Journal of Materials Processing Technology 164–165 (2005) 1120–1127

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

The use of Nd:YAG laser weld for large scale volume assembly of automotive body in white

A. Ribolla, G.L. Damoulis, G.F. Batalha *

Department of Mechatronics and Mechanical Systems Engineering, Polytechnic School, University of S. Paulo, Av. Prof. Mello Moraes, 223105508.900 Sao Paulo, SP, Brazil

Abstract

This paper describes how Nd:YAG laser welding and laser brazing technologies became useful and applicable in huge scale production lines at the beginning of the millennium. The shown case concerns the laser welding and laser brazing processes of steel roof and side panels with material addition and also laser welding of complete body geometry without material addition, both using two stations for two different models.

Keywords: Laser; Welding; Nd:YAG; Cover glass; Spatter

1. Introduction

Considering the most recent typical automotive bodies, it is very common to find around 4500 resistance spot welds, many meters of MIG and MAG weld beads and also few meters of LASER weld. Fig. 1 shows trend regarding the use of some of these body joining techniques along the last five decades. It is notorious the increase of the use of cold welds (clinch), especially because aluminum alloys have been more constantly applied to the automotive processes [1–3]. LASER weld applications have also been increasing. Some companies are studying processes where 20–30 m LASER welds can be applied (adding tailored blanks). In some cases, LASER welding is commonly replacing MIG, MAG and resistance spot weld processes. It is kind of evolution that cannot be avoided [1]. Another advantage for LASER welds is that access to process parts is only necessary by one side. This feature leads to a reduction of internal reinforcement in order to keep the same structural strength and stiffness, as no more process holes are needed to provide accesses to the welding pliers. As the number of components decreases the body weight is reduced.

According to an increased consumer request on product improvements and the needs of new manufacturing management, the automotive engineering and its fabrication processes became progressively more innovative. Some of these innovations sprout from esthetic needs, others from intrinsic products needs. Regarding these needs, it should keep in mind that difficult access to parts of a body in white, often leads to a project failure and bad crashworthiness; especially when this access is indispensable for a good assembly match in order to weld or either to keep the structure tight enough. New light materials, as well as new technologies like tailored blanks and hydroformed parts are reasons that strongly instigate new trends for the welding technology [4–7]. By introducing them, it is possible to save weight, reducing fuel consumption and pollutant hazardous emissions [8,9].

Concerning all these needs, several automotive industries decides to apply LASER in geometry stations for LASER weld body in white assembly. This paper describes a case study for the Nd:YAG LASER use in flexible working cells for automotive body assembling at the plants of a Brazilian world class automotive industry, promoting discussions about its work cycle, operational problems and procedures problem of attesting the assembled body in its correct geometry.

* Corresponding author.
E-mail address: gilmar.batalha@poli.usp.br (G.F. Batalha).

0924-0136/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmatprotec.2005.02.104

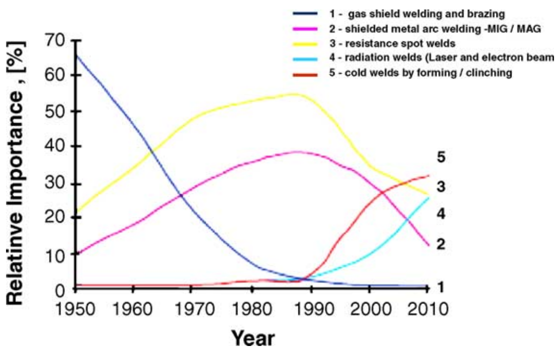

Fig. 1. Trends for welding processes in automotive body in white assembly, not regarding conception type (steel, aluminum space frame or multimaterial conception) [1].

2. Nd:YAG LASER weld joining automotive body in white

2.1. Cost factors and the Nd:YAG LASER weld technology

Laser beam joining technology offers to manufacture joints of all light metals and their combinations, allowing a weight reduction accompanied by high production efficiency and improved performance in use. Regarding the cost factor for the application of new technologies as laser joining and light material, a recent work from Schubert et al. [10] estimates the cost saving over the life time for the reduced fuel consumption, for lighter passengers cars, as approximately € 9.4/kg, regarding a conventional cost in the range between € 14/kg for steel components and € 55/kg for aluminum alloy structures. He postulates a typical cost distribution showed in Fig. 2. Therefore the manufacturing costs can be estimated as 25% of the total costs. Following this approach, by determining the cost of the laser joining process, it could be possible to start a decision whether a laser joined auto body can be economically manufactured.

2.2. Nd:YAG LASER joining technologies

The LASER used in the geometry stations for LASER weld body in white assembly is a continuous wave (CW) Nd:YAG LASER, which is one of the most versatile LASER sources used in materials processing (see Figs. 3 and 4). Among others, some advantages that can be found in this LASER weld geometry process using Nd:YAG are:

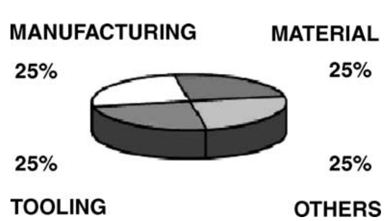

Fig. 2. Cost distribution for typical structures in transport systems. After Schubert et al. [10].

