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MANUFACTURING OF LOOPED DIAMOND WIRE BY UPSET WELDING AND HEAT TREATMENT OF WELD JOINT BASED ON JOULE EFFECT

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Abstract. *Diamond wire sawing of brittle materials, such as Si, SiC and sapphire crystals, is a key process for the semiconductor and photovoltaic industries. This has led to a growing demand for research to investigate the effects of cutting parameters on the surface quality of silicon wafer. One of the approaches involves the manufacturing of a looped diamond wire to reproduce the industrial cutting process. For this, it was necessary to develop a resistance welding machine based on the concept of upset welding and parameterize the process. The high temperatures reached during the welding process cause the cold-worked grains to recrystallize, reducing the mechanical strength of the weld. In addition, the small diameter of diamond wire results in a high cooling rate, leading to the formation of martensite, which has high hardness and low ductility. Given the importance of heat treatment in the manufacturing of looped diamond wire, this work aimed to establish a heat treatment capable to form bainite microstructures in order to increase the ductility of the welding location. The results showed that the heat treatment was efficient and allowed the formation of a predominantly bainitic microstructure, with sufficient mechanical strength for the application of sawing brittle materials.*

Keywords: *diamond wire, upset welding, Joule effect, phase transformation of steel, heat treatment.*

1. INTRODUCTION

The multiple wires sawing process (MWS) has a fundamental importance for the photovoltaic and microelectronics industries. One of the main reasons, is that such process is used to machine mono and polycrystalline silicon, which are used as substrates in the production of photovoltaic cells, computer chips, and power semiconductor devices; like sapphire crystals, which are used as substrates in the manufacturing of special glasses and Light Emitting Diodes (LEDs). A common characteristic of these materials is their high brittleness and low fracture toughness, which reduces its machinability and prevents them from being cut by conventional methods.

One of the MWS technique used to slice wafers from the larger ingots is the diamond wire sawing, which is a technology that emerged as an alternative for the wire slurry sawing technology, that uses a steel wire and abrasive slurry, formed by SiC abrasives dispersed on polyethylene glycol. Among the advantages presented by the diamond wire sawing are the higher material removal rate, greater potential for recycling of the debris/chips, and better surface quality generated by the cut.

In industrial applications, a web formed by multiple wires arranged in parallel and equidistant is used to cut a larger ingot into hundreds or even more than one thousand wafers simultaneously. Basically, the machine-tool utilizes spool-to-spool movement, which involves two main spools: one that is used to feed the process with a single diamond wire; and another that takes the worn-out wire. The system is formed by a set of tensioners, pulleys and rollers with parallel and equidistant grooves which guide the diamond wire and form a wire web. The diamond wire performs a reciprocating movement during the sawing. Figure 1 illustrates a typical multiple wire saw (MWS) machine-tool used in the industry (Klocke, 2010).

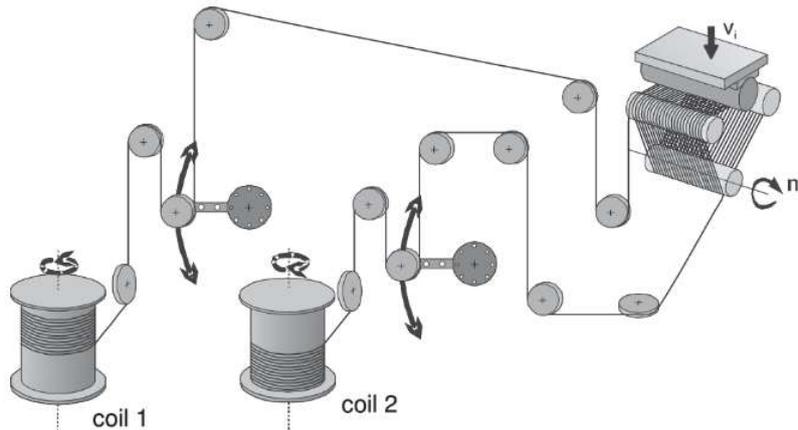


Figure 1. MWS machine-tool (Klocke, 2010).

