Experimental Investigations on the Optimum Driver Configuration for Electromagnetic Sheet Metal Forming*

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Abstract

Electromagnetic forming is a high speed forming process especially suitable for materials with high electrical conductivity such as copper or aluminum. In case of materials with comparatively low electrical conductivity (e.g. stainless steel or titanium) the use of so-called driver sheets is a common approach. Various publications proved that this way materials with low electrical conductivity and even non-conductive materials can be formed. Although the use of driver sheets is common practice, there are no or only contradicting recommendations regarding the optimum driver sheet configuration.
Based on experimental investigations of the electromagnetic sheet metal forming process, this paper investigates the optimum material and thickness of the driver sheet. The results prove that aluminum should be favored over copper as driver material. The optimum driver thickness was found to be dependent on thickness and electrical conductivity of the workpiece. Even in case of a workpiece made of aluminum the use of a driver sheet could enhance the efficiency of the process.

Keywords

Electromagnetic forming, sheet metal forming, driver materials

* *This work is based on the results of the transfer project TE508/34-1 within the research group PAK343 which is kindly supported by the German Research Foundation (DFG). Thanks also to the industry partners TRUMPF Werkzeugmaschinen GmbH + Co. KG, TRUMPF Hüttinger GmbH + Co. KG, and Outokumpu Nirosta GmbH for their participation and intensive support within the transfer project.*

1 Introduction

Electromagnetic forming is a high speed forming process using pulsed alternating magnetic fields for a contact-free application of forces to the workpiece. Referring to WINKLER [1], the repelling force between workpiece and coil decreases with decreasing electrical conductivity of the workpiece. This hinders or completely prevents electromagnetic forming of materials with low electrical conductivity such as stainless steels or titanium.

The dependency of the magnetic forces on the electrical conductivity can be attributed to the smaller amount of eddy currents induced into the workpiece. This, in turn, weakens the shielding of the primary magnetic field so that the field penetrating through the workpiece increases. An indicator for the shielding is the ratio of workpiece thickness t_W to skin depth σ_S. Taking into account the discharge frequency f as well as electrical conductivity κ and permeability μ, the skin depth is defined as follows:

$$\sigma_S = \sqrt{\frac{1}{\pi \cdot f \cdot \kappa \cdot \mu}} \qquad (1)$$

To ensure that the amount of the penetrating field is sufficiently small, the ratio t_W/σ_S should be at least 1.5 [2]. Assuming a given workpiece geometry and material and taking into account the definition of the skin depth σ_S according to Eq. (1), this ratio can only be affected by increasing the discharge frequency f. BELYY ET AL. [3] recommend frequencies between 60 and 100 kHz to form low conductive materials. But, as the discharge frequency is an inherent characteristic of pulse generator and tool coil, this value is not adjustable by the user.

An alternative concept to form materials with low electrical conductivity and even non-conductive materials was introduced by WEIMAR [4]. By placing an additional sheet with high electrical conductivity between workpiece and tool coil (see Figure 1a), hereinafter referred to as driver sheet, a good shielding of the primary magnetic field is attained. Consequently, a large amount of magnetic force is acting on the driver sheet. Due to the contact between driver sheet and workpiece this force is mechanically transferred to the workpiece. If the equivalent stresses in driver sheet and workpiece arising from the magnetic force exceed their yield stress, both parts are formed simultaneously.

2 Driver Sheets in Electromagnetic Forming

When it comes to process design for driver-assisted electromagnetic forming operations three questions arise:

1. Is a driver sheet necessary?
2. Which is the best driver material?
3. Which is the optimum driver thickness $t_{D,opt}$?

Regarding the first point, WEIMAR [4] recommends the use of driver sheets if the electrical conductivity of the workpiece κ_W is below 20 % to 10 % than the one of copper. This equates to a value between 11.2 and 5.6 MS/m. Assuming a discharge frequency f in the range of 10 – 20 kHz, BELYY ET AL. [3] define a threshold value of about 14 MS/m. Neither of them gives an explanation for their recommendation. However, these values correspond to the publications on driver-assisted electromagnetic sheet metal forming summarized in Table 1. Here, the electrical conductivity of the workpiece material is in the range of 10 MS/m (DC04) to 1 MS/m (Titanium).

