Design of Hybrid Conductors for Electromagnetic Forming Coils

S. Gies[1*], A. E. Tekkaya[1]

[1] Institute of Forming Technology and Lightweight Components, TU Dortmund University, Germany
*Corresponding author. Email: Soeren.Gies@iul.tu-dortmund.de

Abstract

The use of hybrid coil turns made of steel (St) and copper (Cu) is originally motivated by the increased mechanical strength compared to monolithic copper conductors. Due to the differing electrical conductivities of the two materials, the hybrid design also changes the current density distribution in the conductor cross section. This affects crucial process parameters such as the magnetic pressure and the Joule heat losses.

The effect of the hybrid conductor design on the process efficiency is investigated. An electromagnetic sheet metal forming operation using a one-turn coil with rectangular cross section is used as reference case. The copper layer (CuCr1Zr) was deposited on a tool steel substrate (X40CrMoV5-1) using a selective laser melting process. The copper layer thickness is varied ranging from a monolithic steel conductor to a monolithic copper conductor. The workpiece (EN AW-5083, t_W = 1 mm) is formed through a drawing ring so that the final forming height is a qualitative measure for the process efficiency. The experimental results prove that the efficiency in case of a properly designed hybrid conductor can exceed the efficiency of a monolithic copper coil. The current density distribution in the hybrid cross section is investigated by means of numerical simulations. This way a deeper insight into the physical effects of a varying copper layer thickness is gained. The results reveal that the optimum layer thickness is not just a function of the coil cross section and the current frequency. It is also affected by the coil length and the resistance of the pulse generator.

Keywords

Electromagnetic forming, Working coils, Coil design, Hybrid conductors

1 Introduction

The use of copper for the turns of electromagnetic forming coils is state of the art. This choice of material is primarily motivated by its high electrical conductivity to ensure a high process efficiency. At the same time the coil turns also need to possess a high mechanical strength to bear the electromagnetic forces without failure. This additional requirement causes a conflict of aims, since an increased mechanical strength leads to a decreased electrical conductivity in most cases. A good trade-off between both properties can be reached with high-strength copper alloys such as CuCr1Zr. Compared to pure copper the electrical conductivity of this age hardening alloy is only 10-15% lower but has a 3 to 4 times higher mechanical strength (Belyy et al., 1977).

Another approach to combine good electrical and mechanical properties is a hybrid conductor design. In this case, the conductor cross section consists of two different materials: A copper layer for a high electrical conductivity and a steel substrate for the mechanical strength. Finckenstein (1967) used a galvanically applied copper coating of 0.5 to 1 mm to reduce the Joule heat losses of a compression coil made of spring steel. In contrast to that, Schmidt (1976) recommends a copper layer thickness of 5 mm in case of a tool-steel substrate. These entirely different coil designs for comparable applications reveal the high uncertainty due to a missing physics-based design approach. A first step towards a deeper understanding about the effects of hybrid coil structures on the electromagnetic forming process was taken by Risch et al. (2008). Based on a time-harmonic simulation the effect of a varying copper layer thickness on the magnetic force between coil and workpiece was analyzed. For the substrate material of the spirally shaped flat coil a low-alloyed steel with an electrical conductivity of 7.1 MS/m (12.2 % IACS) was considered. The deformation of the workpiece was neglected and all coil configurations were simulated with the same imposed discharge current (f = 19 kHz). The results prove, that a copper layer thickness of t_{Cu} = 0.5 mm increases the magnetic force by more than factor of two compared to a monolithic steel coil. In case of a copper layer thickness of $t_{Cu} \approx 0.2$ mm the force amplitude is even higher than in case of a monolithic copper coil. Risch et al. (2008) attribute this effect to the increased current concentration in the copper layer facing the workpiece. Numerical investigations for a one-turn coil by Golovashchenko et al. (2006) confirm this conclusion. The current density of a monolithic steel coil in the area facing the workpiece is nearly doubled when a copper coating is applied.

