APPLICABILITY INVESTIGATION OF JOINING TECHNOLOGIES FOR DIAMOND CORE BITS

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Abstract

For the joining of two metallic components of different material quality, different methods of welding or soldering techniques are used. In this case, these two material qualities are given by the segments containing diamond particles, and thin-walled steel tube. In our previous paper we analysed welded joints with two different kinds of laser sources. In this paper we extend the previous investigations with the analysis of capacitor discharge welded and flame soldered samples. We examine the microstructure of the joints and record the chemical element maps to determine if alloying was formed. Joints are also subjected to fracture and hardness testing. This investigation shows that the applied joining technology meets the increased technical requirements because the joining zone must bear high mechanical and significant thermal loads during usage.

Keywords: *joining technologies, welding, soldering, diamond segment, material investigation.*

1. Introduction

Nowadays, many methods of welding or soldering techniques are used to attach diamond segments. The development of the segment composition and geometry requires the development of joining technologies as well. Beside the currently applied laser welding, we look for the joining process that meets both technological and the cost expectations. The newly used joining technology should meet both environmental and technical requirements.

Product development projects of Diamond core bits have been in the direction [1], that it is necessary to deal with the technological development as well. Therefore, we have investigated in a previous article [2], how different laser sources have an impact on the joining zone and therefore we are investigating new joining technologies as well.

In this paper we complement our previous article with the evaluation of samples with capacitor discharge welding and flame brazing. As a first

step, we look at the effect of the technology on the product and we will deal with the optimization later

2. Technological experiments

2.1. The process of experiments

We choose the Ø102 mm drill bit from our product portfolio (Figure 1.) – during serial production we use solid state laser for its welding – and we manufactured some samples with capacitor discharge welding and flame brazing technology, as well. The reason that the flame brazing was chosen is that we sell segments separately, as well and the customer brazes these segments with this technology themselves. The chosen drill bit has 8 segments, which are attached on the frontal area of the tube equally.

We used laser welding – current serial joining technology – as a base and we compared capacitor discharge welding and flame brazing to this. We investigated the effect of these joining technologies on the joining zone and the segment.

2.1.1. Lézerhegesztési kísérlet

For the experiment we used the Trumpf TruDisk 4002 laser source (max. 4.0 kW performance laser source with a wave length of 1.03 μm).

The laser source is in connection with a fully automated machine. The segments are added in an internal two-point feeding-positioning unit from a vibrating feeder which attaches the segments on the frontal surface of the tube which is positioned by a robot. Due to the structure of the machine the laser head moves during welding and only 1 segment is welded at a time. During welding, the segment feeder prepares the next segment on the other side of the two-point positioning device in order to reduce the manipulating time and to provide fast positioning of the next segment.

2.1.2. Capacitor discharge welding experiment

For the experiment we used a vertical welding machine, the parameters are the following: 198/160 V pulse voltage and 3,2 bar pneumatic clamping pressure.

There is only one segment welded at a time due to the structure of the machine. The segments pass through a feeding device to the electrode. Another electrode is connected to the tube. The components are contacted then the clamping pressure is applied. After that the energy stored in the capacitor is guided on the electrode and by this the welding is done.

2.1.3. Flame brazing experiment

The experiment was performed by manual procedure. We started the process by sanding the frontal surface of the tube and the bottom of the segment with P80 sandpaper, and then we applied flux on their surfaces. We attached the segment on a tube and heated the tube with the flame. We started the heating from further away and slowly

got closer to the segment in order to avoid overheating. When a narrow yellow stripe appeared – which indicated the correct temperature – we added welding material in the joining zone and spread it with the flame. After the solidification of the brazing material we cooled the environment of the bond with compressed air.

2.2. The joining technologies used for the experiments

2.2.1. Laser welding

The wave-length of the laser beam depends on the quality of the material which is forced to do induced emission. This monochromatic coherent laser beam is focused on the welding spot with the help of optical components. In the small diameter focus spot, a really high performance density can be achieved, and by absorption the electromagnetic radiation is transformed into heat in the materials to be welded. In a narrow band the heat melts the boundary of the joined pieces and behind the passing radiation a narrow heat-effect, low distortion seam is formed [3, p. 77.].

Power density affects the depth / width ratio of the seam and by the shape of the joint it affects the cooling rate and the melting time. This not only determines the microstructure of the seam, but also the time periods when the bonding zone passes through a critical temperature range.

As a result of high power densities, the rapidly emerging melt is separated by a specifically large interface from the solid and the melt volume is small compared to the total volume of the work-piece, so the melt rapidly cools. Such an increase of heating and cooling rate significantly affects the amount of the phase change material.

