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MICRO-COILS BASED ON CAST MICROWIRE

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Abstract: It has been appraised the optimal configuration of inductive coils with given sizes on the basis of cast microwire.

Key words: coil, inductance, microwire.

INTRODUCTION

Inductance coils (IC) have found a broad application as L elements in electronics as well as inductive sensors in metering equipment. One of the main problems in this field of application is miniaturization while increasing rated value of inductance (L). Solution of this problem is complicated due to the necessity of providing high metrological properties, performance and reliability of IC. Despite vast number of rated parameters of IC, the decisive ones are overall volume (V) and rated value L. Generally speaking IC can be described with help of specific inductance defined by coefficient $K = L / V$ ($[K] = \mu H/mm^3$). Sometimes volume of winding (V_o) is used instead of IC overall volume and IC is described with help of specific inductance of winding K_o.

Inductance coils can be divided into film (IC_{flm}) and wire (IC_{wr}) ones on the base of manufacturing method. Thin- and thick-film technology, including multilayer one, is used for IC_{flm} production, while winding technology is used for IC_{wr} production. Current standards of IC_{flm} production provide values of $L \leq 50$ μH at $K \leq 15$ μH/mm^3 (MURATA Company, Japan), but trends of film technology development don't allow to use it for development and production of microcoils with better properties. For such purpose design-manufacturing principles used for IC_{wr} production hold much promise. Thin wire-based IC_{wr} are produced with L up to 10^4 μH and $K \leq 100$ μH/mm^3. Further increase of L and K, first of all in case of microcoils, is defined by opportunity of decrease of V_o, which reaches (0,4 …0,7) V depending on IC_{wr} design. Taking into account current standards, IC_{wr} with $V \leq 1$ mm^3 and length $s \leq 1$ mm can be conditionally referred to microcoils.

Calculation of optimal configuration of inductive coils. Radial IC_{wr} (Fig. 1) with rectangular cross-section of winding and bulk of winding V_o in shape of body of rotation are preferable in terms of miniaturization.

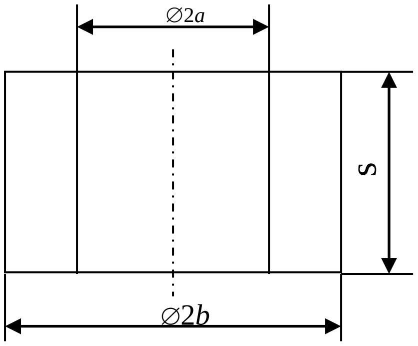

Fig. 1. Radial microcoil with rectangular cross-section

Self-inductance L of radial wire microcoil with rectangular cross-section is defined by its geometrical parameters and environment permeability μ_0 only. Solenoid-shaped and flat coils can be considered as special cases of coil with rectangular cross-section with number of layers and laps of winding within a layer equal to 1, accordingly. Let's estimate impact of separate geometrical elements on properties of such IC_{wr} .

For simplicity sake, let's consider microcoil restricted to overall dimensions 1x1x1 mm.

Simple semiempirical design formulas involving average winding diameter as a direct design variable, besides overall number of laps of winding w_o ($L \sim w_o{}^2$) are well-known. However, at the same time calculation error significantly increases with increase of number of winding layers, that limits use of such formulas in case of multilayer microcoils.

Complete theoretical formula suitable for calculation of self-inductance of such microcoils (at low frequencies), is [1]:

$$L = \sum_{n=0}^{q-1}\sum_{f=0}^{q-1}\sum_{k=1}^{w}\sum_{m=1}^{w}\int_0^{\pi} \frac{\mu_0 \cdot \left(a + \frac{d_2}{2} + h_1 \cdot n\right) \cdot \left(a + h_1 \cdot f\right) \cdot \cos\varphi \cdot d\varphi}{\sqrt{h_2{}^2 \cdot (m-k)^2 + \left(a + \frac{d_2}{2} + h_1 \cdot n\right)^2 + (a + h_1 \cdot f)^2 - 2 \cdot \left(a + \frac{d_2}{2} + h_1 \cdot n\right) \cdot \left(a + h_1 \cdot f\right) \cdot \cos\varphi}}, \quad (1)$$

where: d_2 – overall diameter of microwire with coating;
h_1 – step between layers;
h_2 – step of winding within layer;
a – radius of coil form, i.e. internal winding radius;
b – external radius of coil winding;
s – coil length;
w – number of laps of winding within a single coil's layer;
q – number of coil's layers;
n, f, k, m – summation index;
φ – auxiliary angular parameter of integration element;
q = integer part of $[(b\text{-}a)/h_1]$; w = integer part of (s/h_2); $V_o = s \cdot \pi(b^2 - a^2)$.