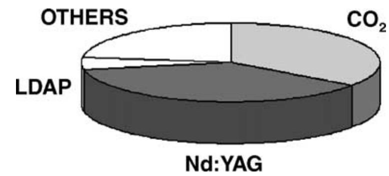

Fig. 3. Market share for laser markets, forecast for 2004. After Anderson [11].

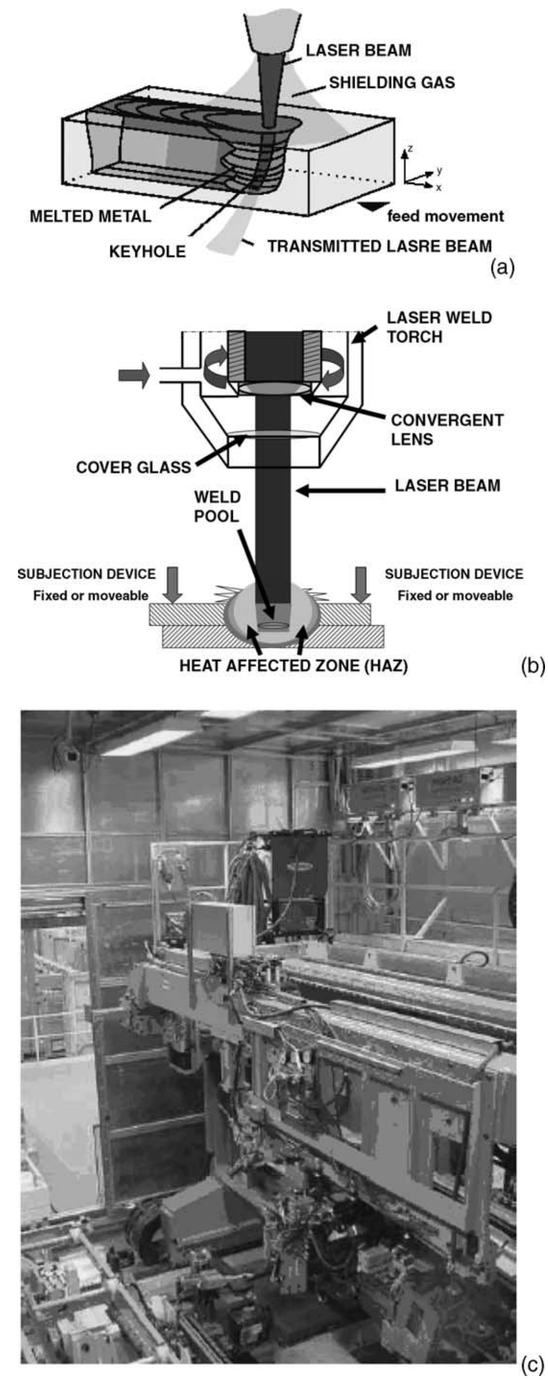

Fig. 4. Nd:YAG Laser welding geometry stations. (a) Laser welding process fundaments; (b) schematic representation of a laser welding torch; (c) the industrial Nd:YAG laser welding facility.

- High absorption of the laser beam by steel sheets, increasing welding process efficiency.
- Spatial flexibility allowed by the use of robots and flexible fibers.
- Coverage of a larger amount of total surface that can be achieved during welding process.
- Reduction of the mobile mechanical basis in the geometry system, caused by the low weight of the optical heads.

The relative robustness and compactness of the laser and the possibility for a narrow beam it produces to be transmitted to the work piece via silica optical fibers are the two main features which have contributed to this appliance to be chosen [9,10]. The main gain obtained by this decision to have a new automotive platform geometry stations using LASER process is how compact they could be built. If instead laser optic heads, common commercial spot welding pliers had been used, it would have been impossible to install and run 16 robots inside 64 m^2.

2.3. Attesting welding geometry at Nd:YAG LASER station

Concerning the assembling stations discussed here, people with the daily responsibility for maintenance during the project were specially engaged in the development steps of the welding and assembly process for a new world class platform. They were in contact with laser appliances manufacturer as well as enterprises with know-how in laser welding technology. The geometry stations (Figs. 5 and 6) were built to perform more than 600 bodies in white assemblies per day. The total amount of welding beads is as follows: 3100 mm long welding beads in the roof with material addition and 3580 mm long welding segmented beads without material addition [12,13].

Two states of art geometry stations, one of them with 16 welding robots and another one with 12 welding robots are responsible for two models geometry using a total of seven laser generators. The robots are divided in two types: 12 of them are 7-axis 25 kg load, other 4 are 6-axis 25 kg load and the other twelve robots are 3-axis 30 kg load robots. The size of the robots was chosen so that it would be able to delivery the LASER beams to a very narrow rift in the process and also to be able to carry both the welding head with integrated beam delivery fiber optics as well as the refrigeration and cross-jet units.