#	Workpiece		Driver		t_D/σ_S	Ref.
	Material	**Thickness t_W**	**Material**	**Thickness t_D**		
1	DC04	0.80 mm	Copper	0.65 mm	1.0	[5]
2	Titanium	0.50 mm	Copper	0.65 mm	1.0	[5]
3	DP600	0.70 mm	Copper	0.60 mm	0.90	[6]
4	Ti-6AL-4V	0.50 mm	CU-DHP	0.50 mm	0.82	[7]
5	X5-CrNi18-10	0.15 mm	EN AW-1050	0.30 mm	0.73	[8]
6	X5Cr-Ni-Mo17-12-2	0.25 mm	Copper	0.10 mm	0.22	[6]
7	X12CrMn-NiN17-7-5	0.08 mm	Copper	0.15 mm	n/a	[9]
8	Titanium	0.08 mm	Copper	0.15 mm	n/a	[9]
9	Carbon steels	0.15 – 0.3 mm	EN AW-6111	1.0 mm	n/a	[10]
10	AZ31B-O (Mg)	0.55 mm	Aluminum	n/a	n/a	[11]
11	Titanium CP-1	0.50 mm	Aluminum	n/a	n/a	[11]

Table 1: *Publications focussing on driver-assisted electromagnetic sheet metal forming*

The material most suitable for the driver sheet has to meet two requirements at once: A high electrical conductivity and a low yield stress. The high electrical conductivity is necessary to ensure a good shielding of the magnetic field. The low yield stress should minimize the forming energy consumed by the driver so that the energy ratio available for the workpiece is increased. Based on this theoretical consideration, aluminum and copper seem to be proper materials. Since copper has a higher electrical conductivity but also a higher yield stress compared to a low alloyed aluminum, an ordinal comparison of copper and aluminum is not possible without further theoretical or experimental investigations. While BELYY ET AL. [3] recommend annealed copper as driver material, DENGLER AND GLOMSKI [12] claim that aluminum should be favored. None of these two contradicting recommendations is based on investigations and the authors do not explain their suggestion. Only DESAI ET AL. [13] gave a comparison of aluminum and copper drivers based on a numerical simulation. The results prove that in case of a workpiece made of stainless steel (κ_W = 1.1 MS/m) the copper driver causes the highest Lorentz forces whereas the aluminum driver leads to the highest collision velocity. As the investigations of DESAI ET AL. focus on the magnetic pulse welding process they conclude that aluminum drivers should be favored. However, this does not necessarily mean that aluminum is also the best choice for electromagnetic forming processes which are rather energy-based than based on the collision velocity. Also the publications listed in Table 1 do not show a clear dominance regarding the driver material used.

A proper thickness of the driver sheet t_D is likewise important for the efficiency of driver-assisted forming processes as the driver material. According to SANO ET AL. [14], there is an optimum value for the driver thickness t_D. In case of a too thin driver sheet the induced eddy currents and, consequently, the resulting Lorentz force acting in the driver are comparatively small. If the driver thickness exceeds the optimum value, only a slight

increase of the Lorentz forces can be observed. As this slight increase cannot compensate the increase of energy required for the deformation of the driver, the remaining forming energy for the workpiece decreases.
Recommendations regarding the optimum driver thickness are contradictory. TILLMAN ET AL. [5] as well as SANO ET AL. [14] recommend a driver thickness t_D equal to the skin depth σ_S. BELYY ET AL. [3] claim that the optimum driver thickness equates to half of the skin depth σ_S. None of these recommendations is proved by experimental investigations. As the authors do not even give an explanation justifying their suggestions, their recommendations must be treated as hypothesis. Only the recommendations given by DESAI ET AL. [13] are based on numerical results. According to their simulation the optimum thickness of an aluminum driver is $0.83 \cdot \sigma_S$ whereas a driver made of copper should have a thickness equal to the skin depth σ_S. For several reasons the validity of these results is doubtful and needs further verification. On one hand the recommendations are based on the observation, that the absolute optimum thickness for copper and for aluminum drivers is identical and equates to $t_D = 0.5$ mm. This result is questionable as the higher electrical conductivity as well as the higher yield strength of copper must cause a smaller optimum thickness compared to the one of aluminum. The failure might be caused as only three driver thicknesses (0.25, 0.5, and 1 mm) have been simulated. This very coarse step size makes it nearly impossible to identify differences in the optimum thickness of copper and aluminum, leading to the wrong assumption that the optimum values are identical. On the other hand, experimental verification of the numerical results was realized by comparison of the joint quality in magnetic pulse welding experiments. Even if an ordinal comparison of the collision velocity based on the joint quality is possible, it does not give an exact value of the deviation between numerical and experimental collision velocity. Also the publications listed in Table 1 prove that there is insufficient knowledge about the proper driver thickness. The wide range of values between $0.22 \cdot \sigma_S$ and σ_S cannot just be attributed to different workpiece properties and thicknesses. The workpiece material in line #5 and #6, for example, is quite similar, but the chosen drive thickness varies by a factor of more than 3.
The investigations discussed so far prove that there is no clear recommendation regarding material and thickness of driver sheets verified by experimental results. Both parameters are crucial for the efficiency of driver-assisted forming operations.
In this paper copper and aluminum drivers are compared by experimental investigations on the electromagnetic sheet metal forming process. The optimum thickness is determined for both driver materials. The effect of variations in charging energy, workpiece material, and workpiece thickness on the optimum driver thickness is investigated.

