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HETEROGENEOUS LASER WELDS OF DUCTILE IRON AND Cr-Mo LOW ALLOYED STEEL

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Abstract: For some powertrain components deep penetration laser welding is considered very advantageous and prospective joining technology. Presented article focuses on heterogeneous laser welds of two widely used materials, ductile iron with pearlitic matrix (e.g. differential carrier) and Cr-Mo low alloy steel (e.g. gears). When homogeneous welds without filler wire are done, both materials show poor laser weldability, because unacceptable welding defects, mainly cracks, are created in the weld. In ductile iron, almost under all welding conditions, cracks in WM and HAZ due to brittle phases (cementite and martensite) are created. Low alloy Cr-Mo steel creates under all welding conditions solidification cracks and microcracks, caused by solidification. Even though homogenous welds of both materials are unacceptable, for heterogeneous welds possibility to create sound welds was found. By mixing of materials approximately 1:1 substantial amount of retained austenite is present in the WM, helping to suppress creation of brittle cracks and also partially suppress solidification cracks. To supress solidification cracks completely, full penetration welds and welds with V shape were used. Also use of Ni filler wire proved successful to create sound welds. The weld joint strength for heterogeneous welds for both used solutions was about 450 N/mm^2, which is less than BM strength, yet acceptable. Occurring phenomena connected with ration of materials mixing and its influence on WM properties, structure and behaviour is explained.
Keywords: Laser welding, LBW, heterogeneous welds, Cr-Mo low alloy steel, ductile iron, weldability, solidification cracks

1. INTRODUCTION

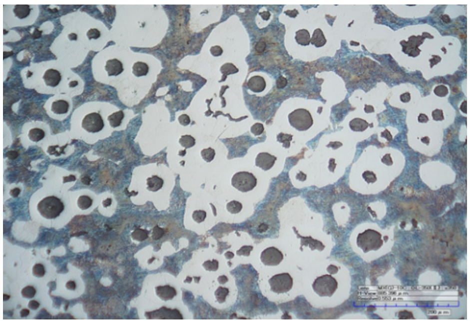
In many industrial areas deep penetration laser welding is considered very advantageous and prospective joining technology as it has economical and technical advantages compared to arc welding techniques. It is fast, precise, has low heat input, it is cost effective and suitable for wide range of materials. For example in automotive powertrain, deep penetration laser welds are for shafts and gears are already used. In powertrain, combination of materials needs to be welded, as e.g. in case of differential carrier made from ductile iron and crown gear from case hardened Cr-Mo steel. Presented article focuses on heterogeneous laser welds of these two widely used materials, ductile iron with pearlitic matrix and Cr-Mo low alloy steel.

2. EXPERIMENTAL

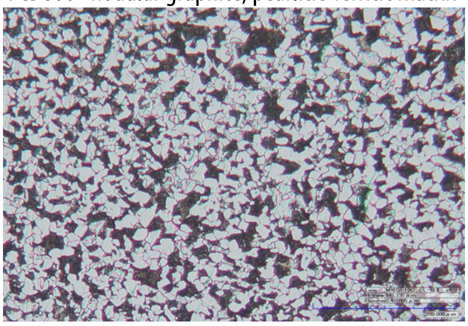
2.1. Base materials

The materials are selected so that they are of wide use in automotive, are of high strength and obtained results are applicable for wider group of materials, HSLA steels and irons. These are ductile iron FCD600 and HSLA steel SCM420. Materials use denominations (FCD600, SCM420) according to Japanese norms, as the research was conducted in Japan.

Material is in as-casted state. Ductile iron is attractive engineering material for its relatively high tensile strength, fatigue strength and good castability. This iron is hypoeutectic. The material solidifies as austenitic. It is used for gears, shafts, valves, tubes, fittings, casings.



FCD600–nodular graphite, pearlitic-ferritic matrix



SCM420–ferritic-pearlitic low alloyed Cr-Mo steel

Figure 1: Microstructure of FCD600 and SCM420 Cr-Mo steel

SCM420 is general use Cr-Mo low alloyed steel, suitable for heat treatment and carburizing. Matrix is feritic-pearlitic. SCM420 has high fatigue strength so it is suitable for use in engine components. The material solidifies as austenitic. It is used for gears, shafts, pistons, automotive industry engine parts.