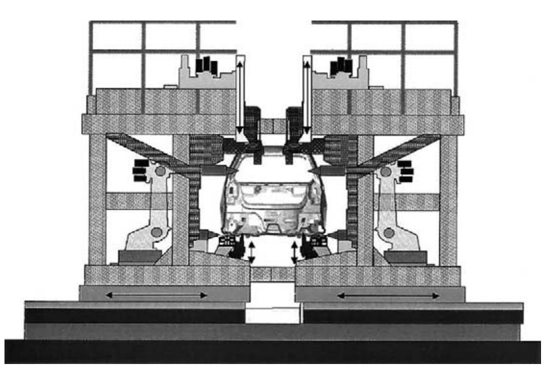

Fig. 5. Automotive body in white Laser geometry station. Arrows show subjection movements.

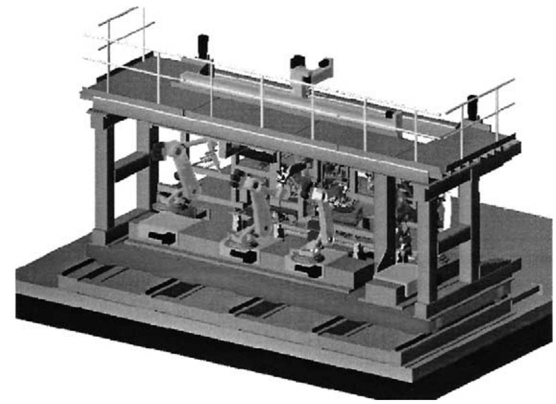

Fig. 6. Side subjection device at an automotive body in white weld geometry station.

The main geometry component in order to guarantee a perfect laser welding accomplishment is the body subjection into the process. Thinking of this theme as a main project subject, a vertical movable table was built to lower the body and fasten the body floor. After the table movement, two geometry devices reach the side parts of the body and take them to the right position. Finally, after the floor and sides fastened, a geometry device for the roof is applied (Fig. 7). This fasten condition is so important that very small differences in their positions would lead to make the process unfeasible because the laser beam focus would be out of range.

The geometry station is a completely closed safety cubic shaped cabin with 400 m^3. Outside and above the cabin were placed on a platform the seven laser generator devices and their respective chillers. The control cabinets for the robots were placed outside the geometry stations, however at the same level. Loading and unloading process is automatically made through a skid roller transport. The welding speed is fixed along the process and its average speed is around 67 mm/s. The laser power is kept in 4 kW and no gas mixture is added to the welding region.

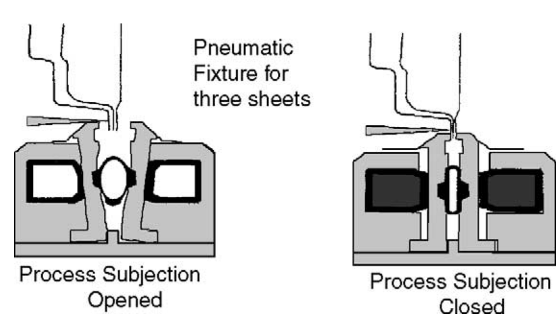

Fig. 7. Two stages subjection for floor and side panel parts.

Table 1
Nd:YAG laser welding station work cycle

In-transport	6 s
Doors closing	3 s
Subjection apply	9 s
Welding	36 s
Subjection removal	9 s
Doors opening	3 s
Out-transport	6 s

3. Laser welding geometry work cycle and down-time

This work was special concerned with efficiencies of the total work cycle of the LASER welding operation. Some typical records are described in Table 1.

Regarding a laser work cycle, two aspects shall be detailed: the optical system protection by a cover glass window and cross jet blowers (see Figs. 8 and 9), as well as the arc lamps life-time [14].

3.1. Control of the laser power losses

The LASER power losses from the source to the workpiece can be enough to cause process abortion. In a process without equipment failure, the variations are mainly depending upon the condition of the cover glass and the cross-jet blower. Other reasons can be considered, however in this case as an equipment malfunction. For example, losses at optical connections and the extend use of arc lamps.

Regarding the laser geometry stations, one extra connection was inserted in the process. Due to the large production volumes, it was predicted that many optical fibers would break early because of the very frequent robots movements and that would cause extra costs changing frequently those optic fiber cables. The solution adopted was to insert one optic joining device to couple two different optic fiber cables with different length. The shorter cable, consequently the cheaper one, would be the cable that connects laser power from the joining device to the robot (non-static cable) and the longer cable and consequently the more expensive, is the one that connects laser power from the joining device to the laser generator (static cable) (Fig. 10).