Despite the diamond wire sawing process be used in the industry for several years and well-established, there is not sufficient knowledge about the influence of cutting parameters on the sawn surface quality and diamond wire wear mechanisms. The process optimization approaches have led to the development of a method that utilizes a single looped segment of diamond wire, in order to obtain a continuous cutting movement and to reach a cutting condition similar to the one employed in the industry (Knoblauch, 2019). This alternative offers advantages over the industrial method that employs multiple wires, including: i) a lower quantity of diamond wire; ii) the ability to perform cuts at continuous v_c ; iii) the ability to vary the cutting speed and evaluate the sawn surface quality; iv) the ability to assess the applicability of the sawing process to other materials.

The looped diamond wire saw machine employs the concept of a band saw, where the cutting tool moves continuously over pulleys. In order to be possible the research with looped diamond wire sawing, it was necessary to develop an equipment for welding of the looped diamond wire segment needed to be developed (Knoblauch *et al.*, 2017; Knoblauch, 2019; Souza, 2019). The equipment to welding the diamond wire segment utilizes the concept of upset welding process, where the heating by Joule effect is used to produce the weld. This equipment is divided into two parts: the device to ensure alignment of the wire ends and the power supply for welding. However, in order to improve the mechanical properties, mainly the tensile strength, of the weld and eliminate or reduce failures due to the welding process, researches were made related to new welding power supply, employing modern technologies and closed-loop current control system (Barcelos, 2023).

Although the effective control over the welding of the diamond wire and appropriate equipment, there is a limiting factor which is the mechanical strength of the welded region since the welding process induces high brittleness. In this sense, it is necessary to perform a subsequent heat treatment to increase the ductility of this region. Based on the aforementioned, this study aims to evaluate the heat treatment of the weld joint of looped diamond wires employing an upset welding device.

2. MANUFACTURING OF THE LOOPED DIAMOND WIRE

In this section, the proposed welding process and heat treatment for the manufacturing of the looped diamond wire will be presented, along with the essential key aspects necessary to understand the challenges involved in the welding and application of looped diamond wire.

2.1. DIAMOND WIRE

Basically, there are three methods for attaching diamond grits to the steel wire core: resin bonding, brazing alloy bonding, and the electroplating process. The electroplated diamond wire is predominant in the market for machining of brittle materials due to its higher abrasive retention and low coating deposition temperature process (Li *et al.*, 2020). The electroplating process used in the manufacturing of diamond wire is the same as such employed in the production of diamond tools, where the diamond grits are fixed and coated with a thin layer of electroplated Ni on the tool base.

Electroplated diamond wires are commercially available in diameters ranging typically from 120 μm to 450 μm , depending on the manufacturer. In this study, just the diameter wire of outer diameter of 350 μm is used. The non-use of diamond wires with smaller diameters is related to the difficulty to prepare and align the diamond wire surface ends for welding process.

These diamond wires use a high-strength cold-drawn steel wire as wire core, also known as piano wire, whose properties are established by ASTM A228 standard (ASTM International, 2014). The cold-drawing process is a forming process carried out at temperatures below the material's recrystallization temperature, in which the grains of the

microstructure undergo strain hardening, acquiring elongated shapes, as illustrated in Figure 2. This manufacturing process ensures high dimensional precision, high tensile strength, and high ductility of the steel wire core.

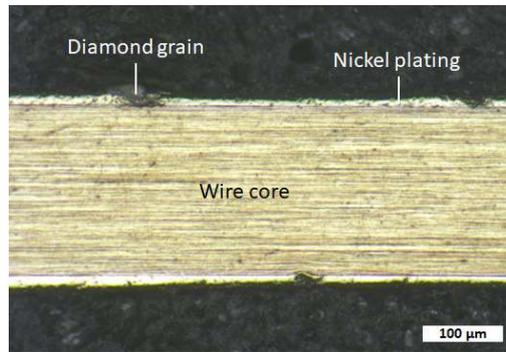


Figure 2. Microstructure of the electroplated diamond wire.

2.2. DIAMOND WIRE WELDING

The manufacturing of the looped diamond wire is performed in two main stages: welding of the wire ends using the upset welding method and heat treatment of the weld joint using heating by Joule effect. Upset welding is part of the group of resistance welding processes, where the heat required for welding is generated by Joule effect during the passage of current (I) through the interface of the workpieces, which imposes an electrical resistance (R) greater than the resistance imposed by the material of the workpieces. This process is used to join a wide variety of parts such as rods, tubes, rings, and profiles with different shapes. Due to the need to apply a forging force (F), this process can be classified as a pressure welding process (Mathers, 2002; Resistance Welder Manufacturers' Association, 2003; Weman, 2003).