Calculation of L was carried out assuming that microcoil winding was winded «lap to lap» and correspondingly, $h_1 = h_2 = d_2$. Dependence of inductance L on internal radius of winding a and overall diameter d_2 of microwire (MW) is shown on Fig. 2.

Besides evident fact of increase of L while reducing MW diameter (due to the increase of laps of winding w in a layer and number of layers q), it's apparent that decrease of internal diameter of MW winding up to $2a < 0,6b$ is not effective, since relative elongation L in this case is insignificant. At the same time such reduction results in significant technological difficulties. Thus, the only way to increase absolute and specific inductance of winding (L and K_o) of IC_{wr} is reduction of overall MW diameter d_2, which significantly depends on core diameter d_1.

Minimal core diameter of drawn copper-based MW with self-adhesive coating which can be achieved nowadays is about 10 µm at d_2=12,5 µm (ELEKTRISOLA Company, Germany). Application of glass-coated cast MW (GCM) is very promising for further miniaturization of IC_{wr} [2]. Process of casting from liquid state of metal allows to obtain MW based on Cu, Ag, Au and metal alloys with core diameter $d_1 \geq 1$µm and coating thickness from 1,5 to 5 µm depending on d_1 within a single technological stage.

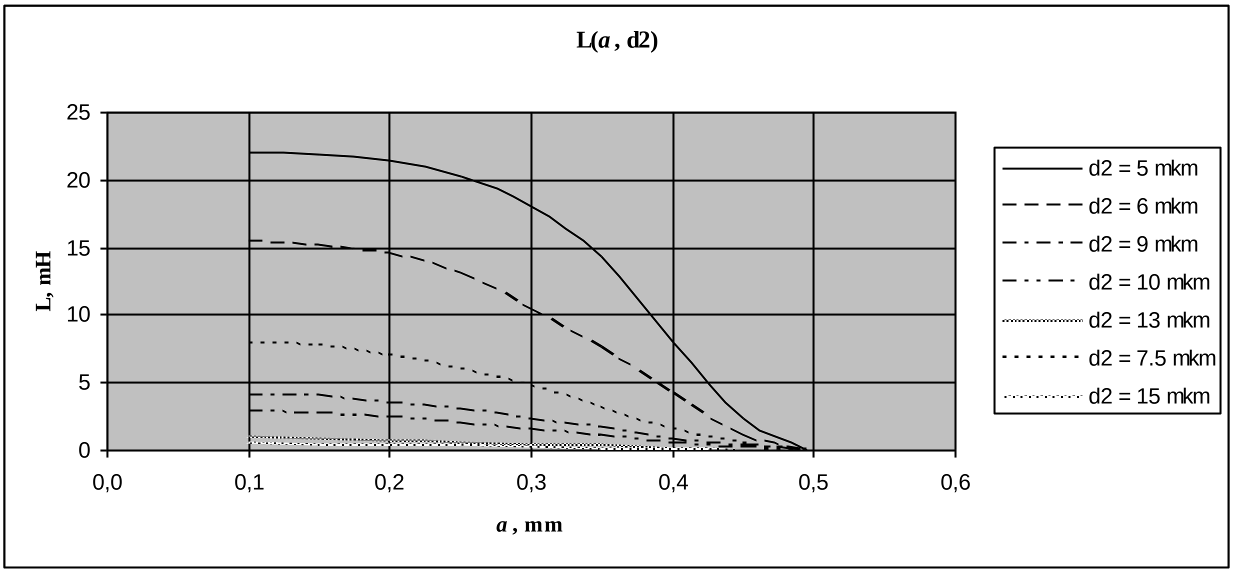

Fig. 2. Calculated dependence of inductance of microcoil on minimal radius of winding and diameter of MW