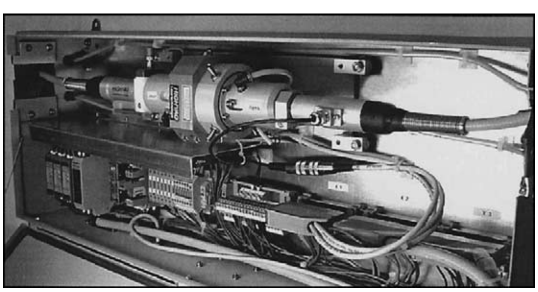

Fig. 8. Optical heads with cross-jet integrated for weld without material addition.

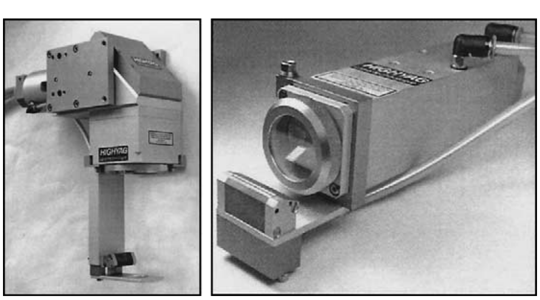

Fig. 9. Optical head with cross-jet integrated used for weld with material addition.

Fig. 10. Optical joining device used for coupling two different length optical fibers.

The price of process quality can be sometimes a disadvantage for a specific product. One theme regarding this concern is always how expensive a process can be. If we consider the total amount of energy spent in order to generate a certain amount of laser energy, certainly many manufacturers would give up in laser processes. For instance the energy yield rates obtained for the processes stations discussed here (from electrical energy supply to the heating on the metallic surface) regarding continuous production are at best processes conditions only 2%.

3.2. Cross-jet blower and cover glass protection window

Some frequent activities concern a visual check up of the cover glass protection window and also the removal of the particles deposited on the surface of the fixtures and on the cross-jet blower [14].

In order to determinate the points when the change of a cover glass must take place, the operators or maintenance specialists use their clinical eyes. No kind of measure is used as part of a procedure to reference change in a time-line. Through the welding, sparks and spatter from the melted material get stuck on the outside of the optical head components (as illustrated in Fig. 11).

The short focal distance used is one of the reasons for this problem. However, experience has shown that not only focal distance but also the robot trajectory programmed position can make difference in cover glasses degradation.

The function of the cover glasses is to protect the focusing lens from dust and spatter occurring during welding. The main parts of an optical head are the fiber optical joining, re-collimating and focusing lenses, mirror and cover glass. In order to protect the cover glass from spatter and dust, a cross-jet unit is placed between the process and the cover glass.

This unit creates an air shield between the cover glass and the focus point and this inhibits most of the sparks to reach the cover glass. The effect of spatter on cover glasses is a poor laser beam that results in a bad weld process. Laser generator devices make use of automatic gain control circuits. However, as most of AGC circuits, the whole power range scale cannot be corrected by it and the effect of contamination on the cross-jet blower creates an unstable cross-jet function, meaning increase of cover glass degradation. Nowadays, as there is not any efficient method for automatic cleaning, it is necessary to have a manual cleaning control of the equipment adding time and costs penalties per process cycle.

Recent developments outstands an on-line control for the cover glass protection window by means of a CCD video signal recorded in line trough the laser weld beam path (Fig. 11). It enables a control the optical efficiency and its cleanness degree, i.e. presences of spatter particles, dust or smoke deposited on it [8,14–20].

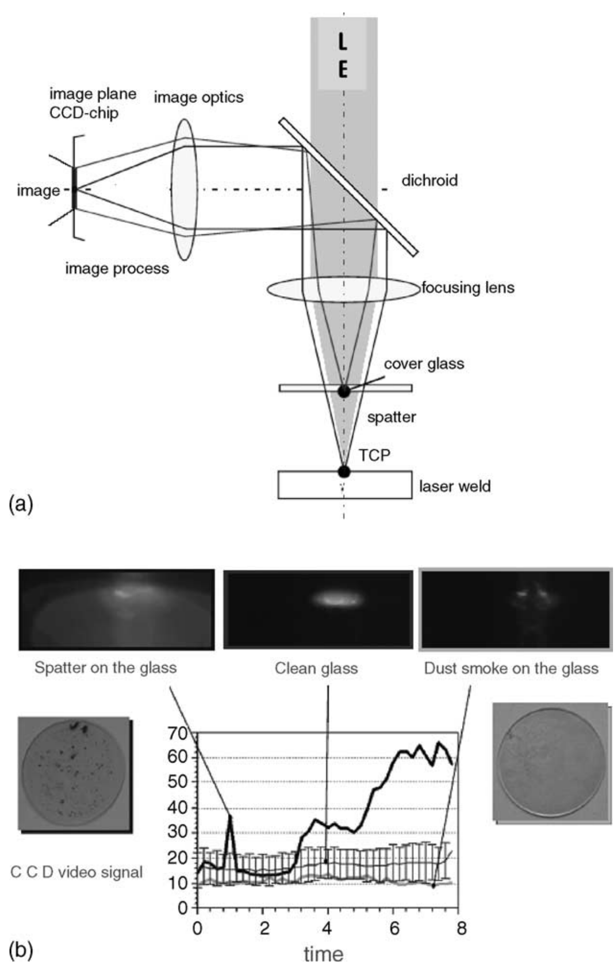

Fig. 11. The cleanness of the cover glass and CCD video camera records. After Hoffman et al. [18]. (a) CCD video signal; (b) CCD video signal intensity vs. time.