3 Experimental Setup and Procedure

The setup used for the experimental investigations is depicted in Figure 1a. Instead of a closed die only a drawing ring was used to facilitate free forming of the workpiece and the driver (Figure 1b). A flat forming coil with *n* = 7 turns and an outer diameter of d_o = 65 mm was used. The coil was connected to a Maxwell Magneform pulse generator. Two capacitor banks with a total capacitance of *C* = 629 µF and a maximum charging voltage of *U* = 8 kV were selected. Inner inductance and inner resistance of the chosen pulse generator configuration equate to L_i = 60 nH and R_i = 4.2 mΩ respectively, leading to a short circuit frequency of f = 25 kHz.

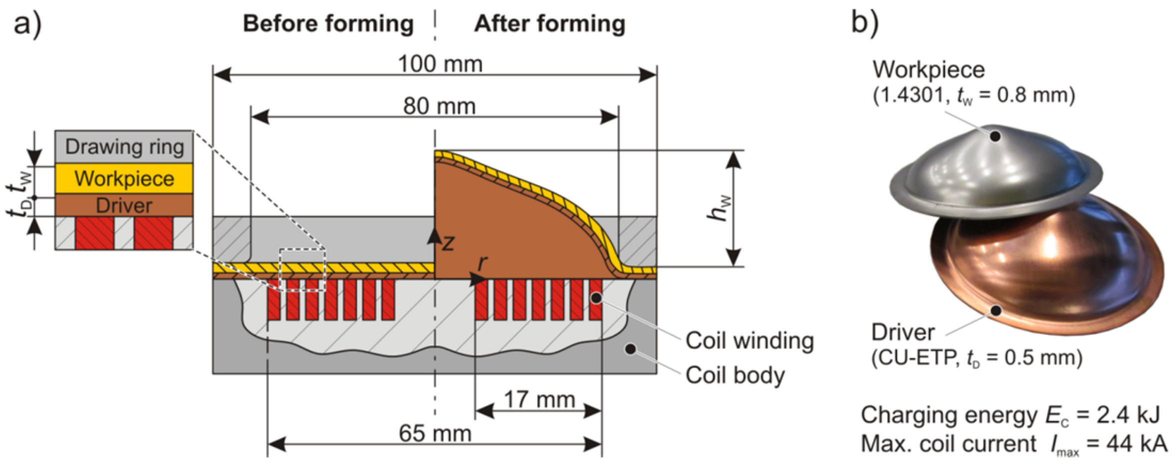


Figure 1: *a) Experimental setup for free forming experiments b) Workpiece and driver sheet after electromagnetic forming process*

Two stainless steels and one cold-rolled low carbon steel were used as low conductive workpiece materials. Additionally, the wrought aluminum alloy EN AW-5083 was used to analyze the effect of the electrical workpiece conductivity κ_W on the optimum driver thickness. With the exception of EN AW-5083 the workpiece thickness was varied from 0.5 to 1.0 mm. The wrought aluminum alloy EN AW-1050A and the copper alloy CU-ETP (CW004A) were used as driver materials. For the experiments with low conductive workpiece materials the driver thickness was varied in the range of 0.3 mm to 2.0 mm (see Table 2). To identify the comparatively small optimum thickness when using the aluminum alloy EN AW-5083, additional drivers with a thickness of 0.05, 0.1, 0.15, 0.2, and 0.25 mm were used. Within all experiments workpiece and driver sheet had a constant outer diameter of d = 100 mm. Mechanical and electrical properties of the workpiece and driver materials are summarized in Table 2.