The high-performance laser beam - contrary to the electron beam - is a low-divergent monochromatic light beam, providing a high energy density without any vacuum and allowing any optically accessible surface to be machined. The main disadvantage is the significant surface state dependence of energy absorption and low efficiency.

There are 2 mayor conditions for welding different metallic materials (alloys):

- the 2 metals should be able to melt at the same time and form a joint melt. This condition can hardly be achieved if the melting points of the two metals are far away from each other or their heat conductivity is different. Owing to this, if necessary, the laser beams are guided asymmetrically to the harder melting metal;

Figure 1. Catalogue picture of $\varnothing 102$ mm drill bit

– the 2 metals should be metallurgically compatible so there should not be intermetallic phases, transition compound forms during the welding process. If we are talking about the joining of 2 alloys we cannot make conclusions from the equilibrium diagram, we must carry out pre-experiments [4, p. 15–16].

Before laser welding there is no need to do any preparative manufacturing on the surface of the tube or the segments and there is no need to add filler material to form the joining.

2.2.2. Capacitor discharge welding

During the pulse welding of the capacitor the required energy for the welding is conducted. To the special transformers of the workpiece by earlier charged capacitor via a thyristor. The charging time is between 0,5...2 seconds and the welding time is between 3...10 ms [5].

Special properties of capacitor discharge welding's are described by the following process values: steep increase in current, short welding time, large welding currents, low heat input, low network load, high reproducibility, ability to weld pieces with different thicknesses, ability to weld different raw materials (e.g. steel, brass), ability to weld stainless steels. Ability to weld thin plates and the ability to weld pieces with galvanic coating.

The greatest advantage of the welding is the steep increase in current and the fast heat transfer to the welding zone. This results in reaching the welding temperature faster without heating up the surrounding material.

In case of the capacitor discharge welding method there is no need for filler material to form the bond, however, a pre-manufacturing operation on the surface of the segment and the tube is necessary. There can be two kinds of operation:

- the frontal surface of the tube is knurled and the surface of the segment stays flat;
- the frontal surface of the tube stays flat and cross directional grooves are made in the surface of the segment.

2.2.3. Flame brazing

The brazing is performed with molten brazing material which has lower melting point than the materials to be joined. During brazing, the connection is achieved by mutual diffusion. The criterion of the brazing is that the materials to be joined can be dissolved in a solid state. If the mutual dissolve criteria is not fulfilled then the molten brazing material will form an adhesive

like bond similar to sticking. Based on the brazing materials melting point and the required brazing temperature for this and furthermore the expected strength of the bond weldings can be divided into 2 groups:

- soldering, which is performed at lower temperature than 450°C and with maximum 50 MPa binding strength;
- brazing, which is performed at higher temperature than 450°C (mainly lower than 900°C) and with maximum 300 MPa binding strength [3, p. 136].

Brazing provides relatively high strength and the binding can be applied at higher temperature as well. Neither the tube nor the segment surface needs pre-manufacturing before brazing, but the use of flux is justifiable at the beginning of the process.

2.3. The materials used for the experiments

2.3.1. Segment

Production of the segment manufacturing is based on powder metallurgy technology. First the powders are mixed then a machine builds the segment layer by layer. Meanwhile the machine can add diamond particles with defined size in specific positions. This process is fully controlled, though the thickness of the layers and its quantity can be freely changed.

Diamond segments have 2 main zones. One is the cutting zone which is necessary for the cutting, the other is the neutral zone which is necessary for the welding. The density of the segment is set to a specific level. Density of the segment influences the welding, the cutting speed and the wear rate of the cutting zone during drilling.

The chemical composition of the segment's neutral zone: Astalloy-Mo = 99,8 %, Graphite powder = 0,2%, Zn-stearate = 0,5%, density of the segment is 7870 kg/m³.

2.3.2. Steel tube

We attached the segments of a thin-walled steel tube which is cold-drawn and made of E235+C (1.0308) according to the standard EN 10305-1 [6], wall thickness 2±0,15 mm.

The chemical composition of the tube: C ≤ 0,17%, Si ≤ 0,35%, Mn ≤ 1,2%, P ≤ 0,025%, S ≤ 0,025%.

2.3.3. Brazing material

For the flame brazing experiment we used Fontargen A324 brazing material (Ag=49%,

Zn=23%, Cu=16%, Mn=7,5%, Ni=4,5%) % based on the standard EN ISO 3677 [7] and Easy-flo™ 100 Flux Paste. The recommended brazing temperature for the brazing material is 690 °C.

3. Investigation methods of the joining zones

Welded bonds or seams are usually examined the same way as raw materials are investigated. During non-destructive investigations the investigated pieces do not get damaged.

Non-destructive investigation methods:

- visual inspection;
- geometrical examination;
- minimal test;
- radiology examination (x-ray examination) radioactive isotope examination);
- magnetizable powder examination;
- fluid penetration (paint diffusive, penetration) examination;
- ultrasonic investigation;
- eddy current test;
- CT investigation.

