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SUSTAINABLE FABRICATION OF SOLID-WIRE ELECTRIC CONTACTS: ULTRASONIC WELDING VS. SOLDERING

ODRŽIVA PROIZVODNJA ELEKTRIČNIH SPOJEVA OD PUNE ŽICE: ULTRAZVUČNO ZAVARIVANJE NASPRAM LEMLJENJA

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Abstract

Sustainable joining technologies are important manufacturing processes for the production of high-quality joints of electrical connections. High-quality connections must have high electrical and thermal conductivity to reduce energy losses during their lifetime, they must have high mechanical properties to achieve a long service life, and they must be manufactured with lower energy consumption. In this article, the properties of solid wire electrical contacts produced by ultrasonic welding and soldering were compared. Ultrasonic welding of thin solid copper wires was performed with a copper ring. A particular focus of this study is on the energy used to produce these joints. The research included electrical resistance, peel strength and

Rezime

Održive tehnologije spajanja važni su proizvodni procesi za proizvodnju visokokvalitetnih električnih spojeva. Visokokvalitetni električni spojevi moraju imati visoku električnu i toplotnu provodljivost kako bi se smanjili gubici energije tokom životnog veka, moraju imati visoka mehanička svojstva da bi postigli dug vek trajanja i moraju biti proizvedeni sa što manjom potrošnjom energije. U ovom radu, podređena su svojstva punih žičanih električnih spojeva proizvedenih ultrazvučnim zavarivanjem i lemljenjem. Ultrazvučno zavarivanje punih bakrenih žica izvedeno je sa bakarnim prstenom. Poseban fokus ove studije je na potrošenoj energiji koja se koristi za proizvodnju ovih spojeva. Istraživanje je uključivalo ispitivanje električne otpornosti, te

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tensile strength tests. The results of the electrical resistance showed similar electrical resistance between the two processes. The result of mechanical strength shows that ultrasonic joints achieved higher mechanical strength. The most important result is that ultrasonic welding consumed only 11% of the energy to produce the joint compared to soldered joints.

ispitivanje nosivosti na ljuštenje i zatezanje. Rezultati električnog otpora pokazali su sličan električni otpor između dva procesa. Kada je riječ onosivosti rezultati pokazuje da su ultrazvučni spojevi postigli veću mehaničku nosivost. Najvažniji rezultat je da je ultrazvučno zavarivanje potrošilo samo 11% energije za proizvodnju spoja u odnosu na zalemljene spojeve.

1. Introduction

The current global trend is electrification and automation in all areas. This means that the production of electric motors is increasing because they are becoming more and more present in our everyday lives. As production increases, so does the energy consumption involved in their production. One of the most important processes in the production of electric motors is the joining of copper wires with conductors and contacts. To be used effectively, these wires must be connected to electrical conductors or contacts that offer mechanical strength, vibration resistance, temperature resistance and high conductivity. Engineers must select suitable joining technologies, considering the load conditions, service life, manufacturability and sustainability, as each joining method has its advantages and disadvantages. Common technologies for joining wires to conductors or contacts include electrical resistance welding, soldering, crimping and welding with mechanical energy [1]. In this article, we will focus on soldering and ultrasonic welding, their sustainability and the quality of the resulting joint.

Soldering, which uses heating methods such as oxyfuel, electrical resistance, induction and laser [2], is versatile and joins wires and conductors with different cross-sections without process changes. The quality depends on an optimized joining gap, overlap, cleanliness, uniform temperature and stability of the factors. This results in large joints with low electrical resistance and high strength, but is prone to corrosion [3-6] and microstructural changes [3,7,8]. High potential differences and different compositions between the wire and the filler material can lead to deterioration [9]. Filler materials often contain toxic lead [10], and silver solder, which is commonly used with copper, is expensive and a critical raw material [11].

Ultrasonic welding (UW) is a promising technology for joining wires and braids without filler material by converting electrical energy into high-frequency mechanical vibrations to create a metallurgical bond [12]. With UW, different wire cross-sections can be welded with a single tool, ensuring excellent thermal and electrical conductivity without melting the base materials [2]. However, the strength of ultrasonic joints is sensitive to peel strength, especially in wire welding. Reinforcing elements such as rings can increase the strength of the joint, especially for wires with smaller diameters [13-15]. Increased welding time or energy can lead to material thinning and lower joint strength as the sonotrode penetrates deeper [16-19].