The basic principle of resistance welding is based on the Eq. (1), which expresses the relationship between the heat generated and the current flowing through a conductor for a certain period of time (Resistance Welder Manufacturers' Association, 2003; Weman, 2003).

$$Q = I^2 \cdot R \cdot t. \quad (1)$$

where, Q is an amount of heat generated (Joules), I is the effective value of current (Amperes), R is the total electrical resistance of the circuit (Ohms) and t is the duration of current application (seconds).

Resistance spot welding, also known as upset welding, is performed on a butt joint, where the workpieces are clamped in the welding fixture using two electrodes. The electrode material should have low electrical resistance and high thermal conductivity to prevent overheating. The wire ends are pressed against each other, and a current is applied between them for a short period of time. To ensure uniform heat generation in the weld joint and prevent slippage of the ends during welding, it is crucial to have uniform surface roughness and parallelism between the contact surfaces. These desired quality characteristics are achieved by sanding the diamond wire ends using 800 mesh sandpaper using an auxiliary device. The auxiliary device clamps the wire ends during sanding and ensure the perpendicularity of the sanded surface in relation to the wire axis.

Since the highest electrical resistance in the welding circuit occurs at the interface of the workpieces (R_3), a significant amount of heat is generated in this area due to Joule heating effect. The high temperature in this region softens the metal to a plastic state, and with the application of a forging force, the two parts can be joined. The resistance spot welding process with a butt joint is illustrated in Figure 3.

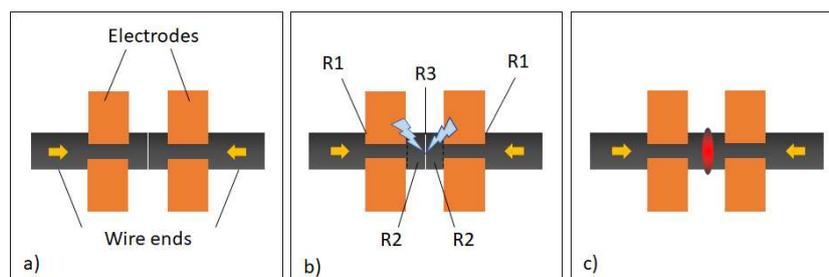


Figure 3. Upset welding steps: a) force application; b) current application; c) weld formation (adapted from(Barcelos, 2023)).

The total electrical resistance of the welding circuit R is the sum of the resistances between the two electrodes, as represented by the Eq. (2):

$$R = 2R_1 + 2R_2 + R_3. \quad (2)$$

where, R_1 is the electrical resistance at the contact between the electrode and the workpiece, R_2 is the electrical resistance of the workpiece and R_3 is the electrical resistance at the interface of the workpieces.

2.3. HEAT TREATMENT

In this work, the heat treatment is performed on the weld region immediately after welding stage with the wire still fixed in the welding device. The objective of this heat treatment is to increase tensile strength. Due to the small diameter (in this case of $350 \mu\text{m}$) of the used diamond wire, the cooling rate of the weld joint tends to be very high, and if no heat treatment is performed, occurs material hardening by the formation of a martensitic microstructure. The enhancement of the mechanical properties can be achieved through an austempering heat treatment process, aiming to obtain a bainite formation after the heat treatment, as illustrated in Figure 4.

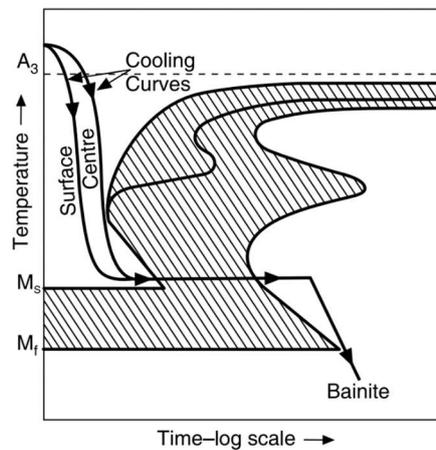


Figure 4. Characteristic cooling curve for austempering treatment (Rajan, Sharma and Sharma, 2011).

Austempering is recommended for high carbon steel alloys and involves heating the material above the critical A_3 temperature, followed by a rapid cooling, typically in a saline solution, and maintaining it at a temperature range between 200 and $400 \text{ }^\circ\text{C}$ above the M_s point, allowing the transformation from austenite to bainite. Finally, it is continuously cooled to room temperature (Rajan, Sharma and Sharma, 2011).