Destructive investigation methods:

- breakage test;
- hardness measurement;
- energy dispersive spectroscopy;
- macroscopy examination;
- optical light microscope inspection;
- scanning electron microscope investigation;
- tensile test;
- bending test;
- impact test;
- fatigue test.

The drill bits have to fulfil their mechanical requirements. First, they have to fulfil the non-destructive investigations, used in serial production (Visual inspection, Geometrical examination, Minimal test) and then destructive tests (Breakage test) were performed on them. Finally the welded seam and the heat-affected zone were examined (Macroscopy examination, Scanning Electron Microscope investigation, Hardness measurement).

4. Test results of joining zones

4.1. Test results of non-destructive tests

4.1.1. Visual inspection

Purpose of the test: checking the seam based on the requirements defined.

The result of the test:

- no defect can be seen in the laser welded seam;
- extrusion from the high-level plastic deformation can be seen on the capacitor discharge welded seam;
- the flame brazed sample shows consistent thickness of brazing material.

4.1.2. Geometrical examination (Segment offset)

Purpose of the test: to determine the average value of the segment offset (segment position relative to the outer surface of the tube), which should be between 0,9<average<1,4 mm.

Applied measuring device: digital dial gauge.

The result of the test:

- laser welded sample: average = 1,29 mm;
- capacitor discharge welded sample: average = 1,16 mm;
- flame brazed sample: average = 0,923 mm.

It can be established from the measurements that the average value is within the tolerance for all three samples.

4.1.3. Geometrical examination (Segment tilt)

Purpose of the test: to determine the average value of the segment tilt (the parallelism of the segments on the lateral surface of the tube), which should be $\pm 0,2$ mm.

Applied measuring device: digital dial gauge.

The result of the test:

- laser welded sample: average = -0,018 mm;
- capacitor discharge welded sample: average = -0,225 mm;
- flame brazed sample: average = 0,001.

It can be established from the measurements that the average value is within tolerance for laser welded and flame brazed samples. The average value of the capacitor discharge welded sample is out of tolerance. This can be the consequence of the high-level plastic deformation during welding.

4.1.4. Geometrical examination (Segment twist)

Purpose of the test: to determine the average value of the segment twist (difference between the radius of the segment and the radius of the tube), which should be max. 0,4 mm.

Applied measuring device: digital dial gauge.

The result of the test:

- laser welded sample: average = -0,07 mm;
- capacitor discharge welded sample: average = -0,225 mm;
- flame brazed sample: average = -0,032 mm.

It can be established from the measurements that the average value is within the tolerance for all three samples.

4.1.5. Geometrical examination (radial runout on the segment)

Purpose of the test: to determine the average value of the radial runout on the segment (radial runout measured on the surface of the segment while rotating the core drill bit), which should be max. 0,55 mm.

Applied measuring device: digital dial gauge.

The result of the test:

- laser welded sample: average = 0,35 mm;
- capacitor discharge welded sample: average = 0,515 mm;
- flame brazed sample: average = 0,104 mm.

It can be established from the measurements that the average value is within the tolerance for all three samples.

4.1.6. Minimum test

Purpose of the test: with the required minimum limit, ie. 9 Nm of torque, should be loaded for each segment. An insert (in a fitting shape), which is connected to the torque wrench is put on the segment of the product to be examined, which is connected to a torque wrench with torque limiter. For the quality testing of welded joints, the segments are loaded with the minimum torque prescribed.

There was no damage in the joining zone for either of the samples, so the minimum torque was borne by each segment without damage (breakage).

4.2. Test results of destructive tests

4.2.1. Breaking test

Purpose of the test: to determine the average value of the breaking torque, which should be min. 9 Nm. An insert (in a fitting shape), which is connected to the torque wrench is put on the segment of the product to be examined, which is connected to a torque wrench with torque limiter. After resetting the wrench, we break the segment off and read the displayed value.

The result of the test:

- laser welded sample: average = 16,4 Nm;
- capacitor discharge welded sample: average = 24,7 Nm;
- flame brazed sample: average = 13,3 Nm.

All 3 samples have reached the drawing requirements, because we measured higher breaking value than the minimal specified value.

