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Technical Paper

Bitter coil design methodology for electromagnetic pulse metal processing techniques

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ABSTRACT

Electromagnetic pulse metal processing techniques (EPMPT) such as welding, forming and cutting have proven to be an effective solution to specific manufacturing problems. A high pulse magnetic field coil is a critical part of these technologies and its design is a challenging task. This paper describes a Bitter coil design using a newly developed methodology for a simplified analytical calculation of the coil and complementary finite element models (FE) of different complexity. Based on the methodology a Belgian Welding Institute (BWI) Bitter coil has been designed and tested by means of short circuit experiments, impedance and B-field measurements. A good agreement between the calculated and the experimental design parameters was found.

1. Introduction

In a certain range of thicknesses and materials combinations EPMPT are more competitive than of the same name conventional manufacturing methods. However a wide industrial use of the technologies is limited, partly due to a lack of compact engineering guidelines for a coil design. The main purpose of the present work is to develop such guidelines for a pulsed Bitter coil.

Different types of coils categorized by Furth et al. [2] can be used for EPMPT. On the basis of an analysis of manufacturing techniques, principal design solutions and performance characteristics of the above-named coils described by Lagutin and Ozhogin [10] one can conclude that within tubular applications the Bitter coils have high reliability, manufacturability and maintainability. These are the key characteristics for an industrial implementation of the coils and factors which defined our choice to develop the calculation methodology for them. The coil is an assembly of the alternating conducting and insulating discs, each with a radial slit as shown in Fig. 1. The contact between the disks is realized due to their overlap.

The Bitter coils can be used with fieldshapers (FS). Unfortunately a joint analytical treatment of the coil and a FS is hugely limited. However the FS can be partially taken into account, but in order to be brief in this article we are focused on the calculation methodology for the direct acting Bitter coil.

The coil design is a complex task and mainly includes the determination of appropriate coil materials, sizes, the electromagnetic parameters such as an inductance, a resistance and the B-field as well as thermal and stress loadings. Most publications dedicated to the high magnetic coil design deal with pulsed coils having constant current density distribution which is according to Kratz and Wyder [9] approximately realized in multi-layer multi-turn coils. Some of the relevant publications within the constant current density coils design are represented below. Wood et al. [18] proposed an approach to a material selection for such a coil. Knoepfel [8] suggested a methodology to calculate main electromagnetic parameters of the coil: the inductance, the resistance and the central field. Similar methodology to find the main design parameters of the coil and its strength was proposed by Dransfeld et al. [1]. A relatively precise and complete design of the coil can be fulfilled in software developed by Vanacken et al. [16].

The pulsed Bitter coils have the current density distribution which is approximately in inverse proportion to the inner radius and therefore the above-mentioned publications become irrelevant in the present case. Nevertheless methods of finding single design parameters of the pulsed Bitter coils are found in specialized literature. For example, the inductance of the Bitter coil can be calculated using a method proposed by Grover [5]. Knoepfel [8] suggested a formula to find the central field of the coil. Moreover, the most comprehensive physical and mathematical interpretations of the general design principles and different calculation techniques of

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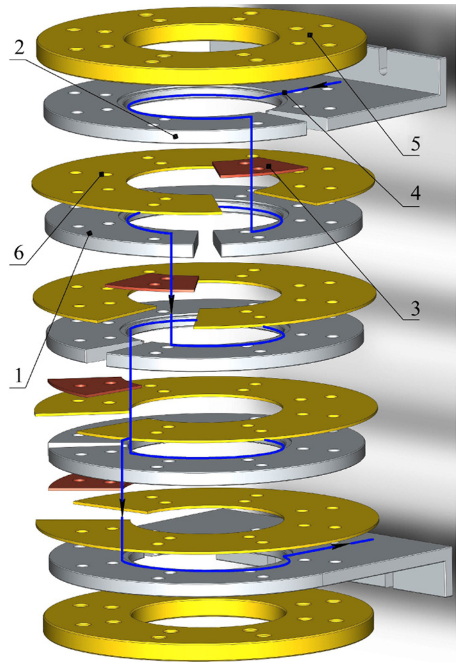

Fig. 1. A principal construction of the Bitter coil: 1 – Bitter plate, 2 – connecting lead, 3 – contact, 4 – current path, 5 – flange, 6 – insulator.

the design parameters of the pulsed Bitter coils are given by Kratz and Wyder [9].