Since the increase in hardness only occurs in the weld joint, it was chosen to perform the heat treatment only in this region, utilizing the same principle used in welding, namely, heating by Joule effect. In this sense, the retention capacity of the diamond grits, as well as the mechanical and metallurgical properties of the remaining diamond wire, are preserved. To achieve this, a current is applied after the consolidation of the weld joint. The welding power source control system is responsible for managing the variables of current and time, allowing the reproduction of a thermal cycle like austempering process, as shown in Figure 4. The main process parameters are: C_1 (welding current), C_2 (heat treatment current), T_1 (holding time for current C_1), T_2 (transition time from C_1 to C_2), T_3 (holding time for current C_2), and T_4 (transition time from current C_2 to zero). The current behavior over time is illustrated in the graph in Figure 5.

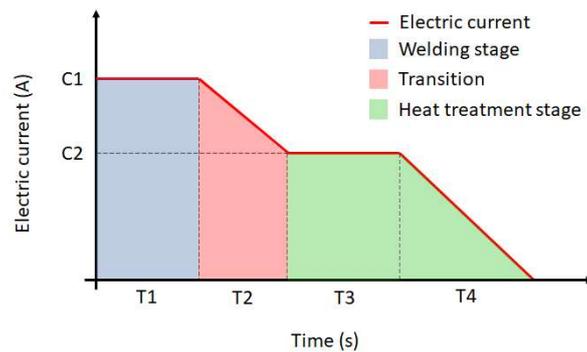


Figure 5. Behavior of electric current in diamond wire welding.

Although it is possible to effectively increase the ductility of the weld joint through this heat treatment, it is not possible to recover the lost mechanical strength due to recrystallization in this region. As shown in Figure 2, the microstructure of the diamond wire core consists of elongated grains, characteristic of cold-drawn steel. When heated above the recrystallization temperature, these grains regain their original shape due to stress relief, resulting in a loss of the mechanical strength in the weld region. Despite being undesirable, this fact does not restrain the use of the welded diamond wire as a cutting tool. However, its lifespan can be drastically reduced when operating under conditions of excessive wire tension or vibration.

In addition to the cutting process parameters, another factor with significant influence on the tool's lifespan is the preparation of the welded joint. As the welding process results in the formation of a burr around the joint, this burr shall be completely removed, in order to avoid the collision between this burr and the machined workpiece surface. Due to its small dimensions, the burr removal is done manually, using a medium/high-grit sandpaper.

3. EXPERIMENTAL METHODOLOGY

In the first moment, experiments were carried out to determine the heat treatment parameters which contribute to the formation of bainitic structures. In practice, it was observed that the welding parameters C1 and T1 exert a considerable influence on the weld formation, meaning there is a range of C1 and T1 values which a well-consolidated weld can be obtained. However, since welding alone does not make the diamond wire loop suitable for use as a cutting tool, due to the high brittleness of the weld joint, the choice of the correct range of the heat treatment parameters are very important to reach the desired microstructure at the end of the process.

During the manufacturing of the looped diamond wires, from all evaluated measurement temperatures methods, no effective temperature measurement method has been found for monitoring the temperature during the welding and heat treatment processes, making it difficult to establish a relationship between the current passing through the weld joint and the local temperature. Therefore, a fixed value was chosen for the heat treatment current, C2, assuming that it should be lower than the welding current, C1, varying only the parameters T3 and T4.

As shown in Table 1, a design of experiments for evaluating the welding and heat treatments procedure were performed, considering 6 parameters combinations, where the following parameters were varied: T3 at two levels; and T4 at three levels.

Table 1. Combination of heat treatment time parameters.

Combination	T3	T4
A1	30 s	30 s
A2	30 s	30 min
A3	30 s	2 h
B1	60 s	30 s
B2	60 s	30 min
B3	60 s	2 h

The looped diamond wires manufactured under these conditions were subsequently subjected to no-load rotation tests to assess the time elapsed until rupture. The heat-treated wires with the parameter combinations with T4 set at 30 seconds and 30 minutes showed lowest performance, since there was breaking in the early rotations, indicating that the heat treatment had no significant effect on the formation of bainitic structures at a level suitable for increasing the weld joint's ductility. On the other hand, when it was used a time of T4 = 2 hours, the performance was satisfactory since the lifespan exceeded 30 minutes at wire cutting speeds ranging between 15 and 20 m/s.