Although the simulation approach of Risch et al. (2008) allows for the identification of a copper layer thickness which maximizes the magnetic force amplitude, it is uncertain how this coil design affects the forming result. Imposing identical discharge currents in the simulation of different coil designs also differs from the real process conditions. In fact, a varying copper layer thickness changes the coil's resistivity and thereby the discharge current. Experimental investigations about the performance of hybrid coils in electromagnetic forming applications have not been published yet. Whether a simulation with the aforementioned simplifications is suitable to identify the optimum hybrid coil design in terms of a maximum process efficiency is therefore not proven.

The following work aims on the development of a validated design approach for hybrid conductors in electromagnetic forming applications. An electromagnetic sheet metal forming operation using a one-turn coil with rectangular cross section is used as reference case. In the first step, free forming experiments with hybrid conductors are performed to analyze the effect of a varying copper layer thickness on the process efficiency. Based on these results a theoretical design approach is derived and validated. The combination of numerical and analytical methods is used to predict the optimum copper layer thickness without time consuming and expensive experiments.

2 Setup and Procedure

A modular one-turn coil with replaceable pressure leads was used for the experimental investigations. The pressure lead geometry including the hybrid cross-section structure is depicted in **Fig. 1a**.

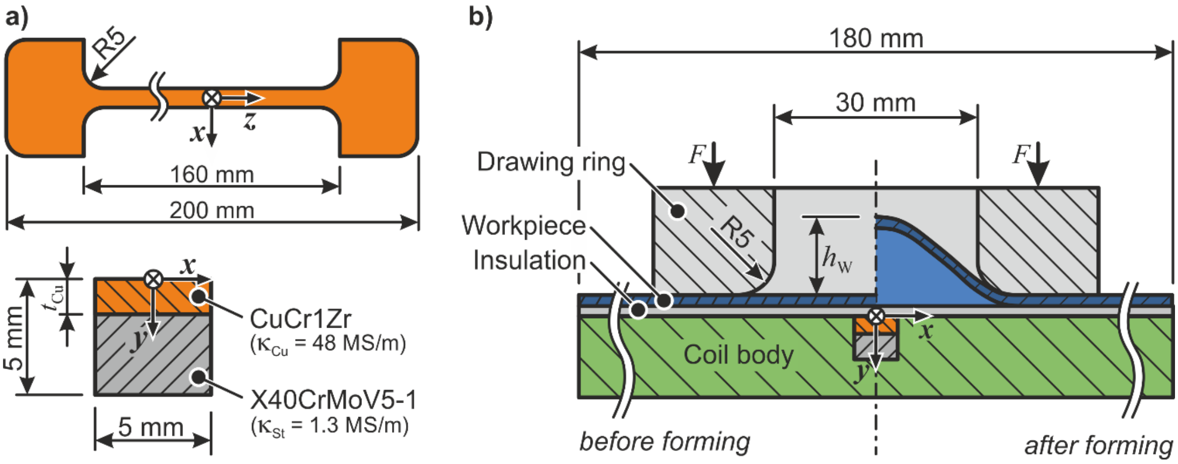

Figure 1: *a) Pressure lead geometry and b) setup for free forming experiments*

The hybrid conductors were manufactured by the Institute for Machine Tools and Factory Management (TU Berlin). The copper layer (CuCr1Zr) was deposited on a tool steel substrate (X40CrMoV5-1) using a selective laser melting process. Details about the additive manufacturing process and the subsequent heat treatment are summarized by Uhlmann and Kashevko (2017). The copper layer thickness t_{Cu} was varied from 0.2 to 3.8 mm. Additionally two monolithic conductors made of pure copper and pure steel were considered. The analyzed copper ratio of the conductor $Q_{Cu} = t_{Cu} / h$ was thus ranging from 0 to 1. The total height h and width w of the conductor cross section was kept constant at 5 mm. A polyester film with a thickness of 0.35 mm was used as electrical insulation layer between workpiece and coil. The workpiece (EN AW-5083, $t_W = 1$ mm) was formed through a drawing ring with rectangular opening (80 mm x 30 mm) (see **Fig. 1b**). The maximum height of the workpiece h_W was measured after the forming operation and can be used for an ordinal comparison of the different coil designs in terms of process efficiency. To analyze the effect of different discharge current frequencies two pulse generators were used. The properties of the generators for the selected capacitor configuration are listed in **Table 1**.