3.3. Arc lamp fluctuating life-time in laser generator cavity

Another expensive problem that takes place during production is the short and fluctuating life time of the arc lamps in the laser generator cavities. Each generator uses 16 arc lamps that should be used during 1500 h following manufacturer advice, however some lamps become week earlier or they explode inside the cavity sooner. Other point concerning arc lamps is that every unsolved problem involving laser beam quality obligatorily leads to a 16 lamp batch complete change.

The actual average running time per lamp is 1950 h and the average number of welded bodies was 204 per lamp. The life time problems lead to interruptions in the production, as when a lamp suddenly becomes out of order it causes relatively long down-time because of difficulties in cleaning the cavity if a lamp has exploded. This down-time can be reduced if a spare upper-part cavity is already ready to be replaced. The bottom-part cavity is always fixed inside the optical system alignment, so it cannot be removed. Fortunately, most of the times, a lamp exchange is not followed by a new procedure of parameter optimization; due to the AGC circuit actuates [14].

Fig. 12a and b shows a schematic representation of how operate the solid laser generator cavities and emissions levels, at the industrial Nd:YAG LASER weld stations used in this

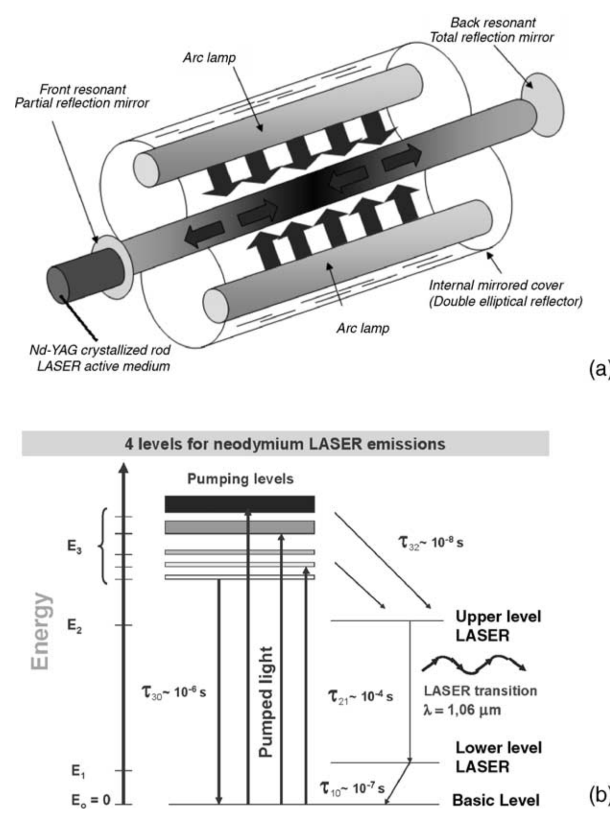

Fig. 12. Nd:YAG LASER generation: (a) operational principle of laser generator cavity. (b) Emissions levels.

work. Trough arc lamp the Nd:YAG rod is bombed, generating a laser beam trough the cavity. As lamp or light source, it can be also used flash lamps (Xe or Kr) or even substituting these lamps by laser semiconductor diodes as pumped light source [15–17].

4. Checking procedures for Nd:YAG Laser weld quality

Checking procedures for laser seam and spot welds are necessary due to the reduced boundary for the laser weld width when compared with the shielded metal arc welding (MIG/MAG). For such weld junctions, it is to be observed that weld defects: like reinforcement, undercut and lack of fusion or incomplete penetration that influence negatively the strength of the weld metal, mainly at dynamic loadings. Regarding the admissible irregularities, this determination should obey specific standards for the quality tests.

4.1. Strength validation

To guarantee the quality of welded and brazed parts during production, it is common to perform tear-down tests. With the use of pulling tongs, hammer and chisel, the welded joints are stressed until they break. The weld is always regarded as OK if the fracture occurs in one of the metal sheets and not in the welding bead. One of the tear-down tests is to cut a 50 mm slice of the side-roof joining (laser brazing using material addition, $CuSi_{13}$), Fig. 13. Using tongs to pull it, it is possible to find a 1 t force before the steel sheets stress to break. For each body analyzed, many cuts are made along the welding bead, perpendicular to the welding direction. Those cross-sections are then analyzed in a microscope where the occurrence of cracks and pores are determined as well as the penetration width and depth [4].