Works on application of 6-20 µm cast MW in IC_{wr} have already been started at Institute "ELIRI" (Chisinau) in early eighties [3]. Accumulated experience on development of miniature converters of non-electric magnitudes on the base of cast MW [4] allows to develop research and development of microcoils. Achieved level of technology and available equipment provides winding of GCM on coil formers with diameters starting from 2 mm. Calculated dependencies of specific inductance K of microcoil on minimal radius of winding a and MW diameter d_2 have shape similar to curves $L(a, d_2)$. According to obtained results limiting values of K (providing that

$K = 0{,}5 \cdot K_o$) in case of such microcoil can exceed $2 \cdot 10^4$ μH/mm, that two multiples greater than the same parameter of microcoils made by well-known companies. Works on implementation of design of such coils on the base of copper-based GCM are being carried out at Institute «ELIRI» now.

In many microcoil applications such property as resistance of winding R is a quite important parameter. For instance Q-quality of microcoil depends on the abovementioned parameter. *R* can be calculated with help of simplified formula:

$$R = \frac{4\rho \cdot w}{d_1^2} \cdot \sum_{n=0}^{q-1} [(2a + h_1)(n+1)] \qquad (2)$$

Fig. 3 shows calculated dependence of introduced coefficient of conventional Q-quality $Q_\omega = L / R$ on microcoil geometrics and diameter of copper-based cast MW used for winding.

As may be seen from the figure coefficient of conventional Q-quality Q_ω has improper maximum in the range of *a* values from 0,15 *b* to 0,3 *b* depending on MW diameter d_2, maximum drifts to the range of greater values of internal radius of winding while reducing the said diameter. It means that there is no sense to reduce diameter of coil core which is base of a coil under a definite critical value in order to improve Q-quality of coils based on thin MW.

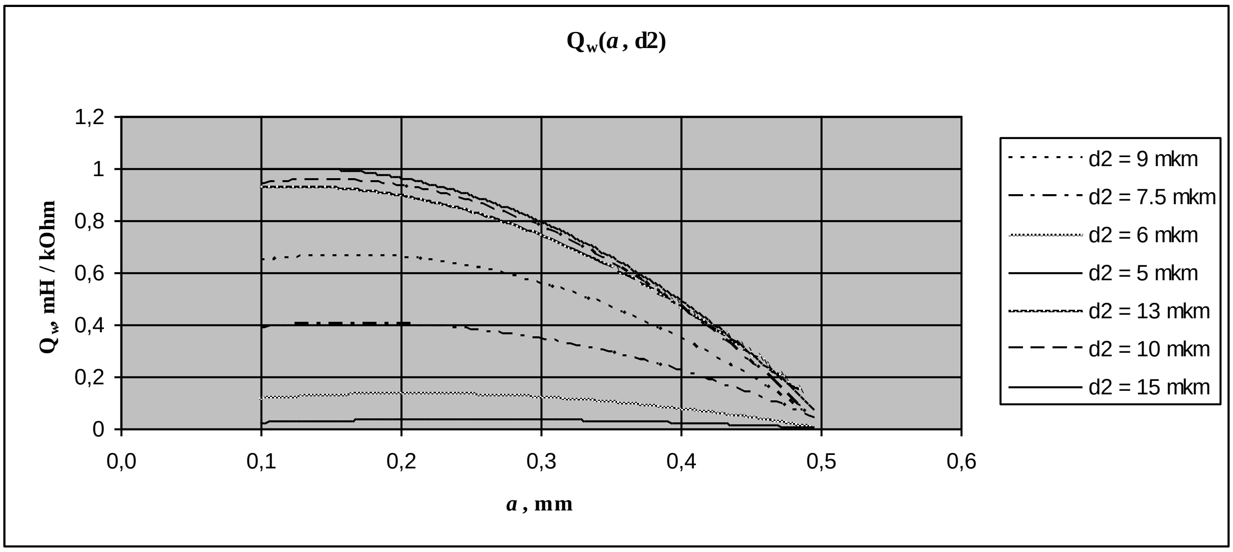

Fig. 3. Dependence of conventional Q-quality $Q_\omega = L / R$ on IC_{wr} geometrics

Technology of microcoils from a cast microwire. While designing and developing manufacturing methods of GCM-based microcoils it's necessary to take into account its specific properties (micron dimensions, glass-coating) and small overall dimensions of IC_{wr}. Tests show that core diameter must be no less than 0,2 mm and core length must be no less than 1 mm that follows from condition of inflexibility of core which receives winding. It's expedient to use such core, especially based on a magnetic material one, for GCM-based microcoils, since glass-coating sinters between laps of winding as well as with core itself. Anyway, while implementing such technology it's necessary to match temperature coefficients of expansion of MW and core.