Pulse generator	SMU 0612 FS	Magneform 7000
Maximum charging energy $E_{C,max}$	9 kJ (@ 15 kV)	20 kJ (@ 8.16 kV)
Capacity C	80 µF	629 µF
Inner inductance L_i	40 nH	60 nH
Inner resistance R_i	4.2 mΩ	4.2 mΩ
Ringing frequency f^*	89 kHz	25 kHz

Table 1: *Properties of the pulse generators used for the experimental investigations*

For the sake of transferability, the experimental results in chapter 3 are presented as normalized parameters. The corresponding parameter value in case of a monolithic copper conductor ($Q_{Cu} = 1$) is used as reference. These reference values are listed in **Table 2**.

	SMU 0612 FS		Magneform 7000	
	1.5 kJ	**2.5 kJ**	**1.5 kJ**	**2.5 kJ**
Forming height $h_W(Q_{Cu} = 1)$ in mm	4.83	6.76	2.98	4.38
Current amplitude $\hat{I}(Q_{Cu} = 1)$ in kA	145.6	186.3	98.2	125.1
Damping $\beta(Q_{Cu} = 1)$ in 1/s	2.4e+4	2.2e+4	2.1e+4	2.0e+4

Table 2: *Measured process parameters in absolute values (monolithic copper conductor)*

Two-dimensional time-harmonic field simulations are performed with Ansys. Only the coil turn and the workpiece are considered. The components are modeled as fixed rigid bodies according to the initial arrangement (see Fig. 1b, before forming). According to the results of a convergence analysis the spatial discretization of the coil cross section is set to a homogenous density of 12 elements/mm. The electrical conductivity of the workpiece (16 MS/m), the copper layer (48 MS/m) and the steel substrate (1.3 MS/m) are assumed constant.

3 Free forming experiments

The results of the free forming experiments are summarized in **Fig. 2**. The measured forming height of the workpiece $h_W(Q_{Cu})$ is normalized using the forming height in case of a monolithic copper conductor $h_W(Q_{Cu} = 1)$. The normalized values above 1 thus prove, that the forming height of a monolithic copper conductor can be exceeded using a proper hybrid design. Since an increased height equates to an increased plastic strain energy E_φ, normalized heights above 1 also indicate an enhanced process efficiency $\eta = E_\varphi / E_C$.

With values of 5% (SMU) and 17% (Magneform) the maximum forming height increase shows a pronounced dependence on the pulse generator used. In contrast to that, the copper layer ratio which leads to the maximum forming height ($Q_{Cu} = 0.24$) is identical for