When contrasting the mechanical properties of resistance spot welds and laser spot welds (without filler material), it could be noted that the laser weld can be nearly five times longer than a resistance one. Once it should remember that is possible to use one spot weld at least each 50 mm, less than this could results in a weld nugget bad formation. This is caused by an electrical current loose, originated by a deviation to other spot weld point in the neighborhood, the so-called shunt effect or derivative current. Fig. 14 shows two tensile test pieces, with steel sheets thicknesses of 0.75 and

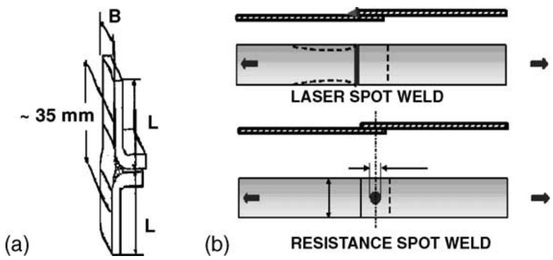

Fig. 14. Tensile test—Laser brazing (a); laser spot weld and resistance spot weld specimens for single lap (b).

1.0 mm, respectively. The first one laser welded and the second one resistance spot welded, forming weld nugget diameter of 3.5 mm. The literature relates for the single lap tensile test pieces showed at Fig. 14, that the laser spot welded specimen reaches an ultimate strength of 10.8 kN, when it starts to neck, but not exhibiting fracture. At the resistance spot weld, the maximal strength reached is 2.4 kN with rupture at spot weld, presenting an ultimate tensile strength five times lower than laser one [4,20–22].

4.2. Visual testing and metallographic evaluations

The visual inspection allows only for the evaluation of macro defects visible at the laser weld metal pool. In all practical cases an apparent observation without so much aids resources is the first evaluation procedure for the weld junction. The external abnormalities can be verified and evaluated trough a visual inspection. Metallographic evaluation can be also carried out at several sections and junction positions of automotive body in white, as a function of the metal sheet thickness (Fig. 15). All the weld geometry parameters related to welding process can be verified trough a simple optical evaluation for the nominal standardized values.

At Fig. 16 it can be seen that total weld line width as well as its thermal affected zone present sharply thinner when compared with other traditional welding process, suitable to perform this joining operation. Aiming an optimal quality for the laser welds, demands an analysis of the weld penetration trough a metallographic examination.

Fig. 17 illustrates the standard DIN 32511 defining series of characteristic for evaluation of laser welds.

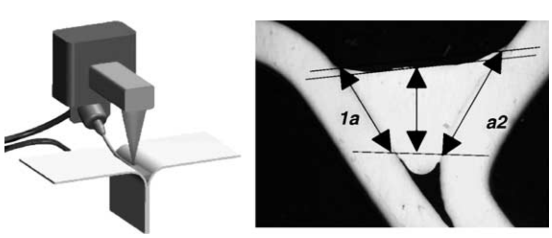

Fig. 13. LASER brazing with addition material ($CuSi_3$).

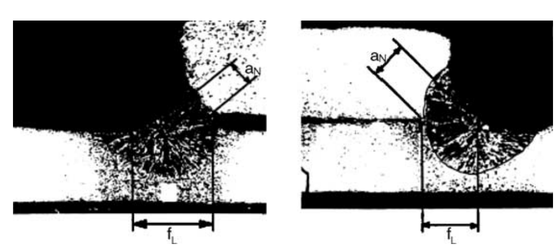

Fig. 15. Weld geometry—metallographic evaluation.

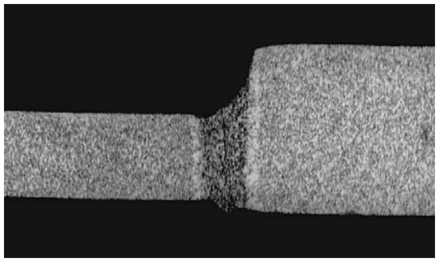

Fig. 16. Metallographic image of a laser weld without material addition.

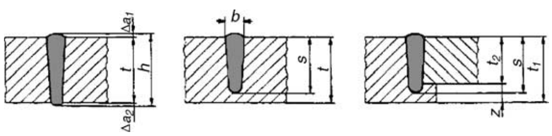

Fig. 17. Laser welds definition by DIN 32511.

4.3. Pores and the influence of the zinc coating

It is common that some pores appear. Pores are a result of a gas flowing through melted material. Some of them are caused by some sheet dirt evaporation or even sheet coatings (e.g.: Zn) evaporation. This dirt, most of the times, can be oil traces from the stamping process. However, the main pore problem is the intrinsic pore problem. In this case, the gas that causes the pore is a zinc gas. Zinc is a protective layer against corrosion applied to the steel sheet and its boiling point is 907 °C. Steel has a boiling point of approximately 3000 °C. With these references, it is notorious that zinc has the property of evaporating sooner compared to the steel sheet parent metal [14,23,24].