Logar et al. [19] have analysed both processes in detail. The results show that the thermal shock test does not affect the quality of the connections. They also showed that the electrical conductivity of both methods is comparable and that UW joints with a ring can withstand higher loads than soldered joints.

While research confirms the suitability of both methods, there are no studies on their sustainability and energy consumption. Since the early 2000s, the term 'sustainability' has become increasingly important due to the growing need to protect the environment and its resources. The industrial sector currently accounts for 25% of energy consumption in Europe [20], emphasizing the need for sustainable techniques to reduce resource consumption and promote environmentally friendly production.

2. Materials and methodes

2.1 Materials and preparation of samples for welding and soldering

The sketch of the specimens prepared for welding and soldering is shown in Figure 1. A 0.71 mm diameter wire of C11000 copper was used for experimental welding. The wire was coated with two different coatings, one over the other, the first being polyester and the second polyamide-imide. The coating itself can withstand 200 °C [21].

Before preparing the welds, the coatings were removed with a special preparation of Abiofix, which has 3 hard blades on the cutting head. By rotating the head, the blades close and grind the coating off the wires.

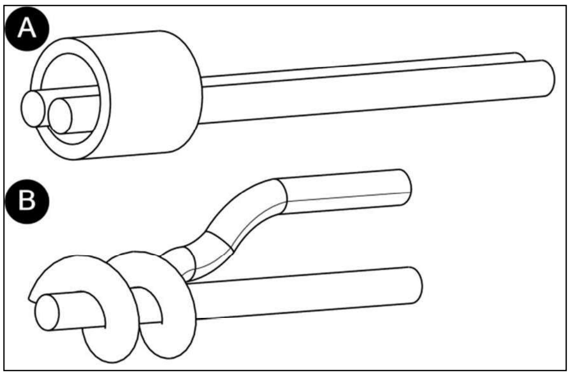

Figure 1. *A sketch of sample wires ultrasonic welding (A) and for soldering (B)*

Slika 1. *Skica žica za ultrazvučno zavarivanje (A) i za lemljenje (B)*

The wires for ultrasonic welding were putt inside the ring (Figure 1A). The dimensions of the ring used for the UW were an inner diameter of 2 mm, an outer diameter of 3 mm and a length of 4 mm.

The copper wires for soldering (Figure 1B) were prepared by wrapping the wires. The solder used was BrazeTec S 15, which contains 15% Ag and 5% P [22]. The detailed mechanical properties of C11000 copper and solder BrazeTec S 15 are listed in Table 1.

Table 1. *The physical properties of copper C11000 wires [23] and solder BrazeTec S 15 [22]*

Tabela 1. *Fizička svojstva bakarnih žica C11000 wires [23] i lema BrazeTec S 15 [22]*

Properties	C11000	BrazeTec S 15
Melting range [°C]	1083	645-800
Density [g/cm^3]	8.89	8.4
Tensile strength [MPa]	380	250 with Cu
Elongation [%]	1.1	10
Electrical conductivity [m/Ωmm^2]	57 - 59	7
Operating temp. of brazed joint [°C]	-	150

2.2 Soldering and Ultrasonic welding of prepared wires

The experimental joining of the wires was made by soldering and ultrasonic welding. Soldering was performed using an Oswlad gas generator. The generated gas (hydrogen and oxygen) produces a neutral flame that develops a temperature of about 3650 °C and can be used for welding, brazing, or soldering of all nonferrous materials in a short time [24].

In our case, we first preheated the wires for 10 seconds and then solder them after they reached about 450 °C. Ultrasonic welding was performed using the Branson GMX-W1 ultrasonic wire splicer.

This is a fully automatic ultrasonic wire splicing system can make connections with a cross-section of 0.06 mm^2 to 32 mm².

All joints were made by 'Welding To Energy', which means that the main triggering parameter is the energy required to form a joint, which was kept constant for all tests, allowing the time to be adjusted to suit the condition of the materials during welding. Experimental welding parameters are shown in the Table 2.