For a more detailed analysis, new samples were produced with the same welding conditions for metallographic analysis and microhardness testing of the weld joints (see Table 1). Thus, two welded joint samples were obtained for each of the established conditions. To reveal the microstructure, a chemical etching was performed using 2% Nital during a time of 5 s. The microstructure of the samples was analyzed using optical microscopy (Olympus Bx60M) with a maximum magnification of 500x. Hardness analysis was conducted along the weld joint, resulting in 13 measurements for each sample. As shown in Figure 6, the hardness measurement was done from the weld joint and moving towards the ends, with a distance of 150 μm between each indent mark.

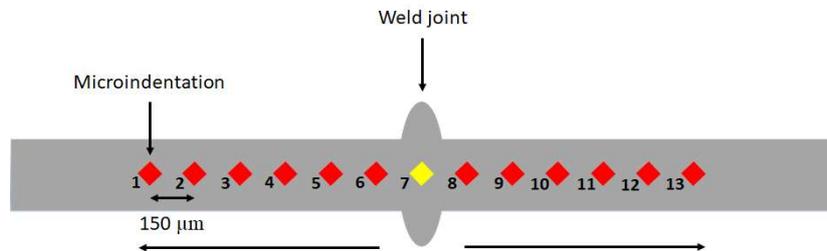


Figure 6. Microhardness test methodology.

4. RESULTS AND DISCUSSIONS

One of the first aspects observed in the welds of diamond wires is related to the Heat-Affected Zone (HAZ). A well-defined line can be noticed, marking the beginning of recrystallization zone, and delineating the HAZ. In the welded diamond wire, the width of this region is determined by the electrode positions, and it is present in all welds. In addition to defining the path of the current, the electrodes absorb a significant portion of the convective heat transferred to the region of the diamond wire beneath them, acting as a barrier. Figure 7 clearly depicts the recrystallization phenomenon.

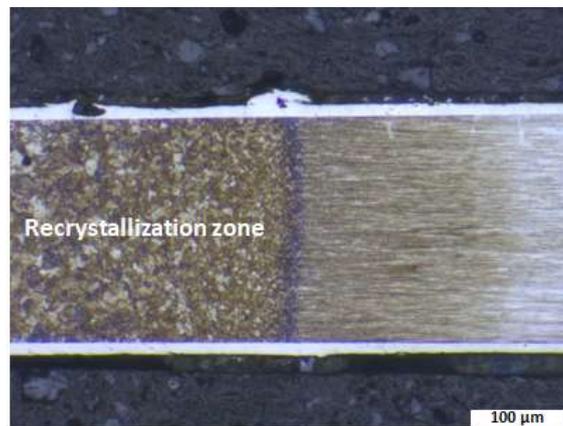


Figure 7. Recrystallization zone.

As discussed previously, the small dimensions of the diamond wire utilized in this study results in a rapid cooling of the material after welding, leading to an excessive hardening of the weld joint through air quenching. Although metallographic and hardness analyses were not performed on non-heat-treated weld joints, a similar effect could be observed in the heat-treated joints when the T4 parameter was set to 30 s, indicating that there was insufficient time for bainitic transformation. Figure 8 shows the microstructure of a heat-treated weld joint obtained from parameter combination B1, clearly demonstrating the prevalence of martensite in both the HAZ and the weld joint. The high hardness of martensite justifies the premature wire breakage observed during the no-load rotation tests.

