Laser cladding in the use effects on nitrided and PVD coated steels used for die-casting using various process parameters and techniques

Pojavi pri laserskem navarjanju nitriranih in PVD prevlečenih jekel za orodja za tlačno litje z uporabo različnih parametrov in tehnik

D. Bombač[1], *, M. Fazarinc[1], M. Pleterski[2], J. Tušek[2], T. Muhič[3]

[1]University of Ljubljana, Faculty of Natural Sciences and Engineering, Aškerčeva cesta 12, SI-1000 Ljubljana, Slovenija
[2]University of Ljubljana, Faculty of Mechanical Engineering, Aškerčeva cesta 6, SI-1000 Ljubljana, Slovenija
[3]TKC, d. o. o., Trnovska 8, SI-1000 Ljubljana, Slovenija

*Corresponding author. E-mail: david.bombac@ntf.uni-lj.si

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Abstract: Repair welding of die-casting tools is approach to extend life cycle of expensive dies. Issues addressed in this paper are problems emerging from repair welding of surface treated steels e.g. nitriding, oxidizing, hard coating or duplex-treating. Cladding tests were carried out on various gas nitrided and oxidized or hard coated chrome martempered steel used for die tools. Observed welding defects were extensive hot cracking and copious formation of gas pores. For duplex-treated surfaces a procedure with preceding laser remelting and laser welding is proposed. Minimized negative effects of the base and welded material were found.

Izvleček: Reparaturno varjenje je postopek za podaljšanje trajnostne dobe dragih orodij za tlačno litje. V članku so obravnavani problemi, ki nastajajo pri reparaturnem varjenju površinsko obdelanih jekel: nitriranje, oksidiranje, prevlečenje ali zaporedna površinska obdelava z različnimi procesi (na primer nitrirnanje in nato PVD prevlečenje). Preizkusno varjenje je bilo izvedeno na različnih plinsko nitriranih in oksidiranih ali prevlečenih vzorcih iz kromovega maraging jekla

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za livarska orodja. Zaznane varilne napake so bile znatne razpoke in številne plinske pore. Za dvojno oplemenitene površine je predlagan nov postopek varjenja s predhodnim pretaljevanjem. Ugotovljeno je bilo zmanjšanje negativnih efektov podlage in varilnega materiala.

Key words: laser cladding, repair welding, die-casting tool steel, nitriding, oxidizing, PVD coating
Ključne besede: lasersko navarjanje, reparaturno varjenje, jekla za orodja za tlačno litje, nitriranje, oksidacija, PVD-prevleke

INTRODUCTION

Parts for automotive industry made from aluminium or plastic are usually casted or moulded. Casting dies are subjected to various complex impact and thermomechanical loads in their working environment. High stresses lead to a plastic deformation of the die during tool's lifetime. Thus, it is required that steels used for casting dies should have some properties such as resistance to high temperatures, thermal deformation, thermal shock during working processes, etc. Depending on a tool application, typical damage and failure mechanisms may differ. A thermal fatigue cracking is the most important life limiting failure mode in the tools for die-casting.[1–4] It is often observed on the tool surface as a network of fine cracks or as individual and clearly pronounced cracks. Formation of thermal fatigue cracks leads to loss of a surface material in form of small fragments. Other common reasons for damage are tension cracks caused by constructional notches, local adherence of a casting alloy and tool i.e. soldering, and steel erosion promoted by the cast molten metal or plastic flow.[5, 6] While moulds for plastic injection moulding are subjected to lower working temperatures their pressure cycles are higher and therefore, mechanical fatigue damage and overload failures might occur. Life time for aluminium casting dies is usually 10^4 cycles.[7] Increasing demand for reduction of manufacturing costs dew to economical reasons requires the exploration of adaptable and reliable solutions for extending the life time of the dies using nitriding, oxidizing, PVD coatings or various duplex treatments. Further extension of the life time of the dies is achieved with die repairing techniques such is surface welding.