Pores can be controlled by reducing the amount of zinc on the steel sheet and the only way to guarantee a uniform application and decrease of zinc is using an electric process for zinc deposition. Melted zinc deposition demonstrated to be always a problem regarding pores control.

The laser weld process with material addition at the body roof is a finish weld process meaning that this weld bead is not only a structural weld bead but it is also a visible weld bead. In this case, pores are a huge problem and every time they appear, a rework must be done. On the other hand, for laser welding without material addition, pores are not such a huge problem because they do not appear very frequently and they are not visible most of the time. Pores do not appear in this case because the zinc gas generated at the laser beam

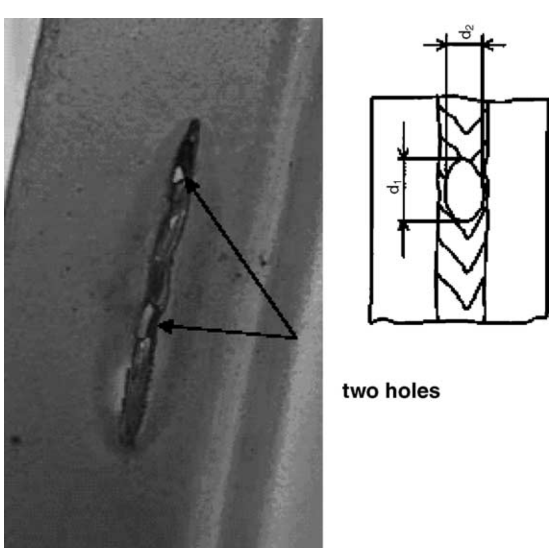

Fig. 18. Porosity formation or holes in the laser weld bead.

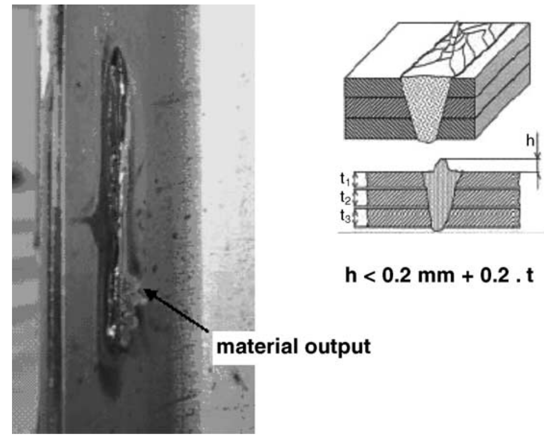

Fig. 19. Output of zinc gases.

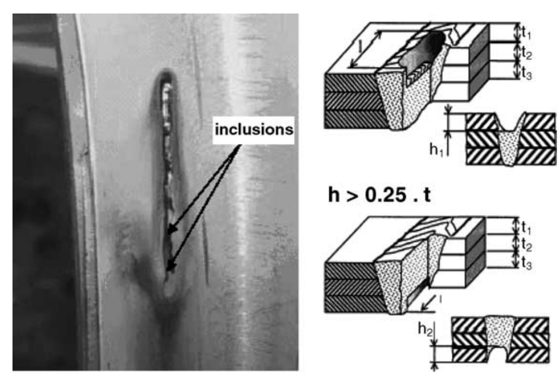

Fig. 20. Oblong at the superior or inferior metal sheet.

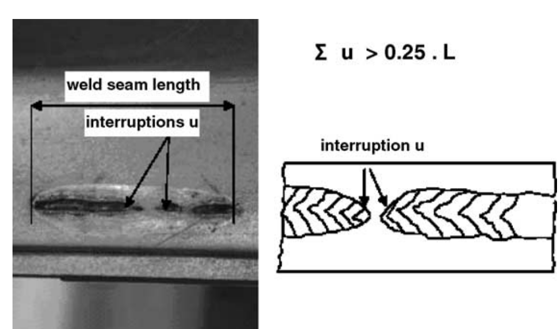

Fig. 21. Interruptions failures at the laser weld bead.

focus is liberated between the steel sheets (see some weld failures at Figs. 18–21).

5. Summary and conclusions

Although some disadvantages must be considered, more advantages in laser welding are offered as a variety of benefits over other types of welding. Deep penetration of precise narrow welds, small heat affected zone, low heat input, fast weld times, minimum part distortion, no secondary processing and high repeatability can be mentioned as great advantages.

As shown by the experience in large scale production, the continuous average power at the work piece delivered by a 4 kW, continuous-wave Nd:YAG laser source can be used for body large scale welding of steel alloys, which is still dependent on surface preparation.

All the tensile tear-down tests failures were occurring away from the weld region, indicating that the requirements of failure in the applied material for the structural welding of steel bodies have been fulfilled. This possibility has been achieved by optimizing laser and process parameters during these last years.

Acknowledgements

This paper involves activities from the professional master program on automotive engineering held at EPUSP in cooperation with the Brazilian automotive industry, the support of Volkswagen do Brasil Ltd. is gratefully acknowledged.

