Single-turn Coils for Magnetic Pulse Welding of High-strength Steel Parts

V. I. Krutikov*, S. N. Paranin, A. V. Spirin, E. Yu. Zaytsev

Institute of Electrophysics of the Ural Branch of the Russian Academy of Sciences, Yekaterinburg, Russia
*Corresponding author. Email: krutikov@iep.uran.ru

Abstract

Magnetic pulse welding provides high quality joining of fuel pin cladding for fast nuclear reactors. The tool coil there operates under the most stressful conditions: 40 T magnetic fields with tens of microseconds duration. This requires minimal coil inductance and affects the capabilities and lifetime of the coils. Two approaches are being practiced to enhance the coil durability: material research and construction optimization. The first approach considers the use of high strength steels or composite materials for the coil working area. The present work is aimed to realize the second approach – the use of multi-position coils in order to maximize the number of parts welded in one coil.

Experiments and finite element modeling were carried out for two designs of two- and four-position single-turn coils, which were made to process several workpieces in one current pulse. The main parameters measured and calculated were the magnetic field between the coil and the workpiece, and the ratio of its amplitude to the discharge current, B_m/I_m. *The currents flowing through the coils were about 700 kA, which correspond to the magnetic fields of 40–45 T. The FEM modeling revealed a 17–19% drop of the magnetic induction near the insulated slit, which, however, did not prevent the helium-tight joining of the tubes to the end plugs.*

Keywords

Electromagnetic forming, Magnetic pulse welding, Coil design, Multi-position coil

1 Introduction

Magnetic pulse welding (MPW) is a technique which is capable of joining similar or dissimilar materials in solid state (Kapil & Sharma, 2015). It is a kind of impact welding which employs a high magnetic field to accelerate one joining part (the flyer) against another (the target). It is already used in industry for joining electrical (PSTproducts, 2021a), automotive (Khalil et al., 2020) and other components. In terms of the size scale of the joining parts, MPW takes an intermediate position between the explosive welding and laser spot impact welding (Wang & Wang, 2019), and its process parameters can be controlled with more accuracy than for explosive welding. MPW is used for rather small parts of several tens of millimeters in size. It usually operates with high pulsed magnetic fields of 10−20 T in amplitude at frequencies of 5−100 kHz. Copper and aluminum are the best flyer materials for MPW due to their high conductivity and good deformability. In order to join steel or other materials with high resistivity by MPW a driver shell of copper or aluminum should be used.

MPW gives high quality joining of small parts of high-strength steel like fuel pin end closures for fast nuclear reactors (Brown et al., 1978; Lee et al., 2015; McGinley, 2010). Further industrial application requires sustainable tool coils, which can operate at 40 T magnetic fields and more than 30 kHz discharge frequencies. Thus, the tool coil should have high strength and low inductance as well. Single turn coils made of hardened steel meet these requirements, however, their sustainability should be improved as much as possible. Magnetic "saw effect" or simply saw effect is the typical failure mechanism of the tool coils for high magnetic fields. (Adamyan et al., 2018; Saadouki et al., 2018).

The resource of the inductor may be expressed in the number of processed parts. The first way to increase this number is the research on more strong and durable coil materials such as structural steel which may be plated by CuCrZr alloy (Gies & Tekkaya, 2018) or CuNb composite material. Conventional copper and bronze coils have rather short lifetime at 50-60 T magnetic fields (Sharma et al., 2018). The second way is to use tool coils which are capable of processing several workpieces during one current pulse such as multiple joining coils (PSTproducts, 2021b) or multi-position field shapers (Belyy et al., 1977).

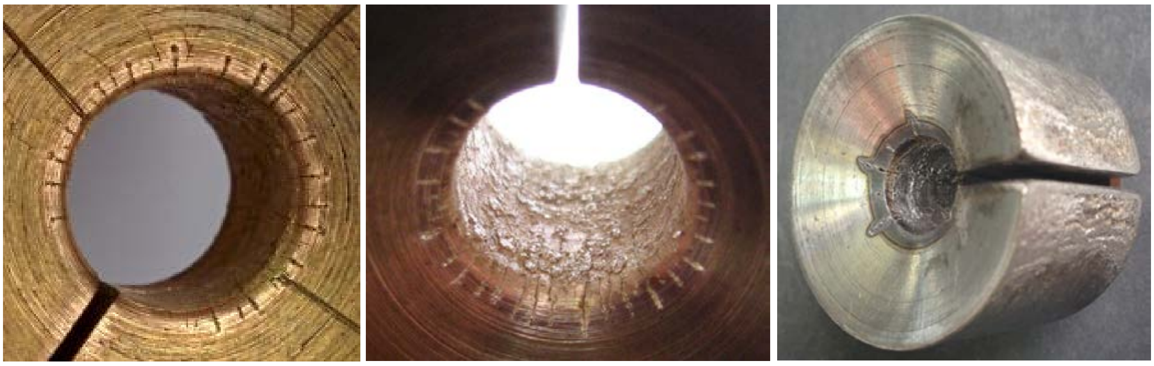
The present paper summarizes the experience on the use of two-position single-turn steel coil for magnetic pulse welding of small high-strength steel workpieces and proposes a four-position coil with predictable magnetic field distribution.