Nitrided die casting tools have a lot of advantages i.e. easier separation of a casted part and mould, less frequent cleaning of the die-core system and increase of the service life for up to 50 %.[8] Available reports show that plasma nitriding improves thermal fatigue resistance due to high residual stresses in the diffusion layer and improves its tempering resistance. It is also reported that thermal cracks remain localized in the compound layer.[9] Another surface improvement is oxidation i.e. process that creates a lubricant oxide film to prevent soldering and adhesive wear in high pressure die casting tools, usually performed after nitriding. Further improvements are made using hard coating based on nitrides and carbides of transition metals, e.g. CrN, CrC, TiAlN, TiB_2.[10] Deposition of these coatings is made by physical or chemical vapour deposition (PVD or CVD). These coatings further reduce erosion, soldering, and corrosion but lack in improvement of the thermal fatigue resistance of hot working steels in die-casting conditions. None of the above mentioned surface treatments provides an optimum solution for all failure mechanisms,[11] therefore the best choice is a combination of surface improvements designed specifically for each application.

Repair welding and refurbishing of dies is performed to remove the traces of heat cracking, surface wear, erosion, and stress cracking, thus significantly increasing the tool life cycle.[12, 13] Repair welding of dies is performed by welding with covered electrodes, tungsten inert gas (TIG) welding or laser cladding by wire. Later approach is done by pulsed Nd:YAG laser beam focused at the tool damaged surface while an operator adds a filler wire in the molten pool. Laser repair welding is particularly appreciated due to exact positioning and focalization control of the beam allowing elevated accessibility even in thin and narrow areas that cannot be welded conventionally.[14] Although repair welding is carried out on majority of the tools it is considered critical for improved surfaces due to occurrence of welding defects. Furthermore each surface improvement combination has specific repairing technique, meaning that improvements of repair welding process are necessary.

The primary goal of this study was to investigate problems emerging from laser repair welding of damaged improved die surfaces without prior removal of the damaged parts or surfaces by milling or grinding. Researches were conducted by optical and electron microscopy for metallographic analysis and microhardness measurements for hardness profiles of welded structures.

Experimental procedure

Repair welds investigated in this paper were performed on a high performance AISI H13 (X40CrMoV5-1; Wr.N 1.2344) chromium-molybdenum-va-

Table 1. Parameters of laser repair welding process

Pulse shape (cf. Figure 5)	General			Ramped up			Ramped down		
Code (cf. Figure 5)	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3
Energy per pulse [J]	11.2	12.9	14.9	11.1	13.1	13.2	11.4	12.8	14.4
Pulse power [kW]	1.3	1.6	1.7	1.3	1.6	1.7	1.4	1.5	1.7
Pulse duration [ms]	6.5			6.5			6.5		
Pulse frequency [Hz]	7			7			7		
Spot diameter [mm]	0.6			0.6			0.6		
Travel speed [mm/min]	0.55			0.55			0.55		

nadium hot-work tool steel. Chemical composition in mass fractions of steel samples was 0.35 % C, 0.03 % Si, 0.5 % Mn, 5 % Cr, 2.36 % Mo, 0.55 % V, and balance Fe. Cut samples were hardened and martempered to hardness of 47 *HRC*. After heat treating, samples were gas nitrided and oxidized or hard coated with TiN or CrN coatings. Gas nitriding was performed at 520 ºC for 6 h in a NH_3 atmosphere to a depth of around 80 μm. Oxidation was executed at 500 °C for 4 h in H_2/O_2 atmosphere. The thermionic arc ion plating in a BAI 730 M deposition system was used to obtain CrN or TiN PVD coatings.

Simulation of repair welding was performed using Nd-YAG laser welder and AISI H13 filler wire with 0.5 mm diameter. Effects of the repair welding process parameters were also investigated. Effects of the various laser pulse shapes and different laser welding techniques e.g. frequencies, formation sites, and types of weld defects in continuous seam welds are considered. To resolve a pulse shaping effects, the pulse shapes applied were: general, ramped-up, and ramped-down. Table 1 presents the laser welding and surface remelting process conditions. Continuous seam welds were used as a means of bead on plate welding on specimens to understand the effects of pulse shaping and the formation characteristics of weld defects.