References

[1] R. Neugebauer, IWI 2003, Fraunhofer Institut 2003 Year Report, Chemnitz, Germany.

[2] T. Barnes, I. Pashby, Joining techniques for aluminum spaceframes used in automobiles. Part I. Solid and liquid phase welding, J. Mater. Process. Technol. 99 (1–3) (2000) 62–71.

[3] T. Barnes, I. Pashby, Joining techniques for aluminum spaceframes used in automobiles. Part II. Adhesive bonding and mechanical fasteners, J. Mater. Process. Technol. 99 (1–3) (2000) 72–79.

[4] G.L. Damoulis, G.F. Batalha, Solda a laser em carrocerias automotivas, in: L. Schaeffler (Ed.), Proceedings of the 16th National Conference on Sheet metal forming, LDTM-UFRGS, Porto Alegre, October 21, 2004.

[5] G.F. Batalha, R.C. Schwarzwald, G.L. Damoulis, New trends in computer simulation as integrated tool for automotive components development, in: Proceedings of the Eighth NUMIFORM, Columbus, OH, 2004, ISBN 0735401896 (in CD).

[6] J. Tavares, G.F. Batalha, J. Silva, Formalization of the information system of material management for a case study: tailored welded blank manufacturing, in: Pietrzik, et al. (Eds.), Proceedings of the Metal Forming 2000, Krakow, Poland, Balkema, Roterdam, 2000, p. 495.

[7] A. Szabo-Ponce, G.F. Batalha, Numerical and experimental analysis of tube hydroforming, in: Presentation at Eighth NUMIFORM, Columbus, 2004.

[8] H.K. Tönshoff, Laser based manufacturing—competition or ideal complement to conventional production technologies, in: M. Geiger, F. Vollertsen (Eds.), Laser Assisted Net Shape Engineering 2, Proceedings of the LANE'97, Meisenbach, 1997, pp. 3–17.

[9] P. Hoffman, M. Geiger, Recent developments in laser system technology for welding application, in: Manufacturing Technology—CIRP Annals 44/1/1995, Hallwag Ltd., Berne, Switzerland, 1995, pp. 151–156.

[10] E. Schubert, M. Klassen, C. Walz, G. Sepold, Light-weight structures produced by laser beam joining for future applications in automobile and aerospace industry, J. Mater. Process. Technol. 115 (2001) 2–8.

[11] S. Anderson, Review and forecast of laser markets. I. Non-diode lasers, Laser Focus World (2000) 92–112.

[12] R. Sikora, LASER Groβ Geostation Technologie schulung, 2001.

[13] G.M.B.H. Scansonic, Sistema para união por LASER automático com fio de solda, 2002.

[14] J.K. Larsson, The use of Nd:YAG lasers in future automotive applications, in: M. Geiger, F. Vollertsen (Eds.), Laser Assisted Net Shape Engineering 2, Proceedings of the LANE'97, Meisenbach, 1997.

[15] M. Geiger, A. Otto, Laserstrahlbearbeitung Umdruck zur Vorlesung, LFT, FAU Erlangen Nuernberg, Germany, Stand WS 98/99.

[16] E. Beyer, Schweissen mit Laser, Grundlagen, Springer Verlag, Heidelberg, 1995.

[17] VDI TPT, Laser in Materialbearbeitung, Band 2, Schweissen mit Festkörperlasern, VDI Verlag, Duesseldorf, 1995, ISBN 318401407X.

[18] P. Hoffmann, P. Kugler, J. Schwab, Prozess-und Systemtechnik für das Laser strahl hartlöten, Vortrag zu Loet, ERLAS Erlangen, 2004.

[19] C.J. Nonhof, Material Processing with Nd-Lasers, Electrochemical Publications Limited, 1988.

[20] W.A. Bartel, H.H. Steinmetz, J. Weick, Influence of beam quality and beam forming on process parameters and properties of laser welded parts, in: M. Geiger, F. Vollertsen (Eds.), Laser Assisted Net Shape Engineering 2, Proceedings of the LANE'97, Meisenbach, 1997, pp. 145–154.

[21] Y.S. Yang, S.H. Lee, A study on the joining strength of laser spot welding for automotive applications, J. Mater. Process. Technol. 94 (1999) 151–156.

[22] D.C. Ruiz, G.F. Batalha, Estudo de um criterio de Falha para solda a ponto resistiva e solda a laser, in: Proceedings of the III COBEF Brazilian Meeting on Manufacturing Engineering, Joinville, SC, Brazil, submitted for publication (in portuguese).

[23] Y.F. Tzeng, Pulsed Nd:YAG laser seam welding of zinc coated steel, Welding J. 78 (7) (1999) 238–244.

[24] A. Loredo, B. Martin, H. Andrzejewski, D. Grevey, Numerical support for laser welding of zinc-coated sheets process development, Appl. Surf. Sci. 195 (2002) 230–297.