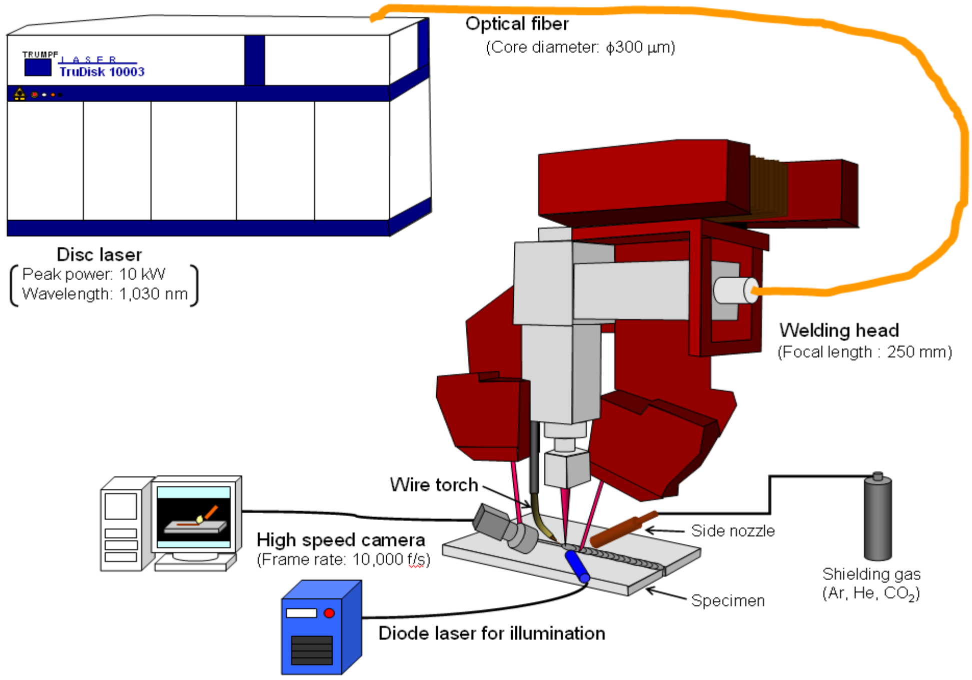


Figure 2: Welding setup – TruDisc 10003 and HighYAG welding head

2.2. Laser machine

Disc laser TruDisc 10003 was used during this experiment. Laser maximum power is 10 000 W and fibre core diameter is 0.3 mm. For Bead on Plate welding experiment welding head by Trumpf was mainly used. The head is using collimation lens 200 mm, focusing lens 200 mm and with connection with 0.3 mm fibre diameter the calculated spot size is 0.3 mm.

2.3. Weld evaluation

The homogeneous bead on plate welds are observed and then heterogeneous I butt welds are done and researched. Weld process evaluation will include systematic observation of the process by high speed video cameras, X-ray melt pool observation, and weld appearance observation by optical means, metallography, electron microscopy, and spectroscopy analysis.

3. RESULTS OF HOMOGENEOUS WELDS

3.1. Bead on plate welding of ductile iron FCD600

BOP welding experiments have been executed to research weldability of ductile iron FCD600. Weld depth and weld area linearly increase with laser power. The function of weld area and heat input per unit length is linear, but the function for weld depth and heat input per unit length is polynomial, limiting maximum weld penetration depth reachable by laser welding by increase of power.

As an example of research results are shown cross sections of experiment, when laser focal spot position was changed from inside of material to outside (-6 mm to +6 mm). From the Figure 3 can be noted, that there is big influence of defocused distance on weld shape. The weld ratio depth/width extremely varies from values 1.2 to 9.3. The low values of ratio 1.2, 1.5 are for fd=+6. And the maximum ratio depth/width, 9.3, 7.8, are for values fd= -2, -4 mm. This is caused by size and shape of keyhole, i.e. energy density.