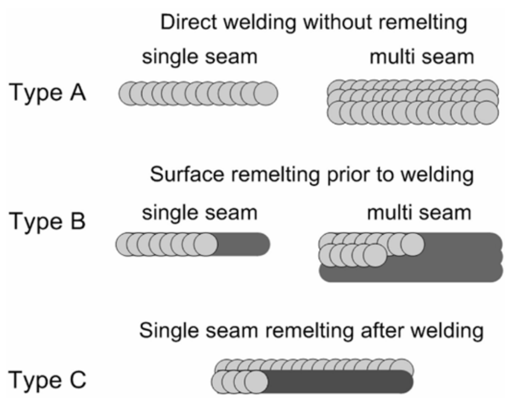

Figure 1. Researched welding techniques

Three types of welding techniques were analyzed in order to improve weldability of improved surfaces. First welding technique designated type A is direct welding without prior surface remelting. Type B involves remelting of whole surface with laser prior to repair welding, where at type C first seam is directly welded and later half of it is remelted and on remelted surface operator deposit next seam. Figure 1 schematically shows all investigated welding techniques.

Cataloguing and characterization of welding defects in the welded layer and the heat affected zone (HAZ) for various welding parameters was carried out by metallographic analysis. Samples for metallographic analysis were prepared with standard grinding and polishing procedures and etched with 2 % Nital solution to reveal welds. Weld morphology and microstructure were evaluated using scanning electron microscope (SEM) and optical microscopy. In addition, microhardness profiles of welds were measured with hardness tester.

Results and discussion

Microstructural analysis of welded nitrided surfaces discloses high concentration of pores. Nature of a laser welding causes abrupt melting and consequent quick solidification. Gases formed during melting therefore stay trapped at the edges of a weld melt pool. High-energy input from laser beam induces dissolution of nitrides in nitrided layer and formation of N_2 gas. Figures 2a and 2b depicts a weld porosities induced by trapped gasses. Sample has been welded with a Type A welding technique and ramped-up pulse with Set 3 process parameters. Analyzed was longitudinal section of the weld (cf. Figure 2b) due to higher probability of discovering weld defects in longitudinal sections compared to cross sections.

Repair welding of a nitrided and CrN coated surfaces is difficult due to formation of cracks at the edges of the HAZ. Their direction of propagation is from pores to apex of the weld due to release of trapped gases. Figure 3a shows weld cracks emerging from pores in the weld. In Figure 3b cracks alongside weld direction in HAZ zone are shown. Depicted repair welded micrograph was obtained from nitrided and CrN coated sample.

Similar defects were present in nitrided and TiN coated welded samples. These types of defectss become apparent only after additional surface treatments and therefore their detection during welding is impossible. Also welding of nitrided and oxidized surfaces causes emergence of pores where dissolute gasses escape from melted weld pool

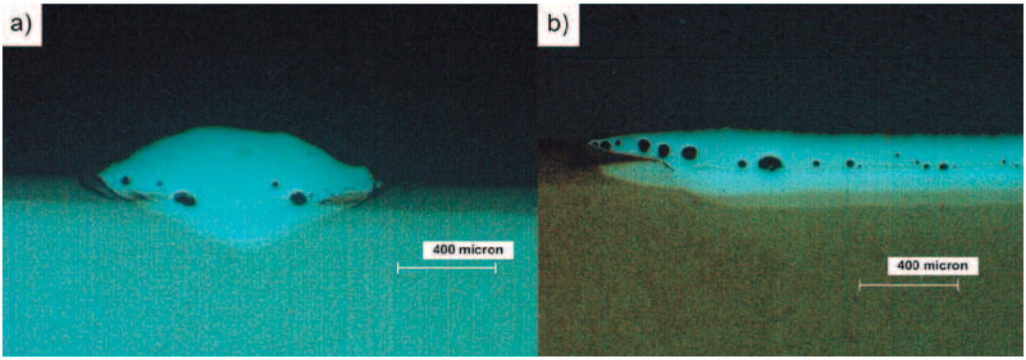

Figure 2. Porosities in weld of nitrided sample; a) cross section, b) longitudinal section