2 Experimental

2.1 Coils application and material and the single position coils

All of the coils in the present work were designed as a load of a low-inductive pulse current generator with 430 μF capacity and 25 kV maximum charge voltage. The generator itself had an inductance of 15 nH. The workpieces were close in size to fuel pins of a nuclear reactor. Magnetic pulse welding of such parts is described in detail in (Krutikov et al., 2014; Lee et al., 2015). The tubes were 7 mm in outer diameter and 0.6 mm in wall thickness. Copper driver tubes of 8 mm in outer diameter with 0.5 mm wall thickness slipped over the end of the tube prior to welding. Thus, the dimensions of the coil working bore were determined as 9 mm in diameter and 12 mm in length. According to previous MPW experience, the coil has to withstand the repeated generation of fields with an amplitude of 40 T.

The first attempt was taken with one of the conventional inductor materials, beryllium bronze or beryllium copper (CuBe2), as can be seen in **Fig. 1a, b.** Unfortunately, beryllium bronze coils noticeably degraded after a few pulses of a 40 T field. Based on some calculations and experience of use, structural steel 30KhGS (0,3% C, 1% Si, 1% Mn) was chosen for the single-turn coils. In the experiments it was capable of passing a few tens of such pulses before degradation by saw effect cracking (Fig. 1c). The use of this and other steels as a field shaper material is described in (Spirin et al., 2017).



a) b) c)

Figure 1: *The coil of beryllium bronze after 5 (a) and 10 (b) pulses of 40 T magnetic field; the coil of hardened 30KhGS steel after 30 pulses of 40 T magnetic field (c)*

2.2 Multi-position coils

2.2.1 Two-position, three-bore coil

In an attempt to increase the productivity of the MPW process, a multi-position single-turn inductor was designed and made of hardened 30KhGS structural steel. It had three insulated bores (**Fig. 2**) so this inductor was supposed to weld three samples simultaneously, however, only two side bores were used for welding, since, in the middle bore, the amplitude of the magnetic field was lower. The assumed path of current flow (Fig. 2a) has the minimal resistance and inductance.