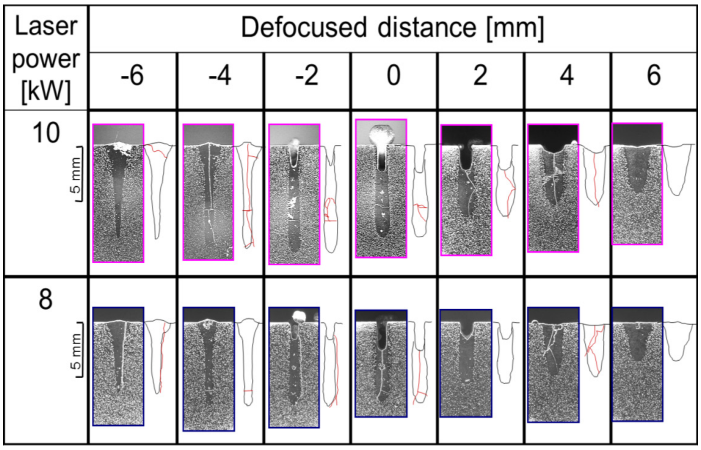


Figure 3: Metallographic micrographs for variation

Formation of cracks is the most severe problem for this material. At almost all welding conditions weld cracking was observed in WM and also HAZ, Figure 3. Typically perpendicular cracks of weld bead have been observed. After fractography analysis the cracks have been defined as quench cracks, caused by thermal stresses and phase transformation stresses combined with low ductility of WM.

By the welding process originally pearlitic-ferritic matrix with C nodules transformed and created WM consisting from cementite, retained austenite and martensite. WM and adjacent HAZ have very high hardness with average values about 900 HV and maximum values over 1000 HV. This structure is connected to cracking.

This material inclines to spatter creation, which causes underfill, shown at Figure 4. Spatter creation and deep underfill was noticed for majority of conditions conducted at focus position.

Figure 4: Weld 8 kW, 50 mm/s, fd=0 mm, high formation of spatter and underfill

At Figure 5 there is schematic of spatter creation based on high speed video camera observation. Problem of spatter creation increases with high power and high welding speed. Easiness of spatter creation is enabled by material properties, low surface tension and low viscosity, high absorptivity of graphite, in combination with too high energy density of laser beam causing intense evaporation and plume generation. Beam energy density for used setting at focal point and near to focal point is too high and for such setting spatter and underfill are easily created. Under such conditions welding does not create quality welds, so out of focus welding needs to be done for Trumpf welding head. Ideally with fd=-4 mm welds with deep penetration, smooth bead surface and almost no spatter are created.

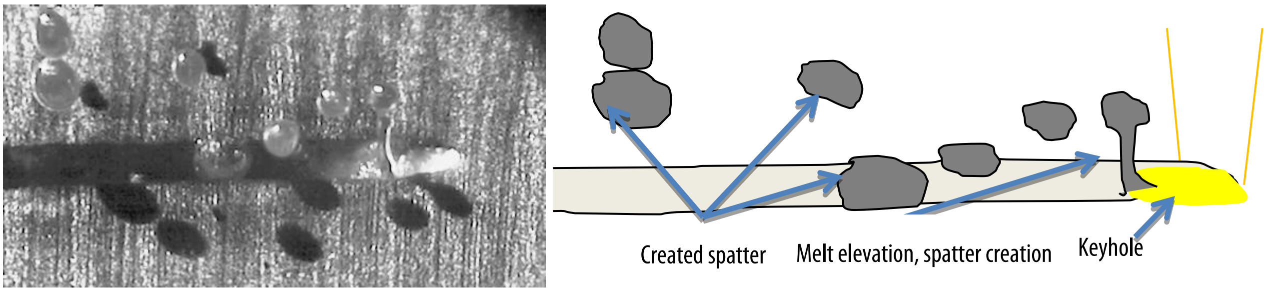


Figure 5: Video and scheme of melt elevation as taken by high speed camera

To suppress cracking tendency of this material, cementite formation has to be stopped. This can be done by very high preheat and slow cooling down of material or use of ductile filler metal that will stop cementite formation.

It can be concluded that laser weldability of FCD600 is poor, because tendency to create brittle phases (mainly cementite, martensite) and creation of quenching cracks. Also spatter and underfill are easily created.

3.2. Bead on plate welding of Cr-Mo steel SCM420

It needs to be stated that the laser weldability of SCM420 is poor, because welding cracks or microcracks have been found in all the welds, under all welding conditions and cracks are the most detrimental welding defect.

It was found that increasing laser power the weld penetration depth is also linearly increasing. The slope of function of penetration depth to laser power depends on weld shape and weld shape is influenced by welding speed and defocused distance. For low welding speeds, the weld has V shape. For higher welding speeds, over 50 mm/s, the weld shape is I, very deep and narrow with high depth to width ratio. It is considered, that this weld shape change is caused by change of melt flow direction in the molten pool.

The I shape welds, welds with high width to depth ratio, inclined to underfill. Welds with plus defocused distance values +fd inclined to have underfill and undercut. The most advantageous setting of defocused distance for minimizing spatter, underfill and undercut is fd=-2, -4 mm.