Table 2. *Experimental welding parameters*

Tabela 2. *Eksperimentalni parametri zavarivanja*

Parameters	Value
Energy [J]	140
Pressure before and during welding [bar]	1.38
Amplitude [μm]	20
Jaw width [mm]	4.46

2.3 Measurement of energy consumption

The power consumption was measured with Metrel Power Q4. The Metrel PowerQ4 is a sophisticated network diagnostic tool designed to analyze and troubleshoot power quality issues in electrical networks. Since the Branson GMX-W1 ultrasonic wire splicer operates on single-phase current, while the Osweld gas generator for soldering operates on three-phase current, we performed the measurements in two different ways. The Branson GMX-W1 ultrasonic wire splicer was measured using the 1-phase 3-wire system, schematically shown in Figure 2A, and the Osweld gas generator was measured using the 3-phase 4-wire system, schematically shown in Figure 2B. Energy consumption together with losses was measured on 10 welding samples for each process.

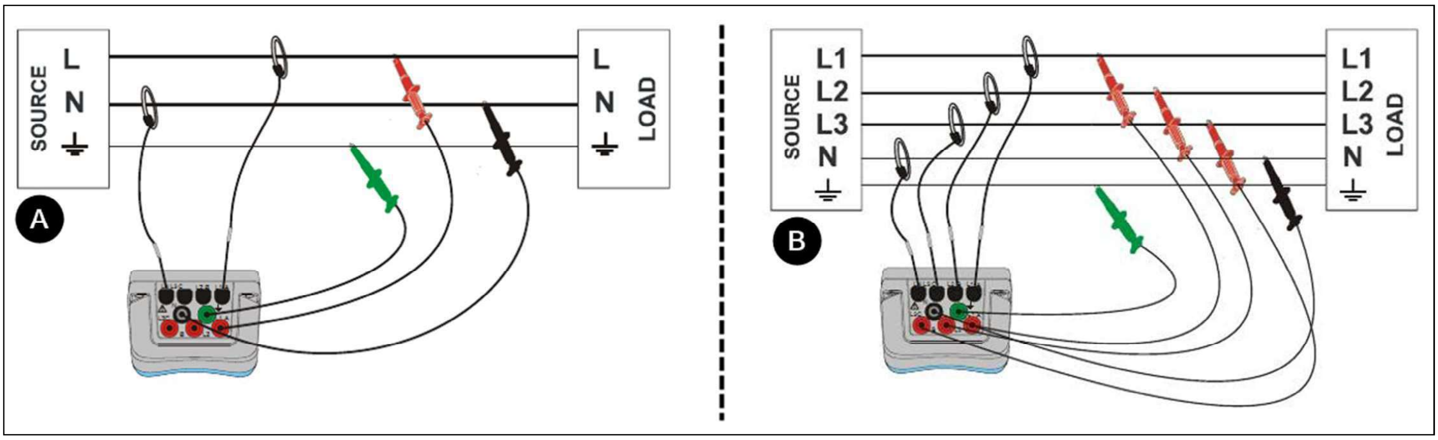

Figure 2. *Measurement of energy consumption: ultrasonic welding with 1-phase 3-wire system (A) and soldering with 3-phase 4-wire system (B) [25]*

Slika 2. *Merenje potrošnje energije: ultrazvučno zavarivanje sa 1-faznim 3-žičnim sistemom (A) I lemljenje sa 3-faznim 4- žičnim sistemom (B) [25]*

2.4 Measurement of electrical resistance

Electrical resistance measurements were performed on 10 UW samples and 10 soldered samples (Figure 3) using the Keysight 34420A nano-volt/micro-ohm meter. The 4-wire resistance measurement was used because of the lower resistance values, since this method eliminates the resistance of the meter contacts. Prior to testing, the wires were also grind at the gage attachment point. The connection clamps were placed/installed 3 mm from the weld or solder joint on each side of the connection. Each sample was measured 3 times. The average of all three measurements was considered. The results were recorded at the microohm level.