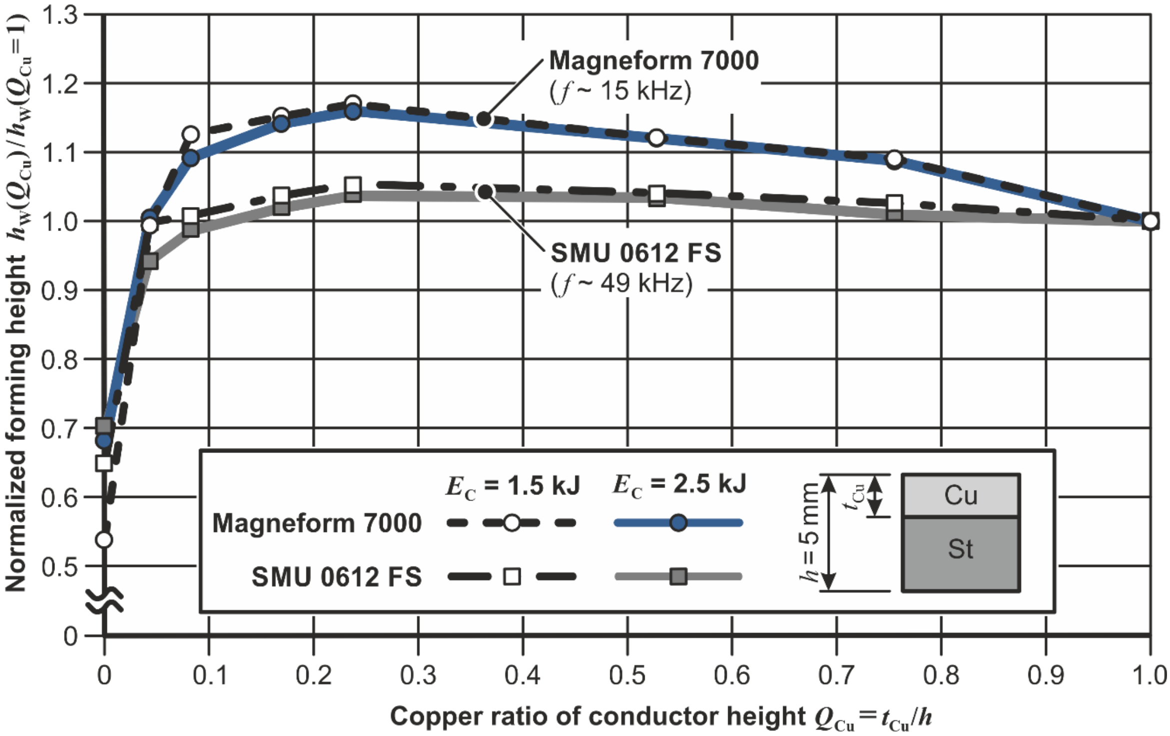

Figure 2: *Effect of the copper ratio on the forming height of the workpiece*

both machines. The discharge current frequency throughout all experiments was f = 15 kHz (Magneform) and f = 49 kHz (SMU) on average, leading to skin depths in the copper material of δ = 0.59 mm (Magneform) and δ = 0.32 mm (SMU). The ratio of optimum copper layer thickness to skin depth thus equates to 2.0 (Magneform) and 3.8 (SMU) respectively. That the optimum layer thickness of a hybrid conductor can be expressed as a constant fraction of the skin depth δ is consequently disproved by these results. As expected, an increased charging energy E_C leads to an increased absolute forming height h_W (see Table 2). However, the course of the normalized forming height is not affected. The optimum copper layer thickness in terms of process efficiency is thus independent of the selected charging energy. This does not mean that the maximum charging energy is independent of the copper layer. A decreasing copper layer thickness causes an increase of the effective coil resistivity. The maximum charging energy defined by a critical level of Joule heating is consequently decreasing with a diminishing copper layer. This additional boundary condition needs to be considered in case of hybrid coil design.

To define a design guideline for hybrid conductors, the physical reason for the existence of an optimum copper layer thickness needs to be discussed. For this reason, **Fig. 3** shows the course of the normalized current amplitude and damping coefficient, which are based on the measured discharge currents. The normalized course of both parameters showed no significant change in case of a varying charging energy E_C. The depicted results in Fig. 3 for E_C = 2.5 kJ are thus also valid for the lower charging energy of 1.5 kJ. The results in Fig. 3 prove that the course of the current amplitude cannot be the principle reason for the maximum forming height in case of a copper ratio of Q_{Cu} = 0.24 (see Fig. 2). For Q_{Cu} > 0.08 the current amplitude is not significantly affected by the copper layer thickness. Only in case