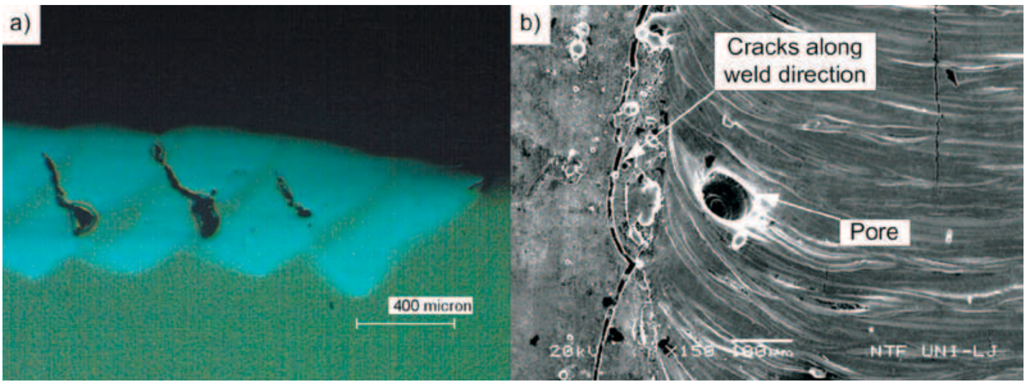

Figure 3. Porosities in weld of nitrided and CrN coated sample; a) micrograph of cracks formed from pores, b) SEM micrograph of cracks along weld direction in HAZ and surface pore

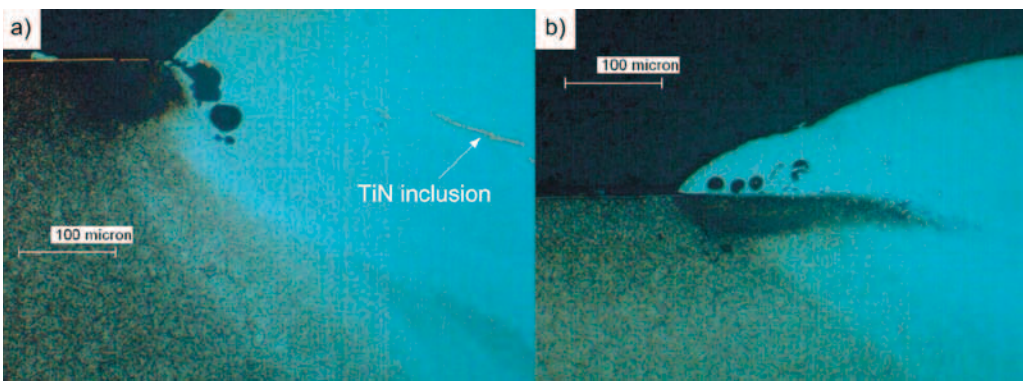

Figure 4. Laser welds on duplex-treated surfaces; a) nitrided and TiN-coated surface, b) nitrided and CrN coated surface

during cooling. Another type of the repair welding defects obtained were cracks along the seam of a weld (cf. Figure 3b). These defects commence due to tensile and compression stress in weld.

Figure 4a depicts traces of TiN coating in the laser weld and porosities at the boundary between the weld and a base material. TiN inclusions from coating in weld could be problematic during grinding and final polishing of weld in die-casting tool. These inclusions have high hardness and can cause increased wear of grinding and polishing tools and consequently loss of shape. Weld micrographs of a nitrided and CrN coated sample did not reveal coating inclusions in the weld. In Figure 4b shows weld of nitrided and CrN coated surface using an inclined beam and type C technique. Repair welding of nitrided and coated samples leads to copious development of gas porosity due to nitrogen release from molten nitrided part of surface or exiting of transitional elements from coatings. Inclusions from coatings in welds also cause problems and are therefore undesired. Therefore, in order to reduce gas porosity investigation of a laser remelting treatment before weld deposition was conducted. The results suggest that using the type C welding technique and close observation of the welding process parameters minimizes the porosity rate. Appearance of pores (cf. Figure 4) at a contact of the weld and the base material is undesired. These pores present danger for peel-off of weld and surface treatment. It revealed that manipulation