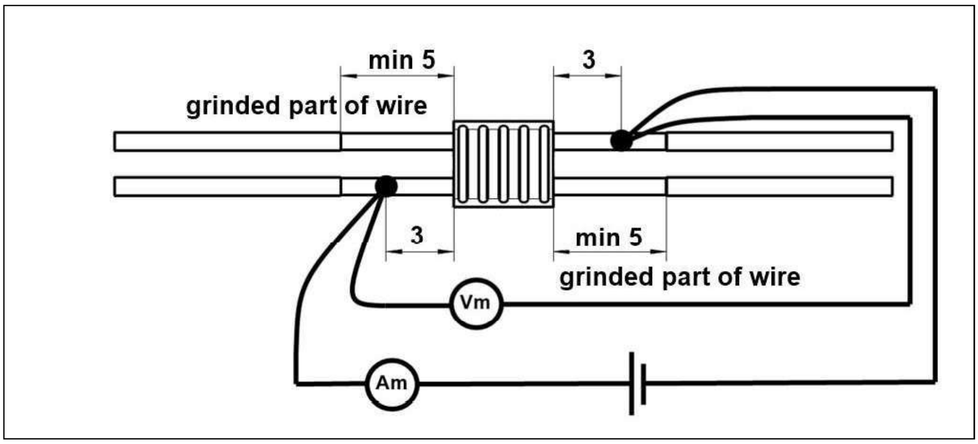

Figure 3. *Display of contact layout for electrical resistance measurement on the example of a UW joint*

Slika 3. *Prikaz rasporeda kontakata za merenje električnog otpora na primeru UV spojnice*

2.5 Mechanical testing of joints

Tensile strength tests and peel force tests were performed in accordance with MAN Truck & Bus AG WORKS Standard M 3455 [26]. The Zwick Z150 universal tensile testing machine with the KAP-S 2 kN load cell was used to perform both tests. The tests were performed using Zwick TestExpert II software. Both tests were done with the pulling speed of 50 (+5) mm/min. The samples were gripped in grips specially developed for testing of wires and cables. Peel force testing was performed on 10 UW samples and 10 soldered samples (Figure 4A), while tensile testing was performed on 5 UW samples and 5 soldered samples (Figure 4B).

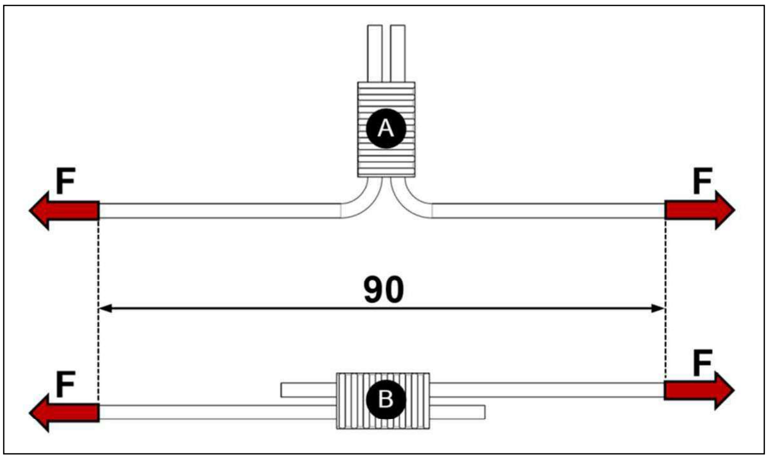

Figure 4. *Mechanical test: peel force test (A), tensile strength test (B)*

Slika 4. *Mehanički ispitivanja: sile ljuštenja (A), zatezne čvrstoće (B)*

3. Results and discussion

In the comparative analysis of energy consumption between ultrasonic welding and soldering it was found that the energy consumption for ultrasonic welding was 1413.8 J ± 110.25 J and for soldering was 20482.5 J ± 1590.28 J. Ultrasonic welding demonstrates a significantly higher efficiency, consuming around 14 times less energy than soldering. It can be also seen from standard deviations, that human intervention in manual soldering has a more significant impact on the soldering process compared to ultrasonic welding. In Figure 5 A, it can be seen that 62787 J of energy was used for the three referenced soldered joints, while only 6085.5 J of energy was used for the three referenced ultrasonically welded joints. It can also be seen (Figure 5 B) that the peak power for ultrasonic welding was 564 W ± 34.67 W, while for soldering was 1968 W ± 50.34 W, which is 3.5 times higher. Additionally, the time needed to make three joints is 2.4 times shorter for ultrasonic welding (18 s vs. 44 s) compared to soldering. This substantial difference highlights the potential for energy savings and efficiency improvements through the adoption of ultrasonic welding in relevant applications.

