner Welding

Remote Laser welding is one of the most common and successful global applications of the disk laser. Many automotive companies as well as suppliers rely on the disk laser tech- nology and have integrated remote welding in their production lines. Some of the well known applications can be found at Daimler, as well Audi and Volkswagen.

The biggest advantage of the remote welding process is the extremely high productivity. Inefficient and unproductive times between welding steps can be essentially eliminated. Therefore, the laser, as a welding tool, can be used in the most efficient way possible. While the laser on time of conventional laser welding applications is about 30-40%, the remote laser process enables laser on times of up to 90%. In comparison to conventional resistant spot welding, the process speed can be increased by a factor of 3 to 10!

Another advantage of laser remote welding is a high flexibility. The geometry of the seam can be adapted to the actual stresses at the weld joint, which enables a continuously optimized laser suitable design. In addition, the seam geometry can be adapted to the local situation. While a slim flange leads to slim C-shape or linear welding geometries, circular C-shapes can be chosen, if the space enables such geometries.

Figure 11 - 13 show a selection of different remote welding applications.

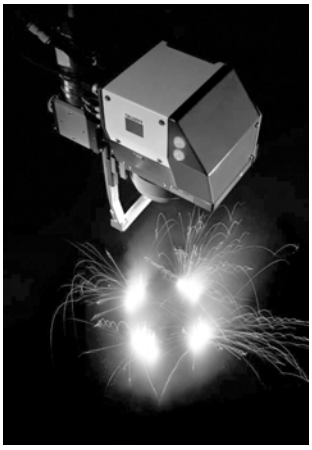

Fig. 11 Remote welding with a TRUMPF pro- grammable focusing optics (PFO)

Fig. 12 Laser remote welded car seat

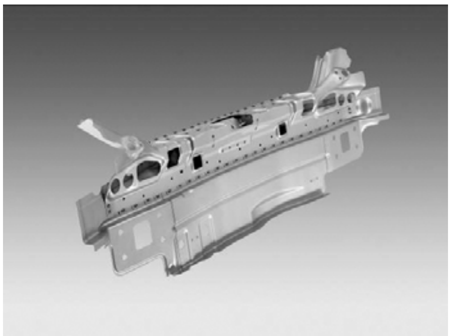

Fig. 13 Laser remote welding in body in white: rear section

12. Conclusion

TRUMPF has further developed its disk laser technology. In 2009 a new series of industrial TruDisk lasers is released, which is the third generation of TRUMPF disk lasers. Compared to the second generation of disk lasers, significant reduction in both investment and running cost is achieved. The actual TruDisk generation is more cost efficient than ever before. The footprint of a 4 kW laser was reduced by 60% without cutting any of the well known fun- ctionalities of the former TruDisk generation. Due to the versatile concept of the disk, both, the output power as well as the beam quality can be adapted to the needs of all applications. While the maximum output power is increased to 16 kW, a beam quality of 2 – 8 mm*mrad is available.

The new generation of disk lasers will set new standards for industrial laser sources regarding price, running cost and reliability. Although the up-time availability of disk lasers is known to be > 99,5%, the modular design allows a service and maintenance friendly system. Most of components can be exchanged by the user, without requiring a TRUMPF service technician.

The wide variety of different disk laser applications reflect the versatility of this laser concept. Applications in the micro area are served as well as in the thick sheet area. With the new “Cutassist” option, the TruDisk possesses a superior intelligence which enables faster cutting on the one hand, as well as better cutting quality on the other hand.

Due to the excellent beam quality, the new TruDisk series is suitable for cutting and welding applications in the sheet thickness range of 0,05 mm to > 15 mm. Remote processes belong to the most common processes of the TruDisk laser. The disk laser is used for remote welding since years with several worldwide manufacturing automotive OEM companies and suppliers. The latest development with the multi-kW TruDisk lasers was the melt pressure induced remote cutting, which can be used with sheet thicknesses of up to 4 mm.

13. Literature:

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