The WM consist of martensite. It has average hardness of 465 HV in WM and adjacent HAZ area.

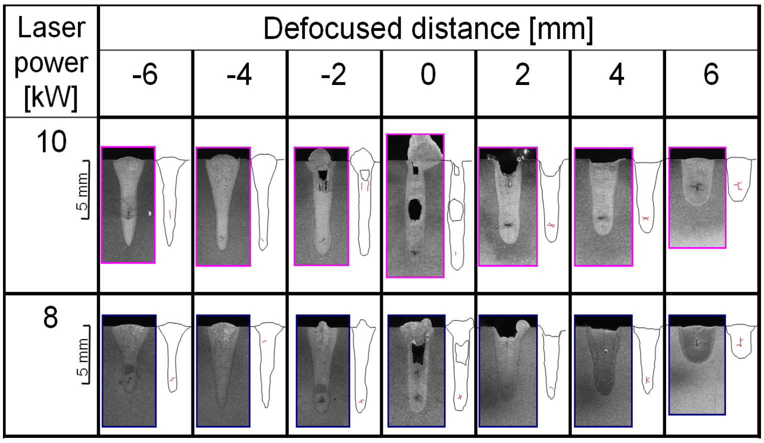
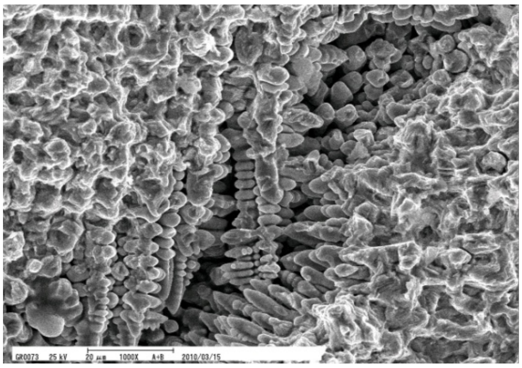


Figure 6: Metallographic micrographs for variation of defocused distance

Cracks have been found in all welds, Figure 6. By fractography analysis the cracks have been classified as solidification cracks, as visible at Figure 7. These solidification cracks and microcracks have been formed for all the welding parameters. Heat input per unit length was increasing the crack size, but minimizing heat input could not completely eliminate the solidification cracking. The EDS analysis proved existence of FeS sulphide inclusions on crack surface and also too high P and S contents was measured at the crack boundary and segregation of these impurities is cause of solidification cracking.



SEM photograph, Mag. 1000x, dendritide
Figure 7: Solidification cracks surface

During X-ray observation, the connection between molten pool movements and solidification cracking was found, when prolonged solidification in the weld bottom distinctly caused creation of large solidification crack. Also welds done with minus defocus that had V shape, have shown decrease in crack occurrence.

For SCM420 the creation of spatter was much smaller than compared to FCD600. It is caused by different material properties, as FCD600 has much lower surface tension than SCM420. It can be compared by schematic Figure 8 for SCM420, and Figure 5 for FCD600.

It can be stated that with high power lasers very deep and narrow welds with minimum distortions are possible at high welding speeds. But because of the P, S impurities and solidification sequence, in SCM420 solidification cracks and microcracks are formed in laser welds and the laser weldability of this material is poor.

To eliminate the cracking the impurities in base metal needs to be lowered be steel manufacturing process or the filler wire with low P, S content can be used during welding. Also if the melt solidification would be unidirectional from bottom of the weld up, the cracks can probably be suppressed. For full penetration welds the melt can freely contract so the thermal stresses are lower probably resulting in lower crack susceptibility.