Despite a sufficient, mainly academically orientated theoretical knowledge on the pulsed Bitter coils design, a simplified but complete industrial design methodology does not exist. The fact has prompted us to rework a thorough academic approach into a compact, industry-friendly methodology of the analytical calculation of the pulsed Bitter coil. This has been done by analysing an applicability of theoretical models describing electromagnetic, strength and thermal parameters of the coil and adjusting them to the present coil embodiment. A principal novelty of the methodology is that every design parameter is modified by asymmetry factors reflecting real geometry of the coil. An implementation of the asymmetry factors and a frequency-dependent resistance has improved precision of the methodology. Moreover several supporting FE models have been developed aiming to partly verify the analytical approach and to get a deeper insight into the design parameters. As it will be shown further the methodology of the analytical calculation is an effective tool for defining the main design parameters. Furthermore each step of the methodology can be fulfilled on a paper. Finally short circuit experiments, impedance and B-field measurements have been used for a verification purpose. A list of the symbols used in this article and the corresponding meanings is represented in Table 1.

2. Methodology of the analytical calculation

The analytical approach can only be applied to the coil having cylindrical symmetry, which means that there is no change in geometry when rotating about one axis, and when magnetoresistance phenomenon, eddy currents, plastic deformations and thermal stresses are neglected. Additionally the field at each instant of time is calculated as the static field of the coil with a certain current density. With the limitations stated above the methodology can be schematically represented in Fig. 2.

The present scheme assumes an approach to the coil design provided that the demanded magnetic field in the gap coil-WP, its rise time, WP geometry and parameters of the pulse generator are known. Ideally the field distribution law in the gap coil-WP must be specified based on demands of an application. A step-by-step explanation of the scheme is represented below.

Initial data for calculation:

1. Demanded parameters of the field: an amplitude magnetic field in the centre of the gap coil-WP B_{max} and the rise time of the field τ are given.
2. A WP geometry characterized by an outer radius r_0, a wall thickness Δr and a work area length Δl as well as WP material properties represented by the conductivity σ, the heat conductivity λ, the specific heat capacity c, the yield strength σ_y and the mass density ρ_m are known.
3. Pulse generator data such as the storable energy W, the maximum current amplitude I_0, the short circuit frequency f_0, the inductance L_i and the resistance R_i are convenient to know for a simulation of a current pulse but this information is not obligatory and can be specified later during the design process.

Material assignment. An insulating material represented by allowable working temperatures, dielectric and ultimate compression strengths, and a coil material described by the conductivity σ, the heat conductivity λ, the specific heat capacity c, the ultimate tensile strength σ_{UTS} and allowable working temperatures initial T_i and final T_f must be defined.

Maximum field in the gap coil-WP. It is known that the maximum achievable field in the gap coil-WP (FS-WP) must be at least 40 Tesla and the rise time must not exceed 25 μs for the most of welding applications. Using an efficiency coefficient introduced by Wilson and Srivastava [17] one can connect the fields in the gaps coil-FS and FS-WP.

Coil geometry value assignment. An inner radius r_1 is defined by the WP outer radius r_0 and an insulation gap g which is typically 0.75–1.5 mm, a nominal length of the coil l_0 is determined by the work area length of the WP Δl, while an outer radius r_2, thicknesses of a turn Δ and the insulation between the turns h, as well as the asymmetry parameters φ, ψ, γ of the turns can be defined using the parameters of the existing prototypes or arbitrarily. Finally a nominal number of turns N can be estimated.

Auxiliary calculations. These are calculations of two form-factors of the coil α and β reflecting relations between the sizes of the coil, an "effective" number of turns η allowing to transform the asymmetrical real to the ideally symmetrical coil, the skin depth characterizing an attenuation of electromagnetic waves in a conductor, the demanded current in the coil, a so-called filling factor ξ describing a structure of conducting and insulating regions in the total cross-section and the material integral connecting physical properties of the coil material with an amplitude field and a pulse length.

Design limitations. The maximum achievable field in the coil is mainly limited by two factors. The first is the mechanical strength of the coil depending on the ultimate tensile strength σ_{UTS} of the coil material, its geometry and a distribution of the current density in it. The second factor is the thermal one and is determined by the thermal physical properties of the coil material, its geometry, the distribution of the current density in the coil, the allowable temperature range and the demanded pulse length. Both factors have to be considered in conjunction and the strongest factor defining the maximum achievable field must be selected. Finally the demanded field in the gap coil-WP B_{max} and the maximum achievable field B_0 are compared and a decision is made according to the scheme.

Inductance of the coil. Geometrical parameters of the coil such as the inner r_1 and the outer r_2 radiuses, the length l_{coil}, the effective number of turns η and a self-inductance factor $\Lambda(\alpha,\beta)$ depending on the coil geometry and the current density distribution in the coil determine the inductance of the coil L_{coil}.