It's desirable to mount a microcoil on support boards of minimal overall dimensions (e.g. 1,2 x 1,2 x 0,2 mm). Leading-out ends of coil winding and thickened output electrodes with diameter no less than 0,03 mm are soldered (welded) to electrical pathways of such boards. IC_{wr} can be hermetically encapsulated with help of microcase which can be mounted using technique of point-to-point wiring or surface mounting. Caseless protection of GCM-based microcoil can be implemented with help of coating with protective varnish or epoxy compound. However, it should be taken into account that case or caseless protection reduces K up to 2-2,5 times in compare with K_o.

Among numerous processing steps of miniature IC_{wr} manufacturing coiling is certainly the main operation. While coiling MW on a coil form with small radius of curvature significant transverse stresses take place in a glass-coating. Besides, tensile stresses owing to tension impact, as well as contact stresses at points of intersections and contacts of laps of winding retain in a winding bulk. In order to remove the said stresses at $d_2 \leq 10$ μm and $2a = 0{,}2\ldots0{,}5$ mm coiling should be carried out at temperature 10-20 $^{\circ}$C over the temperature of glass-coating softening. At the same time such process provides sintering of laps of winding in a single solid unit of a coil.

Significant role while coiling belongs to tightness which must provide the desirable shape of coil winding (e.g. «lap to lap») and must not allow MW rupture while coiling. These conditions are complied at tightness about 0,1 …0,2 of breaking strength. At the same time MW deformation doesn't exceed 0,2 % of relative elongation at rupture. The said value of tightness is an initial parameter for determination of linear take-up speed. Sometimes in order to increase the said speed it's expedient to use cast MW with core based on Cu-Au, Cu-Ag, Au-Ag alloys which are more solid than MW based on a pure metal.

Design of microcoils based on cast MW is a solid glass unit formed while coiling reinforced with metal conductors. Such design reduces irreversible change of L and temperature coefficient of inductance. Experience of GCM application allows to predict that the said temperature coefficient can reach values within a range $(10\ldots50)\cdot10^{-6}$ 1/K, temperature and time stability can reach up to (5 - 50) 10^{-3} % per year in GCM-based IC_{wr}. Special shapes of winding allow to reduce self-capacitance of coil winding, that is, however, a separate problem. Application of such coils is especially promising in inductive sensors, since high resistance is not a limiting factor, but the main role belongs to great value of L and parameters' stability.

Ways of increase of inductance of microcoils. Increase of L can be achieved with help of the abovementioned ferro-magnetic cores. Such materials as ferrite, carbonyl iron, permalloy are used as a base of a core. Manufacturing and application of miniature cores based on ferrite and carbonyl iron is embarrassed owing to their fragility. Drawing of thin wires based on permalloy (e.g. alloy «mumetal») is connected with lots of manufacturing difficulties, however such wires with diameter 0,2 …0,3 мм are produced by some companies (e.g. Goodfellow, England). Application of cores based on bundles of MW with core based on m-metals and coaxial MW with magnetic covering of glass-coating holds much promise especially in case of high-frequency micro L elements.

Determination of optimal diameter of magnetic core in order to obtain maximal inductance at given microcoil overall dimensions is a quite interesting problem. Evidently, that in case of maximal core diameter, i.e. in case of a single-layer coil value L is minimal, since aggregate number of laps of winding ids minimal. While tending core diameter to zero impact of magnetic core tends to zero, too, i.e. in this case, inductance reduces to value of self-inductance of a coil without a core. Therefore, there is some intermediate core diameter depending on its relative magnetic permeability μ and overall coil dimensions, which provides maximal value of K_o.

Accurate calculation of inductance of crossover coil with straight cylindrical magnetic core is quite difficult [5]. Experimental estimate gives optimal value of diameter $2a$ of magnetic core, with relative permeability $\mu \geq 10000$ of order $0{,}6b$. At the same time microcoil inductance increases up to 8-10 times in compare with the same coil without core.

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