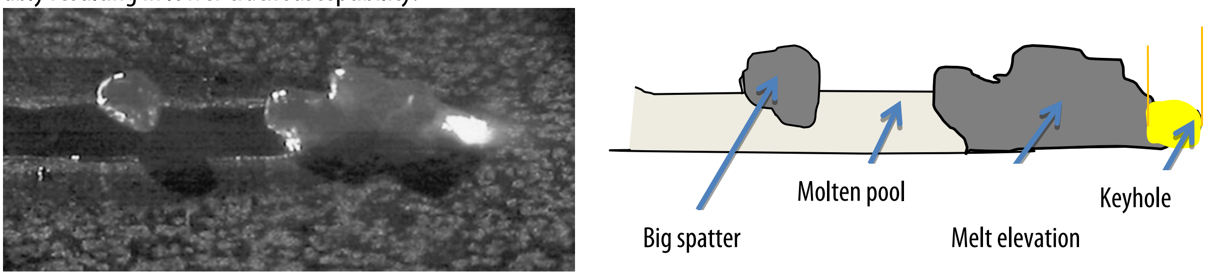


Figure 8: Video and scheme of melt elevation for SCM420– WS3 weld

4. HETEROGENEOUS WELDS: STEEL+IRON

It was considered that by misalignment of a laser beam during butt welding into the ductile iron or steel side, the resulting WM microstructure could be greatly varied and sound welding could be obtained. To research the influence of gradual variation in chemical composition on the resulting WM, butt welding was carried out at a small directional angle against the joint interface-line between two samples. Welding started inside the ductile iron and finished inside the steel, as shown in Figure 9. From this misaligned sample, longitudinal cross section was cut, hardness measured, cracks observed. These results are shown at Figure 10. The width and depth of the weld were around 2.1 mm and depth 8 mm, it was almost constant.

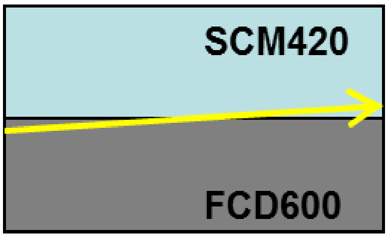


Figure 9: Gradually misaligned laser trajectory misalignment to alter composition

It is found that hardness of WM dramatically changes along the longitudinal axis. The hardness ranges between 400–1000 HV and its evolution resembles wave and 4 areas are distinguishable. This evolution and values of hardness are very similar for all 3 different depths of measurement:

1. At the beginning there is plateau 15 mm long of steady hardness around 1000 HV.
2. Linear decrease of hardness from 1000 to minimum 450 HV, where metals mix 1/1.
3. Increases again to 1000 HV.
4. Decrease to 650 HV.

The cracks are visible at the Figure 10. At the beginning cracks running straight are visible, while at the 2nd half we can notice large cracked area from down to up. The cracks in the first part are cracks due to weld metal and HAZ brittleness. These cracks have usually vertical position; the width of the cracks can reach up to 20 μm. In the later half, the cracks resembles solidification crack. In the half way, between area of brittle and solidification cracks, where the materials were mixed about half to half, there was a decrease in cracks occurrence and also of crack size. The part with fewer cracks that are very thin corresponds with the lowest hardness. Obviously, the material is much more ductile in this region. This extreme change of properties is connected with chemical composition.

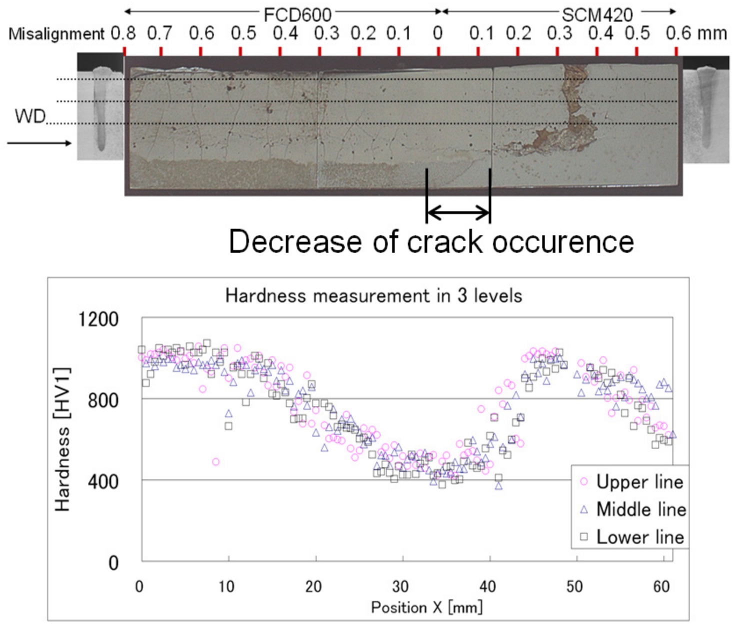


Figure 10: Evolution of hardness along misaligned weld (longitudinal section)

In steel carbon presence has big importance. The graphite inside ductile iron dissolved in matrix of heterogeneous joint and allowed presence of retained austenite, which was supported by TEM analysis. The influence of carbon presence on Ms and Mf temperatures (martensitic transformation), i.e. retained austenite, is widely known [2, 3].