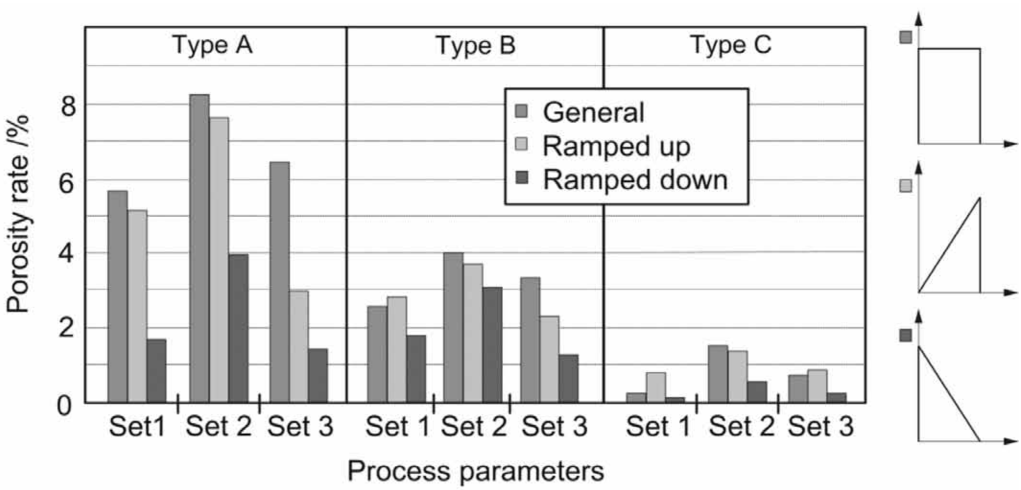

Figure 5. Influence of process parameters, welding technique and pulse shape on porosity rate of weld, with presentation of pulse shapes

of laser beam parameters or inclination of the beam leads to reduction of these type defects. Usage of beam inclination causes a tampon region, which makes excessive cracking of treated surface impossible. It is possible to prevent excess nitrogen evaporation with manipulation of welding parameters. Welding parameters are also important for minimizing the effect of transitional elements (e.g. Cr, Ti) exiting coatings, especially at multi-seam welding.

Unsuitable process parameters, e.g. too high heat input or too low welding velocity are main cause for cracks in HAZ along the seam of the weld due to thermal expansion. With the correct welding process parameters, it is possible to minimize appearance of welding defects. This paper also investigates influence of the process parameters, welding technique and pulse shape on the porosity rate of the weld. Figure 5 shows results of these influences. Depicted in Figure 5 are also pulse shapes marked with colors. Remelting of surface prior to welding causes smaller porosity rate compared to direct welding of surface treated (i.e. nitrided and oxidized or nitrided and PVD coated) surfaces. Type C welding, where each seam is fractionally remelted, has lowest porosity rate. Furthermore, process parameters of the welder and pulse shape are of high importance. As is shown, ramped-down pulse is superior compared to general or ramped-up one. However, it was noticed appearance of low weld fusion penetration or agglutination of weld material. Pulse energy is also very important as pulse energy increase after some critical value leads to declined porosity density in the weld. On the other hand, increase of pulse power causes cracks alongside weld in HAZ and amassment of cracks in surface treated surfaces. One should chose energy per pulse and pulse power specifically for differently treated surfaces.

Figure 6 shows dependences of hardness measured in three depths versus distance from the weld line. Mean hardness value was measured in a horizontal line parallel to the surface for type C welding technique. Depths are designated with letters X for surface layer, Y for middle of the weld and Z for weld apex. Mean hardness in area of weld line are lower for approximately 120 HV_{01} than in area of prior welding remelt line. This is due to tempering effect caused with heat transfer from welding to prior hardened remelt line. Highest measured hardness in remelt line zone was between 720 HV_{01} and 800 HV_{01}. Hardness in weld line was due to tempering effect lower and was between 580 HV_{01} and 650 HV_{01} depending on the depth of the measurement. As expected, it was highest in the apex of the weld due to additional alloying from filler wire.