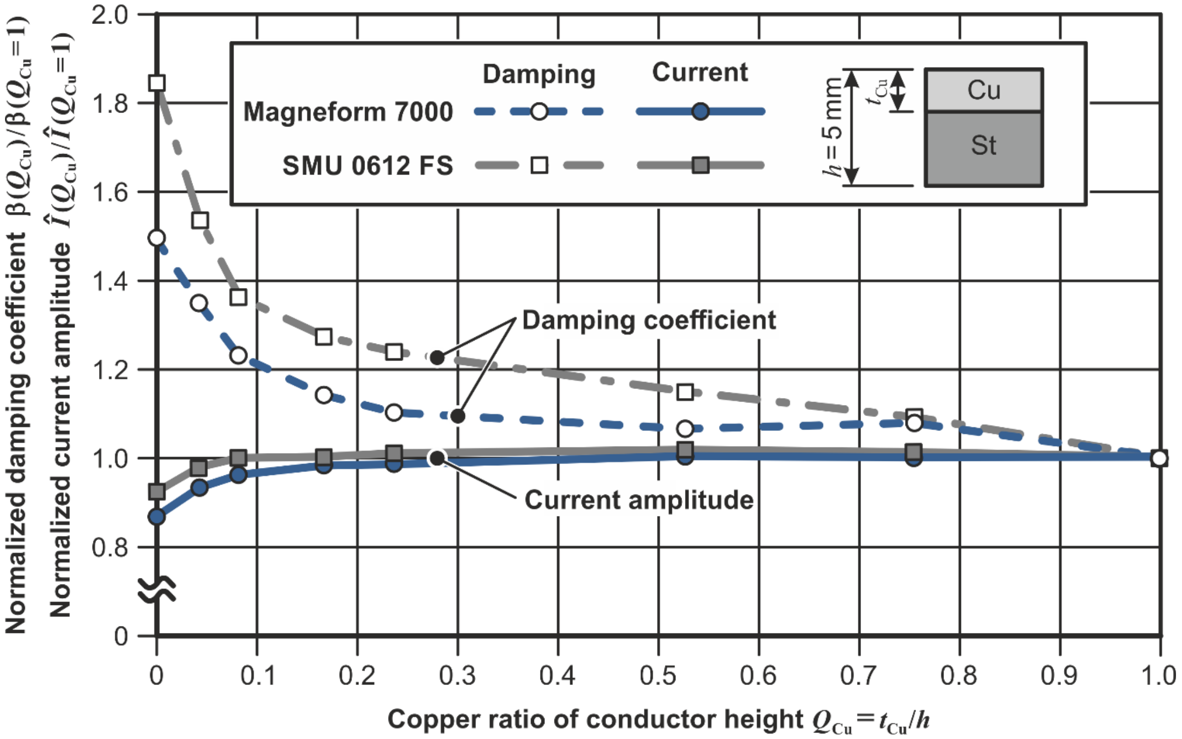

Figure 3: *Effect of the copper ratio on the current amplitude and the damping coefficient*

of the monolithic steel conductor the reduced forming height can be explained with the decreased current amplitude to some extent. The decreasing course of the damping coefficient (see Fig. 3) is also no suitable explanation for the increased process efficiency in case of a properly designed hybrid conductor. A decreased damping leads to higher amplitudes of the subsequent current halfwaves. If the subsequent halfwaves should have an effect on the workpiece deformation at all, this would rather promote the efficiency of the monolithic copper conductor.

4 Theoretical approach for the optimum coil design

The aforementioned discussion reveals that the effect of the copper layer thickness on the forming height is not primarily based on an altered discharge current course. Numerical field simulations are thus required to analyze the non-measurable process parameters.

Initially it was analyzed whether the low-conductive steel substrate affects the current density distribution at all. Focusing on the optimum copper ratio ($Q_{Cu} = 0.24$) the percentage of the total current running through the steel layer equates to 13.8% ($f = 15$ kHz) and 18.9% ($f = 49$ kHz) respectively. The two analyzed current frequencies correspond to the average values in the free forming experiments. The results prove that the steel substrate cannot be assumed as electromagnetically inert component. It was thus considered in all subsequent field simulations.

In **Fig. 4** the course of the normalized magnetic pressure amplitude acting on the surface of the workpiece in case of a varying copper ratio is depicted. The magnetic pressure