By mixing the materials 1:1 suppressing presence of brittle cracks is possible due to presence of retained austenite. Yet small solidification cracks are still present near the weld bottom. To suppress these solidification cracks 2 possible ways were found, as

shown at Figures 11 and 12. Welds done with high minus defocus that resulted in V shape were without solidification cracks and full penetration welds without solidification cracks were done on slab thick 8 mm, Figure 12.

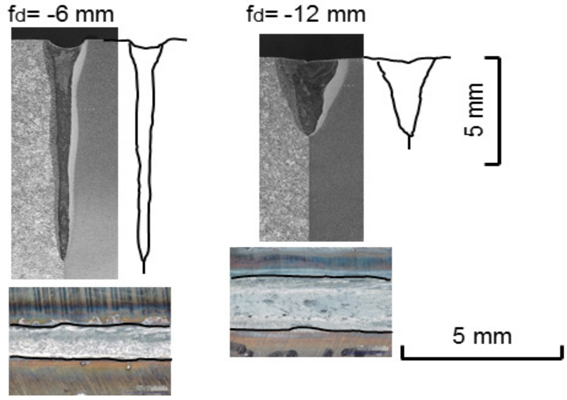


Figure 11: V shaped cross sections and bead views of samples with focal point deeply in material

5. CONCLUSIONS

Research of laser weldability of 2 widely used ferrous materials and their heterogeneous joints was done with focus on penetration depth, weld shape, creation of welding defects and welding process observation.It was found that FCD600 has difficult laser weldability, because almost under all welding conditions quenching cracks in WM and HAZ are created. These are caused by cementite and martensite presence. FCD600 is susceptible to serious spattering and underfill, because of material properties, i.e. influence of low viscosity of ductile iron was noted. The presence of nodular graphite in BM with high laser light absorptivity is increasing laser induced plume temperature and volume thus increasing also spatter. Upon welding the nodules in melt do partially dissolve increasing C content in the matrix, but they do not dissolve completely. The melt behaviour is very simple, the flow of melt is slow, from 25-140 mm/s.

In low alloy steel SCM420 under all welding conditions solidification cracks and microcracks in WM were observed, so this material has also poor laser weldability. The solidification cracks were found to be connected with molten metal flow, which is for this material very complex and fast. The melt flows inside melt pool are of complex circulating pattern, which causes long solidification time and enables long segregation of impurities S, P.

The behaviour of both materials during welding differs significantly. These differences were observed in keyhole stability, creation of spatter, melt pool movements. The main cause of such difference is in chemical composition, physical, thermal and other properties of materials. For example graphite nodules in ductile iron have high absorptivity of laser light, influence laser induced plume, keyhole creation and melt movement. Keyhole depth, i.e. weld depth, in FCD600 is much deeper, because of strong laser induced plume. On the other hand SCM420 has much more complex melt flow inside molten pool.

For heterogeneous welds FCD+SCM, it was found that position of laser beam to the butt weld joint line, i.e. mixing of materials, has dramatic effect on obtained weld metal phase, hardness and cracks presence. When in the mixture ductile iron prevails, the presence of brittle cracks can be observed and when SCM420 prevails, solidification cracks occur. But the extent of cracking is very much decreased compared to cracking of homogeneous BM welds. Near the weld bottom of partial penetration welds, small solidification cracks were typically found.

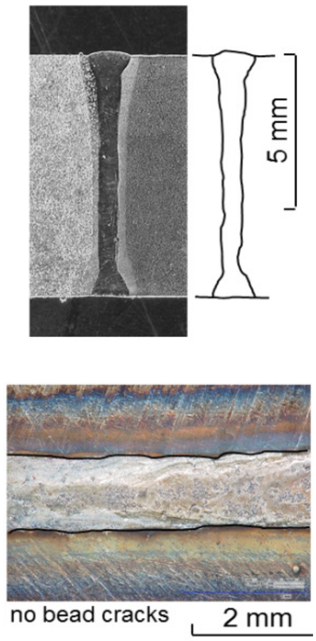


Figure 12: Full penetration weld – sample thick 8 mm, cross sections, upper view of the bead surface

These we were able to suppress by creating full penetration or weld with high minus defocus, weld in shape of V. The weld joint strength for heterogeneous welds was about 450 MPa. This value is smaller than for base materials, yet it is high enough to practically apply the welding method.

It was found that even though both examined materials have difficult laser weldability and differ very much in their behaviour, when laser welded together, sound heterogeneous welds are possible under certain conditions.

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