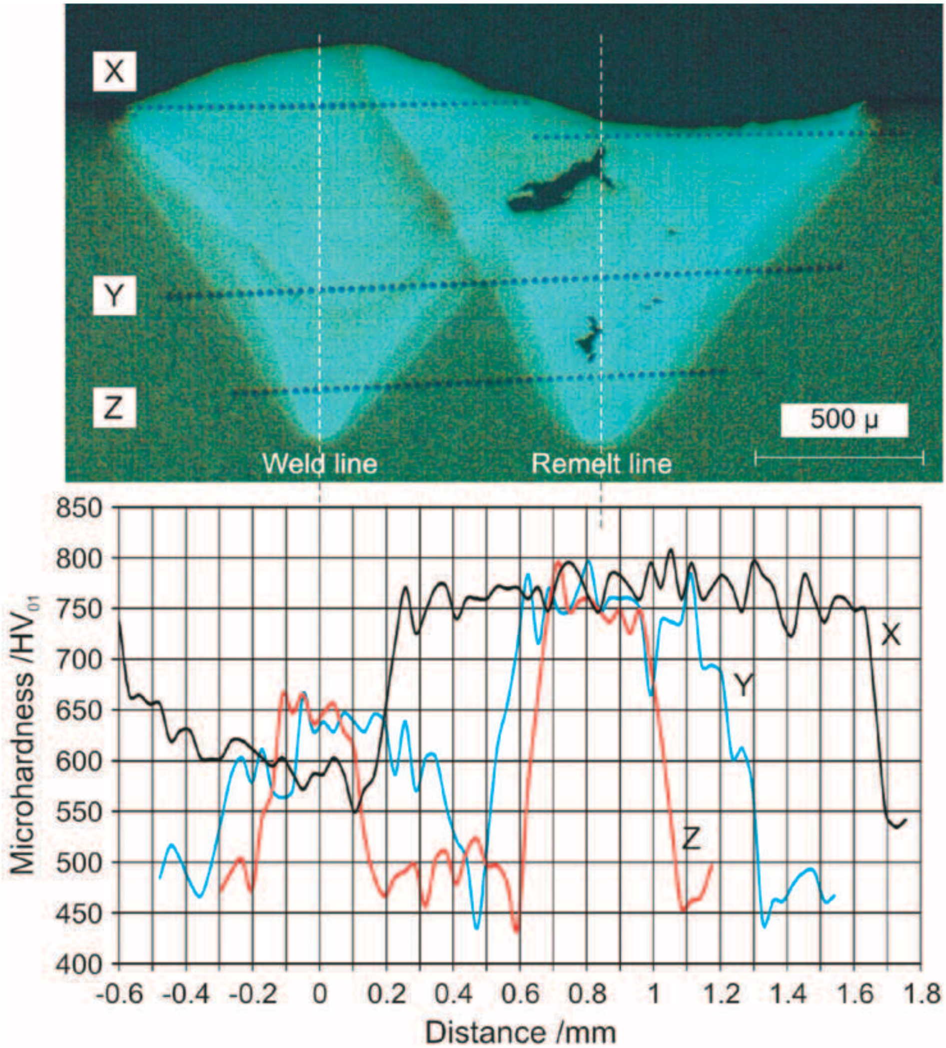

Figure 6. Microhardness profile measured in thee depths of the weld

Measured hardness of base material was approximately 500 HV_{01} and although prior remelting and welding on the remelted zone caused tempering effect, this is not sufficient to reach hardness values corresponding to the base material. Consequently, needed is additional tempering of the welds to obtain uniform hardness profile as is known that increased hardness influences on decreased toughness, which is crucial especially in the lower layers of the tools. Also in Figure 6 can be seen that welding defects due to release of nitrogen gas from nitrides are only in remelt zone. Pores formed as gas trapping were filled with filler wire material. Due to weld deposit, materials in that area was once again remelted and solidified, and as consequence welding porosities were removed. This means special attention is needed to obtain deep enough heat affected zone only to ensure removal of defects and porosities originated from gases in nitrided zone.

Conclusions

From the investigations conducted in this paper following conclusions can be drawn.

- Repair welding of the nitrided samples resulted in the formation of copious gas pores due to nitrogen release during weld metal solidification. Also cracks starting from these voids were detected.
- In PVD coated samples extensive cracking was observed after repair welding tests.
- Special attention should be paid to the first surfacing weld adjacent to the surface. Lower power laser beams and the ramped-up pulse shape should be used in order to reduce the level of surface cracking that may subsequently produce peeling-off of the tool surface at duplex-treated samples. The lowest density of porosity is obtained with the ramped-down shape of a laser pulse and a sufficiently high energy permitting complete remelting of the nitrided layer.
- A combination of welding and preliminary remelting i.e. type B, however, reduces the occurrence of defects, e.g. inclusions and pores, in the surfaced layer, yet this does not provide optimum results since, due to melt spatter, nitride inclusions will persist at the surface and thus pass on to the surfaced layer.
- The occurrence of inclusions, i.e. rests of melted PVD claddings, can be reduced by using "Leading power spike", which will produce evaporation of the cladding.
- Welds made with type C welding technique i.e. simultaneous remelting of welded seams, in combination with a falling pulse resulted in lowest density of welding defects.

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