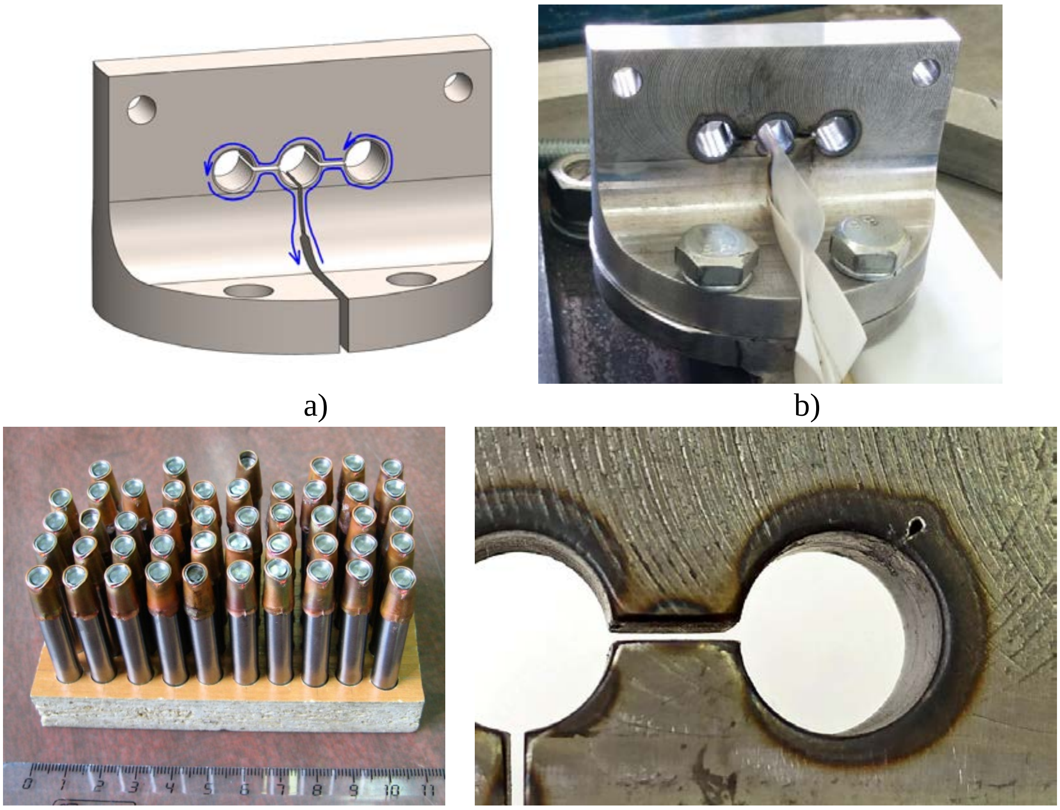


***Figure 2**: The inductor with three bores: a sketch with an assumed current path (a); external appearance of the coil connected to the generator (b); tubes welded to the end plugs (c); the beginning of the saw effect coil destruction (d)*

This inductor was tested at the full battery capacity (425 µF) at a charging voltage of 3.0 kV. The discharge current and the magnetic field in the inductor bores were recorded with a Rogowsky coil and a pick-up coil, respectively (**Table** 1). The modes for measuring the magnetic field were as follows:

1) an empty side bore;
2) the empty middle bore;
3) a side bore filled with a copper tube (⌀8x0,5x13 mm) fixed on a textolite core;
4) the middle bore filled with the same copper tube.

Mode	**U_0, kV**	**I_m, kA**	**B_m, T**	**T/2, µs**	**B_m/I_m, T/MA**
1	3.00	224	10.7	15.0	48
2	3.00	224	9.1	14.7	41
3	3.00	228	13.4	14.8	59
4	3.00	228	11.9	15.0	52

***Table 1:** Parameters and test results of the 3-bore inductor*

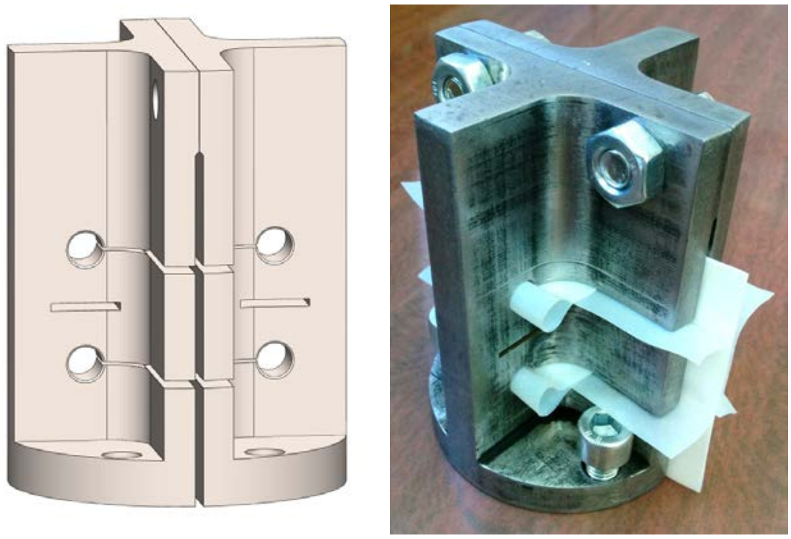
As can be seen from Table 1, the two side bores filled with the copper shell are characterized by a pretty high ratio of field and current amplitudes B_m/I_m = 59 T/MA. Unfortunately, the B_m/I_m ratio was significantly lower in the middle bore, which made it possible to weld only two samples under the same conditions. However, the simultaneous welding of two samples was carried out successfully, which practically doubled the inductor life in terms of the quantity of the processed samples.

In the inductors of this design, specimens of HT-9 ferritic-martensitic steel were helium-tight welded (Lee et al., 2015). The lifetime of one inductor was about 25–35 pulses or 50–70 workpieces (Fig. 2c) with a magnetic field amplitude of about 40 T. The inductor destruction was determined by the saw effect (Fig. 2d), in contrast to the thermal cracking which is common for the bronze coils (Fig.1a, b).