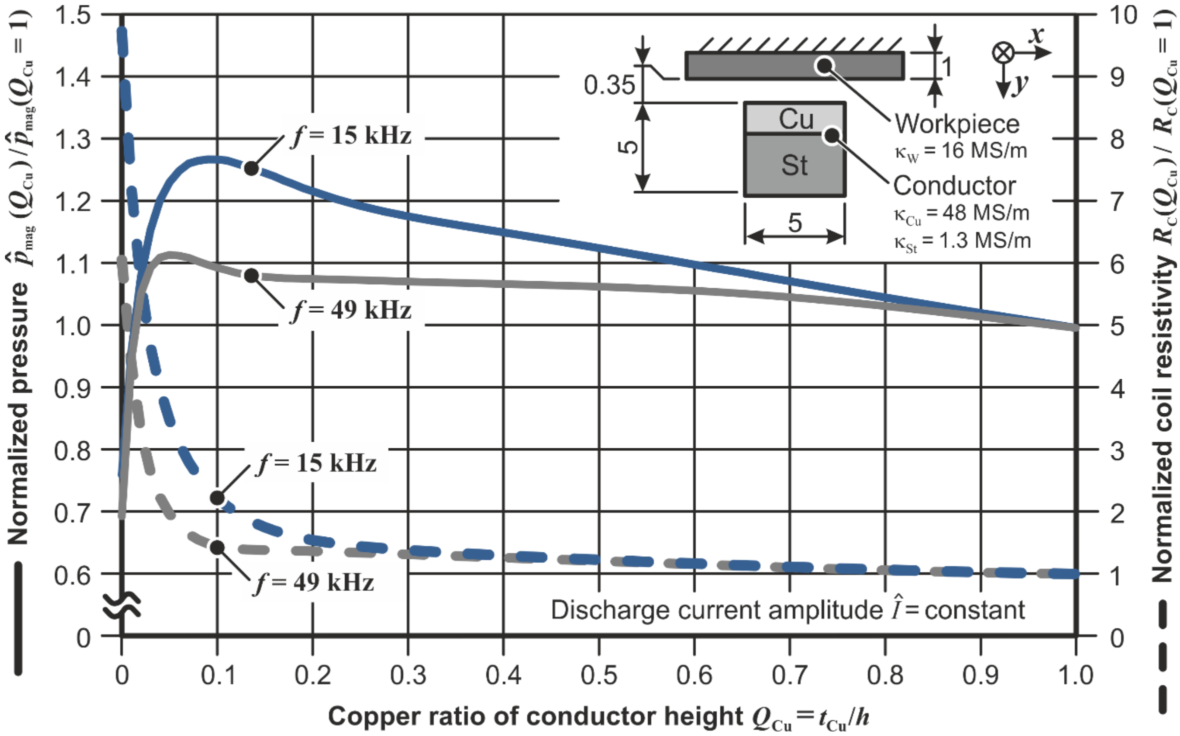

Figure 4: *Effect of the copper ratio on the magnetic pressure amplitude and the coil resistivity (based on time-harmonic simulations)*

is apparently a good starting point for a theoretical determination of an optimum hybrid structure in terms of process efficiency. In accordance with the course of the forming height in Fig. 2 the magnetic pressure also exceeds the value of a monolithic copper coil in a certain copper ratio range and shows a distinctive drop in case of a monolithic steel structure. The more pronounced increase of pressure for the lower current frequency also fits to the differing increase of forming height depending on the pulse generator used (see Fig. 2). The reason for the increased pressure amplitude is a higher current concentration in the conductor region facing the workpiece. The current centroid in the conductor cross-section is thus shifted towards the workpiece so that the effective gap between workpiece and coil decreases. This decreased gap leads to an increased pressure if all other conditions remain unchanged (Kleiner et al., 2005). Due to an intensified skin- and proximity-effect in case of an increased current frequency the current concentration in the near-workpiece region of a monolithic copper conductor is already raised to an elevated level. The effect of a forced current concentration by decreasing the copper layer thickness is thus not as pronounced as for lower frequencies. This explains the lower maxima of the normalized forming height (Fig. 2) and the normalized pressure (Fig. 3) in case of higher current frequencies. Consequently, hybrid conductors will especially enhance the process efficiency in case of pulse generators operating in the lower range of current frequencies (f = 10-20 kHz).