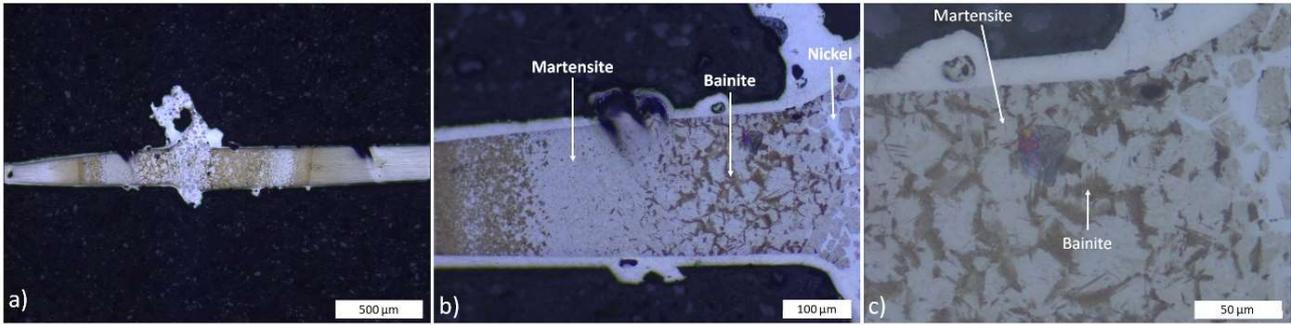


Figure 8. Microstructure of a weld heat treated with T4 = 30 s. a) 50x; b) 200x; c) 500x.

When the heat treatment was carried out with a T4 set to 2 hours, the microstructure exhibited a more uniform appearance, predominantly composed of bainite, as shown in Figure 9. Bainite improves the ductility of the weld joint and, consequently, increases its fatigue resistance.

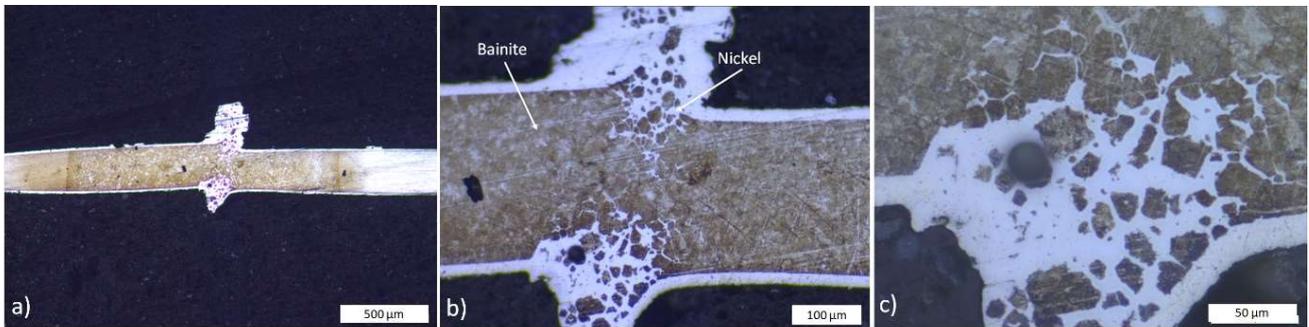


Figure 9. Microstructure of a weld heat treated with T4 = 2 h. a) 50x; b) 200x; c) 500x.

The graphs in Figure 10 depict the hardness profiles of the heat-treated samples using the parameters established in Table 1. In the graphs, it is possible to observe a considerable variation in hardness values and the presence of isolated hard spots for the heat-treated samples using the parameter combinations A1 and B1. This behavior is due to microstructural non-uniformity and the presence of martensite, as shown in Figure 8.

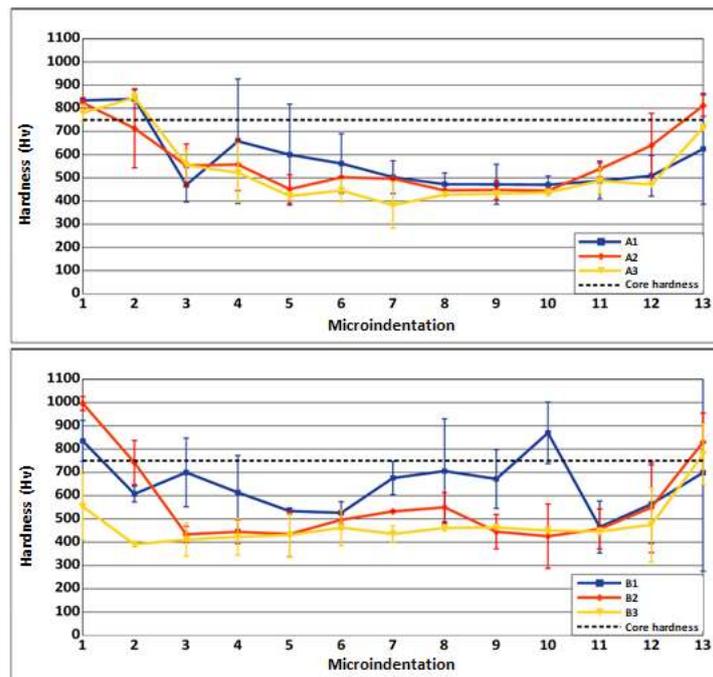


Figure 10. Weld joints hardness profile.