2.2.2 Four-position, four-bore coil

Based on the experience on the three-bore inductor, it was decided to design an inductor with four working bores, to weld four workpieces simultaneously. The new inductor consisted of two halves (**Fig. 3**). Each of the halves was made symmetric, i.e. with vertical and horizontal planes of symmetry in terms of current flow. Each contact between the halves was tightened with two 10 mm bolts. The bottom flange is a contact pad for connecting the coil to the pulse current generator. This design is convenient for connecting the coil to a bifilar line of two current buses. In the contact areas, replaceable copper or aluminum gaskets can be used.

The pulsed current at the frequencies of 30−35 kHz flows mostly in the skin layer of the inner surface of the assembly, including the insulating gap and the inner surface of the cylindrical bores. Horizontal closed slots were made to prevent current from flowing directly between the working bores.



a) b)

Figure 3: *A sketch of the 4-position coil (a) and its appearance (b)*

The discharge current with the magnetic field in one of the bores were recorded within two modes (**Table 2**):

1) in an empty bore;

2) in a bore filled with a fixed copper tube, the same as for the previous coil.

Mode	U_0, kV	I_m, kA	B_m, T	T/2, μs	B_m/I_m, T/MA
1	4.00	260	13.4	17.6	52
2	4.00	261	16.4	17.4	63

Table 2: *Test results of the 4-bore inductor*

This inductor showed a higher ratio of B_m/I_m = 63 T/MA than the previous one. This may be explained by the longer distances on the way of the discharge current which corresponds to a higher inductance on the current way bypassing the working bores. The increase in the coil inductance led to some decrease of the discharge frequency: the current half-period changed from 14.9 to 17.5 μs. This increases the skin-layer of current in copper at room temperature from 0.39 to 0.43 mm which is still sufficient for effective acceleration of the copper driver with 0.5 mm wall thickness.

3 Magnetic field modelling

Due to the fact that steel inductors have successfully shown themselves on welding small cylindrical parts of high-strength steel in the fields of about 40 T, it was decided to investigate them in more detail. The known disadvantages of steel inductors are the low efficiency of converting the total current into the magnetic field in the working bore, and a significant drop in the magnetic field near the insulated slit. FEM modeling was dedicated to discover the azimuthal distribution of the magnetic field in the air gap, as well as the magnetic field diffusion into the copper driver tube and into the inductor steel. Joule heating and mechanical effects were not taken into account at this stage of the work.

The solution of the three-dimensional transient magnetic problem was carried out using the Maxwell 3D module in the Ansys Electronics platform. The parts' sizes matched real inductors, including the inductor-to-generator connection surfaces. Copper driver tube inside the inductor was modeled without the inner steel parts since this tube screens most of the outer magnetic field. The specific resistivity of 45 and 1.72 µOhm*cm for inductor steel and for the workpiece copper, respectively, were taken for the calculation. The specific resistivity of 30KhGS steel was measured by the authors of the present work in (Spirin et al., 2017). The relative permeability µ of both steel and copper was taken as 1 for both materials since the calculation was primarily made for the magnetic fields which are much higher than the magnetization limit of steels. As the tube's collision during MPW occurred in the first current maximum or before it, only the first current half-wave was of interest in the calculations. Therefore, the current was approximated as:

$$i = I_m \cdot \sin(2\pi t/T) \quad (1).$$

The current amplitude was I_m = 700 kA which corresponds to the MPW working value.

Fig. 4 and **Fig. 5** show the magnetic field in the middle section of the inductors at the first current maximum I_m (**Eq. 1**). The calculated B_m/I_m ratios were 65.0 and 65.4 for 2-position and for 4-position coils respectively. The higher calculated B_m/I_m values might be caused by the neglecting of the Joule heating. No significant field diffusion occurred into the workpiece in both cases. The arrows show the directions for the magnetic field distribution plots, illustrated by **Fig. 6**.