Although the course of the normalized magnetic pressure in Fig. 4 shows some similarities with the normalized forming height in Fig. 2, it is no suitable indicator for the optimum copper layer thickness. While the forming height is maximized using a copper ratio of Q_{Cu} = 0.24 the magnetic pressure reaches its maximum for Q_{Cu} = 0.05 (f = 49 kHz) and

Q_{Cu} = 0.09 (f = 15 kHz) respectively. The reason for the considerably smaller optimum layer thickness in case of the pressure course is the negligence of the varying coil resistivity (see Fig. 4). In contrast to the magnetic pressure, the resistivity is increasing with a decreasing copper ratio of the conductor. The consideration if this opposing trend would thus shift the optimum layer towards higher thicknesses.

To merge the effect of pressure and resistivity in one parameter the total Joule heat loss is a suitable figure. According to Werdelmann et al. (2008) Joule heating is the dominant loss mechanism in electromagnetic forming processes. Minimizing the total Joule heat loss will thus maximize the process efficiency. Focusing on the losses in the pulse generator $E_{L,i}$ and the coil $E_{L,c}$, the total Joule heat loss can be defined as

$$E_{L,tot} = E_{L,i} + E_{L,c} = \int I^2(t) \cdot (R_i + R_c)\, dt = \hat{I}^2 \cdot (R_i + R_c) \cdot \int F^2(t)\, dt. \quad (1)$$

Here $F(t)=I(t)/\hat{I}$ describes the normalized time course of the coil current. According to Fig. 4 the coil resistivity R_c is as a function of the copper ration Q_{Cu}. In contrast to that, the internal resistivity of the pulse generator R_i is not significantly affected by the coil design. Minimizing the total Joule heat loss according to Eq. 1 by adjusting the copper ratio Q_{Cu} only leads to a maximum process efficiency if the forming result is not affected. Since the magnetic pressure p_{mag} is also a function of the copper ratio (see Fig. 4) this condition is not fulfilled without further adjustment. With $\hat{p}_{mag} \sim \hat{I}^2$ a varying pressure amplitude can be compensated by an adjusted coil current. The equivalent current amplitude

$$\hat{I}_{eq}(Q_{Cu}) = \hat{I}(Q_{Cu} = 1) \cdot [p_{mag}(Q_{Cu}) / p_{mag}(Q_{Cu} = 1)]^{-1/2} \quad (2)$$

is based on this correlation and leads to identical pressure amplitudes for all coil designs. Considering this equivalent current definition in Eq. 1 ensures that the total Joule heat loss for different copper ratios always refers to the same forming result ($E_\varphi \approx$ const.). Minimizing the loss is thus equivalent to a minimization of the input energy E_C and leads to a maximum process efficiency η. Instead of analyzing the absolute values of the total Joule heat loss according to Eq. 1 a normalized definition is more convenient. Substituting Eq. 2 in Eq. 1 and assuming that the time course of the current $F(t)$ is not affected by the coil design, the normalized definition of the total Joule hat loss equates to

$$\frac{E_{L,tot}(Q_{Cu})}{E_{L,tot}(Q_{Cu} = 1)} = \frac{p_{mag}(Q_{Cu} = 1)}{p_{mag}(Q_{Cu})} \cdot \frac{R_i + R_c(Q_{Cu})}{R_i + R_c(Q_{Cu} = 1)}. \quad (3)$$

Fig. 5 shows the course of the normalized Joule heat loss according to Eq. 3 for current frequencies of f = 15 kHz and f = 49 kHz. The corresponding values of pressure and resistivity are based on a time-harmonic field simulation. In case of the lower frequency the loss is minimized using a copper ratio of Q_{Cu} = 0.19. This value is a good approximation for