When comparing the hardness profiles of the heat-treated samples with parameter combinations A2 and A3, and B2 and B3, a smaller difference is observed when compared to the hardness profiles of the samples treated with combinations A1 and B1. This fact may lead to the conclusion that the heat treatments with a T4 of 30 minutes yield weld joints with mechanical characteristics like those observed in samples treated with a T4 of 2 hours. However, when the microstructure of the samples treated with a T4 of 30 minutes was analyzed using an optical microscopy, the presence of larger grains near the weld joint was observed, resulting in lower mechanical strength in that region. Figure 11 compares the microstructures of the heat-treated samples with parameter combinations B2 and B3, with T4 of 30 minutes and 2 hours, respectively.

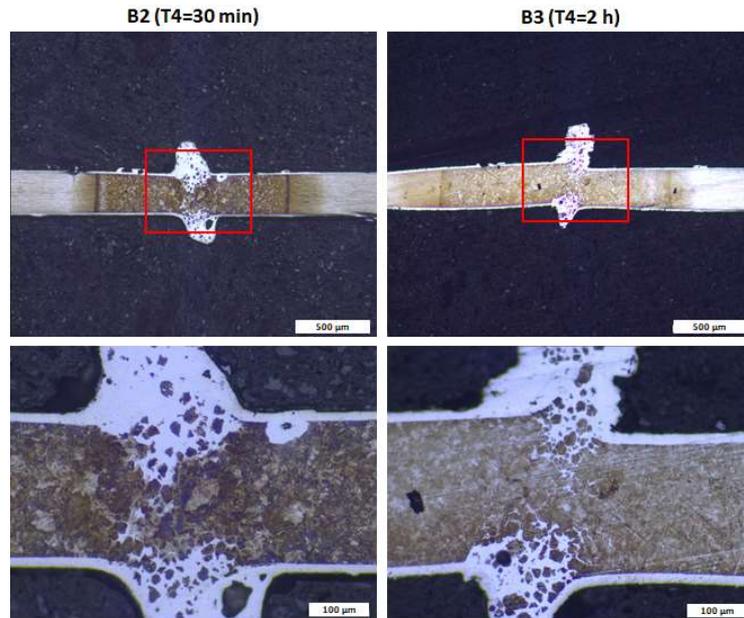


Figure 11. Microstructure of heat-treated samples with B2 and B3 combinations.

This analysis explains the reason why the heat-treated samples from parameter combinations A2 and B2, with a T4 of 30 minutes, showed lowest performance during the no-load rotation tests. Regarding the effect of varying the T3 parameter, no significant differences were observed in the microstructures and performance of the samples during the no-load rotation tests for the tested T3 values. This occurrence was attributed to the proximity of the values used. Therefore, the analyses conducted here focused on the effects generated by the T4 parameter variation.

5. CONCLUSIONS

Based on the results obtained in this research, it is concluded that the welding process reduces the mechanical strength of the diamond wire in two distinct and simultaneous ways: through recrystallization of grains in the HAZ and through the embrittlement of the microstructure due to martensite formation.

As discussed previously, when cold-worked steel is subjected to temperatures above the recrystallization temperature, the stresses induced by cold working are relieved, and the grains return to their original shapes. This phenomenon causes a loss of mechanical strength, and it can only be recovered by cold working the material again, which is not feasible in this case.

Nevertheless, the experiments have shown that it is possible to control the weld microstructure through post-welding heat treatment using the principle of heating by Joule effect and, thereby, avoid the formation of martensite microstructure.

Regarding the experimented heat treatments, it is concluded that, under these conditions, the T4 parameter, which corresponds to the decay time of the thermal treatment current C2 to zero, had the greatest influence on the microstructure formation, and a time of 2 hours was sufficient to bainitic transformation. Furthermore, it was found that the microstructure obtained at the end of the heat treatment exhibited uniformity.

Although the objective of this work has been achieved, the total time spent on manufacturing a loop diamond wire is relatively long due to the heat treatment. It is believed that it is possible to reduce this time by adjusting the temperature of the heat treatment. However, measuring the temperature of the weld joint is a non-trivial task due to the small dimensions of the wire, access to the spot, and limitations imposed by the welding temperature measurement equipment, making the correlation between the current and temperature a complex activity.

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