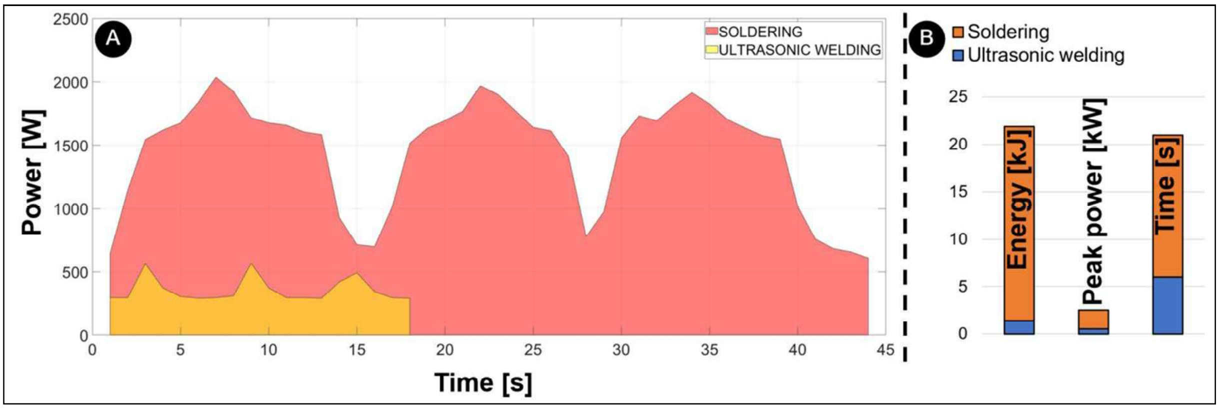

Figure 5. *Power consumption for three ultrasonic reference joints (yellow) and three solder reference joints (red) (A) and a comparison of energy, peak power and time per weld for soldering (orange) and ultrasonic welding (blue) (B)*

Slika 5. *Potrošnja energije za tri ultrazvučna referentna spoja (žuta) i tri referentna spoja za lemljenje (crvena) (A) i poređenje energije, snage i vremena po zavaru za lemljenje (narandžasto) i ultrazvučno zavarivanje (plavo) (B)*

3.1 Measurement of electrical resistance

Figure 5 shows a Box-Whiskers diagram comparing the electrical resistance between UW joints, soldered joints and wire. The electrical resistance of UW samples was 989 μΩ ± 18 μΩ, and electrical resistance of soldered samples was 871 μΩ ± 14 μΩ. The electrical resistance of wire was 976 μΩ ± 14.5 μΩ. Through the mean values, it can be seen, that the results are in the same range. It is logical that the electrical resistances of the different joining methods are not the same, because the cross section of the joint has a great influence on the electrical resistance. It can also be seen that the electrical resistance of the wire and the UW joint were almost the same. So, it can be said that the ring does not have a big effect, but the amount of solder on the soldered joint does. A comparable study was conducted using both an ultrasonic and a soldered joint with 3 wires. The results revealed opposite that the electrical resistance of the ultrasonicaly welded joint was 28% lower [19].

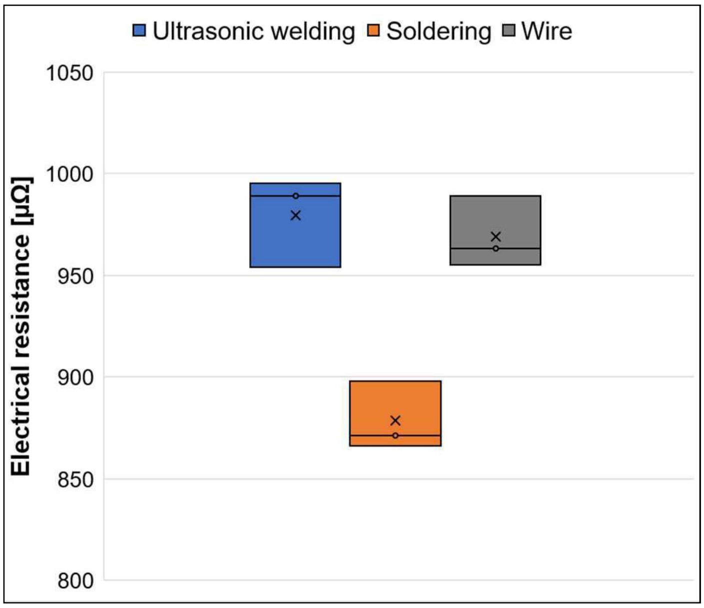

Figure 6. *Comparison of electrical resistance between the UW joints (blue), soldered joints (orange), and wire (grey)*

Slika 6. *Poređenje električnog otpora između UV spojeva (plavo), lemljenih spojeva (narandžasto) i žice (sivo)*

3.2 Mechanical testing of joints

Figure 7 shows a comparison of the peel strength of UW and soldered joints. The peel strength of UW samples was 88.8 N ± 0.35 N, and the peel strength of soldered samples was 38.5 N ± 1.2 N. From the comparison of UW welding and soldering, it can be seen that stronger joints are obtained with UW welding. A comparable study was conducted using both an ultrasonic and a soldered joint with 3 wires. The results point in the same direction, whereby it was found that the ultrasonicaly welded joint had a 42% higher peel strength [19].