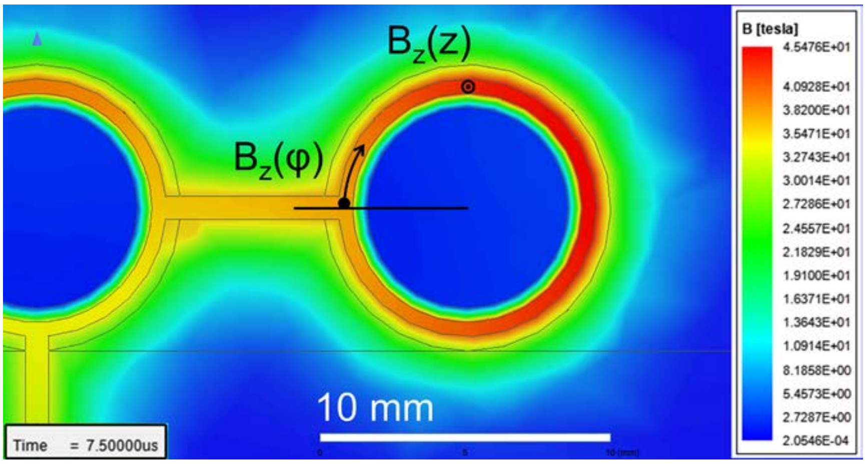


***Figure 4**: Two-position coil: z-component of the magnetic field*

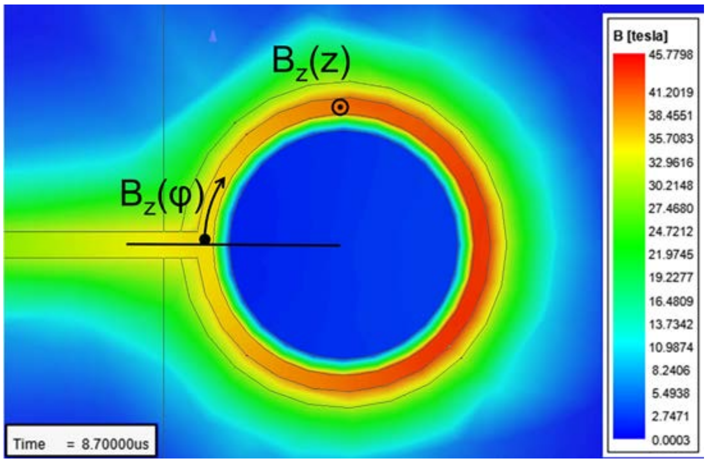


***Figure 5**: Four-position coil: z-component of the magnetic field*

As can be seen from Fig. 6a, the calculated azimuthal non-uniformity of the magnetic field induction was at 17–19% of its maximum value. Nevertheless, the 2-position coil with such characteristics was capable of helium-tight welding of 50 to 70 steel tubes with end plugs which is described in (Lee et al., 2015). The localization of the initial crack (Fig. 2d) coincided with the azimuthal maximum of the calculated magnetic field in the inductor channel (Fig. 6a). The 2-position coil has shown slightly more smooth azimuthal field distribution than the 4-position one. The axial magnetic field dependence (Fig. 6b) is monotonic without peaks at the inductor faces.

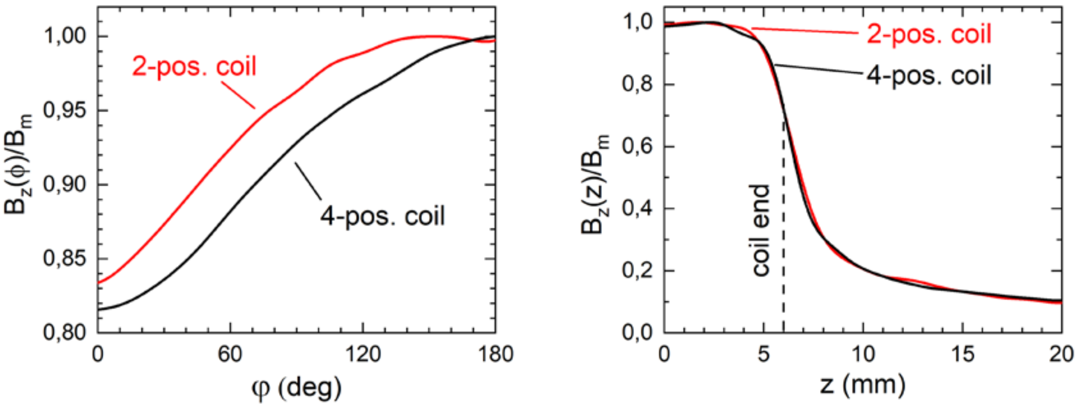


***Figure 6**: Distribution of the z-component of the magnetic field along the azimuthal angle (a) and along the axis (b), corresponding to the arrows in Fig. 4 and Fig. 5*

4 Conclusions

The two-position steel single turn coil has demonstrated its applicability for the magnetic pulse welding of small high-strength steel tubes to the end plugs. The lifetime of one coil was about 50–70 workpieces. Four-position coils which were designed with experience on the former, have shown similar characteristics in magnetic field generation. FEM modeling revealed significant magnetic field non-uniformity on the workpiece circumference, however, the processed tubes were helium-tight welded to the end plugs. Future work will consider coil geometry optimization and more highly conductive alloys or composite materials in order to smooth the non-uniformity of the magnetic field.

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