4.2.2. Microscopy examination

Based on the investigation results of all three samples it can be stated that:

- in the section of the investigated laser welded sample, cavity and crack-like patterns could be observed, mainly on the segment side ([Figure 2.](#));
- in the cross section of the investigated capacitor discharge welding sample, high level plastic deformed zones can be seen in both elements which is a characteristic of the resistance welding ([Figure 3.](#));
- this deformation is even more significant at the extrusion of the molten and annealed metal at the samples outer sides ([Figure 3.](#));
- the microstructure has been distorted on the segment and tube side, as well because of the high-level plastic deformation at the area of the seam ([Figure 4.](#));
- linear and fibrous morphology can be seen (typical in the case of plastically deformed materials) in consequence of the extrusion. This can be observed in the touched zone of the tubes material ([Figure 5.](#));
- in the seam no inclusion, crack or not melted surface could be observed which could cause failure;
- the investigated flame brazed sample shows sufficient gap filling and steady brazing material thickness (200 µm on average) ([Figure 6.](#));
- the brazing is defect free - only minor inclusions like visual elements can be seen on the section ([Figure 7.](#)).

4.2.3. Scanning Electron Microscope analysis

Based on the SEM analysis of all three samples it can be stated that:

- in the solid-state laser welded seam, cavity and micro-crack like visual elements can be observed;
- on the element map of the seam, regarding the main alloys (Mo, Mn, Fe, Cu, C), no significant difference can be seen between the different zones, so no alloy enrichment or alloying occurred ([Figure 8.](#));
- in the capacitor discharge welded seam, micro-crack like visual elements can be seen ([Figure 9.](#));
- on the element map of the seam regarding the main alloys (Mo, Mn Fe, Cu, C) no significant difference can be seen between the different zones so no alloy enrichment or alloying occurred ([Figure 10.](#));

Figure 2. Optical microscope recording of the laser welded seam

Figure 5. Optical microscope recording of the capacitor discharge welded seam

Figure 3. Stereo microscope recording of the capacitor discharge welded seam

Figure 6. Stereo microscope recording of the brazed sample

Figure 4. Optical microscope recording of the capacitor discharge welded seam

Figure 7. Optical microscope recording of the brazed sample

- based on the investigation of the brazed sample only smaller inclusion like visual elements can be seen (**Figure 11.**);
- neither in the neutral zone nor in the raw material of the tube could any microstructure changes can be seen;

Figure 8. Element map of the laser welded seam

– from the EDX spectrum (**Figure 12.**) which was collected from the area seen in **Figure 11**, we chose the elements which specify the composition of the components (segment, tube, brazing material) and we illustrated it on an element map. It can be seen that no alloying occurred.

4.2.4. Hardness examination

The Vickers test is used to check welded seams and joints. For hardness testing of very thin edges and narrow thermal zones the micro hardness measurement can also be used.

The determination of the hardness data of the welded seams and their heat affected zones by the Vickers method, with the knowledge of the material quality and the technological parameters, can provide a variety of information:

– the hardness difference between the base material and the seam can be considered as a kind of ductility change, since the deformation capability is characterized by the hardness, which is

Figure 9. Scanning Electron Microscope recording of the capacitor discharge welded seam

related to the martensite content of the steels. This is influenced by the carbon equilibrium (C+ alloys) and the cooling rate (cooling time) in the given temperature range;

Figure 10. Element map of the capacitor discharge welded seam

Figure 11. Scanning Electron Microscope recording of the brazed sample

- the hardness values measured and illustrated in the perpendicular direction to the longitudinal axis of the seam, the obtained hardness distribution shows the effects of thermal processes and the heat treatment effects in each zone;
- the hardness values measured parallel to the longitudinal axis of the seam, the metal property uniformity can be detected;
- measured values as a function of temperature refer to the thermal stability of the microstructure (e.g. tempering resistance).

In the latter case, the given temperature hardness difference or the temperature difference measured at the specified hardness level can be a qualifying data.

The microscopic sections were used for hardness measurements.

Figure 12. EDX-spektrum a forrasztott mintáról

Figure 13. Hardness gradient of laser welded and the capacitor discharge welded sample

We can see from the hardness measurement of the laser welded sample that the highest values are in the seam. This is characteristic of high

energy density methods. The hardness measurement values of the capacitor welded sample are between a 50 HV0,2 region (Figure 13.).

5. Conclusions

In all 3 sample productions the same components were used as in serial production. The segments and the tubes were chosen from the same production lot to minimize the differences. During the geometrical measurements we realized that the technologies affect these geometrical features. During the next sample productions, we have to take it into consideration or it must be eliminated. Based on the break test results, all the samples have met the drawing requirements because we measured higher breaking value than the minimal specified value.

According to the investigations that we used in the serial production, all 3 samples met the requirements. However, as we were using new joining technologies these investigations are not enough for the qualification.

The additional detailed investigations showed us the differences between the samples. The optical microscopy recordings showed that gas inclusions and micro-cracks can be in the seams. The SEM investigations also confirmed these. The element maps show that alloying cannot be expected in the seams.

In conclusion, it can be stated that the considered joining technologies are suitable, that during an additional sample production the results of the test can be rechecked, and further improvement measures should be defined if further optimization of the joining zone is required.

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