Figure 7. *Comparison of peel force between UW joints (blue) and soldered joints (orange)*

Slika 7. *Poređenje sile ljuštenja između UV spojeva (plavo) i zalemljenih spojeva (narandžasto).*

Figure 8 shows results of tensile strength test. The tensile strength of UW samples was 97.5 N ± 2.1 N, and the tensile strength of soldered samples was 91.3 N ± 1 N. Tensile strength of wire was 109.5 N ± 0.9 N. UW joints have higher tensile properties compared to soldered joints. From the fractures can be also seen that UW joints don't break in the joint but in the area where gripper was attached. A comparable study was conducted using both an ultrasonic and a soldered joint with 3 wires. The results point in the same direction. It was found that the ultrasonicaly welded joint had a 12% higher tensile strength [19].

Figure 8. *Comparison of tensile force between UW joints (blue), soldered joints (orange) and wire (grey)*

Slika 8. *Poređenje zatezne sile između UV spojeva (plavo), lemljenih spojeva (narandžasto) i žice (sivo)*

5. Conclusions

This paper presents a comparative analysis of ultrasonic welding and the soldering of two thin copper wires with ring. The evaluation included the measurement of energy consumption, measurement of electrical resistance, peel strength testing, and tensile strength testing. The study led to the following conclusions:

1. Ultrasonic welding is significantly more energy-efficient and time-efficient compared to soldering, consuming 10-15 times less energy and taking 2-3 times less time to create joints. These advantages, coupled with greater consistency, process stability and reduced human influence, make ultrasonic welding a superior choice for relevant applications.
2. The electrical resistance of ultrasonically welded and soldered joints are similar. However, the soldered joints have a higher electrical conductivity, which is an effect of the amount of solder that is added by hand.

5. Zaključak

U radu je data komparativna analiza ultrazvučnog zavarivanja i lemljenja dve tanke bakarne žice sa prstenom. Evaluacija je uključivala merenje potrošnje energije, merenje električnog otpora, ispitivanje čvrstoće na ljuštenje i ispitivanje zatezne čvrstoće. Studija je dovela do sledećih zaključaka:

1. Ultrazvučno zavarivanje je znatno energetski efikasnije i vremenski efikasnije u poređenju sa lemljenjem, troši 10-15 puta manje energije i oduzima 2-3 puta manje vremena za stvaranje spojeva. Ove prednosti, zajedno sa većom konzistentnošću, stabilnošću procesa i smanjenim ljudskim uticajem, čine ultrazvučno zavarivanje superiornim izborom za relevantne primene.
2. Električni otpor ultrazvučno zavarenih i zalemljenih spojeva je sličan. Međutim, zalemljeni spojevi imaju veću električnu provodljivost, što je posledica količine lema koji se dodaje ručno.

3. Mechanical testing shows that ultrasonic welding produces more resilient joints compared to manual soldering, with more consistent results, highlighting the benefits of automation.

To summarize, ultrasonic welding offers significant advantages over soldering, being more energy-efficient and faster in creating joints, with greater consistency and reduced human influence. While the electrical resistances of both methods are comparable mechanical testing confirms that ultrasonic welding produces more resilient and consistent joints, underscoring the benefits of automation.

3. Mehanička ispitivanja pokazuju da ultrazvučno zavarivanje proizvodi otpornije spojeve u poređenju sa ručnim lemljenjem, sa konzistentnijim rezultatima, naglašavajući prednosti automatizacije.

Ukratko, ultrazvučno zavarivanje nudi značajne prednosti u odnosu na lemljenje, jer je energetski efikasnije i brže u stvaranju spojeva, sa većom konzistentnošću i smanjenim ljudskim uticajem. Dok su električni otpori obe metode uporedivi, mehaničko testiranje potvrđuje da ultrazvučno zavarivanje proizvodi elastičnije i konzistentnije spojeve, naglašavajući prednosti automatizacije.

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