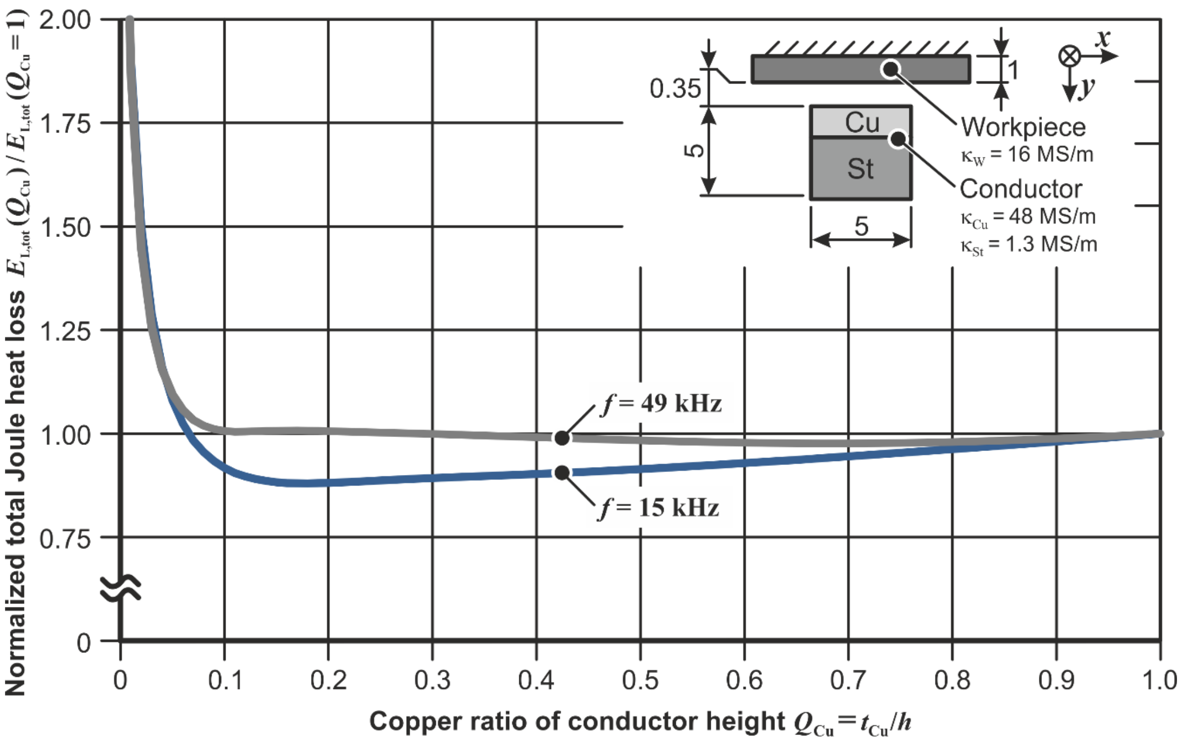

Figure 5: *Effect of the copper ratio on the total Joule heat loss*

the optimum copper ratio of $Q_{Cu} = 0.24$ identified in the experimental investigations (see Fig. 2). The limited potential to decrease the losses in case of the higher discharge current frequency ($E_{L,tot}(Q_{Cu}) / E_{L,tot}(Q_{Cu} = 1) \geq 1$) matches with the marginal increase of forming height. The normalized Joule heat loss according to Eq. 3 is thus a suitable indicator for the benefit and the proper design of hybrid conductors in electromagnetic forming applications. Since this parameter is just a function of magnetic pressure amplitudes and resistivity values it can be determined using time harmonic field simulations. No time-consuming electromagnetic forming simulations or expensive experimental investigations are required.

Eq. 3 also reveals, that an optimum hybrid coil design is not just a function of the coil cross section and the current frequency. With $R_c \sim l_c$ the optimum design of hybrid coils in terms of process efficiency is also affected by the coil length l_c. The increasing resistivity with decreasing copper ratio has a stronger impact on the efficiency in case of a higher coil length. If all other conditions remain unchanged, an increasing coil length thus leads to an increasing optimum layer thickness. A higher inner resistance of the pulse generator R_i has an opposing effect and causes a decreasing optimum copper layer thickness.

Conclusion

The effect of a varying copper layer thickness in case of hybrid coils was investigated by means of experimental, numerical and analytical approaches. For the optimum copper ratio in terms of process efficiency the following conclusions can be drawn:

- Especially in case of low discharge frequencies ($f = 10$-20 kHz) the efficiency of a properly designed hybrid conductor exceeds the efficiency of a monolithic copper coil.
- A time-harmonic field simulation in combination with an analytical approach yields a satisfying prediction for the optimum copper layer thickness.
- The optimum layer thickness is not just a function of the coil cross section and the frequency. It is also affected by the coil length and the resistance of the pulse generator.

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