Material	Elec. conductivity κ in MS/m	Yield stress k_f in MPa	Density ρ in kg/dm³	Thickness t in mm
1.4301 (X5CrNi18-10)	1.4	290	7.90	0.5, 0.8, 1.0
1.4509 (X2CrTiNb-18)	1.5	315	7.70	
1.0338 (DC04)	8.2	199	7.85	
EN AW-5083 (AlMg4.5Mn)	16	162	2.66	1.0
EN AW-1050A (AL 99.5)	34	107	2.70	0.3, 0.5, 0.7
CW004A (CU-ETP)	56	229	8.93	0.8, 1.0, 2.0

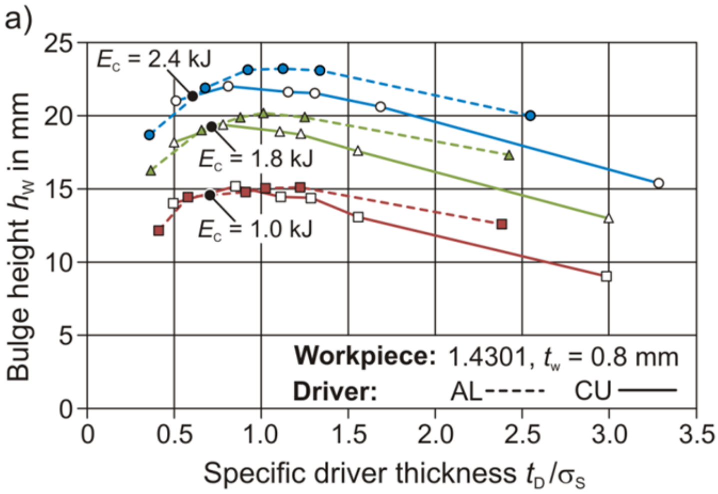
Table 2: *Electrical, mechanical, and geometrical properties of workpiece and driver materials*

After the electromagnetic forming operation the bulge height h_W of the workpiece is measured (see Figure 1a). This parameter is used to evaluate the quality of a driver configuration. To eliminate the effect of a varying discharge frequency f, the driver thickness t_D is divided by the corresponding skin depth σ_S. The dimensionless value obtained this way is used in the following presentation and discussion of the results.

4 Results and Discussion

4.1 Effect of driver material and charging energy

In Figure 2a the bulge height h_W for the stainless steel 1.4301 is plotted against the specific driver thickness t_D/σ_S. Due to nearly identical curves the relevant parameters $t_{D,opt}/\sigma_S$ and $h_W(t_{D,opt})$ for the ferritic stainless steel 1.4509 are summarized in Figure 2b.



b)

Workpiece:		1.4509, t_w = 0.8 mm			
		$t_{D,opt}/\sigma_s$		$h_W(t_{D,opt})$ in mm	
Driver:		AL	CU	AL	CU
Charging energy E_c	1.0 kJ	1.06	0.81	14.03	13.68
	1.8 kJ	1.05	0.80	19.01	17.76
	2.4 kJ	1.24	0.83	22.00	20.78

Figure 2: *Bulge height h_W for the stainless steels a) 1.4301 (austenitic) and b) 1.4509 (ferritic) (workpiece thickness t_W = 0.8 mm, charging energy E_C = varied)*

The curves shown in Figure 2a prove the existence of an optimum value for the driver thickness as stated by SANO ET AL. [14]. This general course of the curves was observed for all investigated combinations of charging energy, driver material, workpiece material, and workpiece thickness.

Summarizing the results of the two stainless steels (see Figure 2), the optimum specific thickness for aluminum drivers ranges between 1.01 and 1.13 with an average value of 1.06. In case of the copper driver the values are in the range of 0.78 to 0.85 with an average value of 0.81. The effect of differences in the electrical conductivity of the driver materials is eliminated in the definition of the specific driver thickness by consideration of the skin depth σ_S. The fact that there is still a difference in the optimum specific thickness for aluminum and copper can consequently be attributed to the differences in the mechanical properties of the two driver materials (see Table 2). A rough definition of the maximization problem which can be used to explain this correlation is given in Eq. (2). This approach takes the magnetic pressure acting on driver $p_{m,D}$ and the pressure required for plastic deformation of the driver sheet $p_{p,D}$ into account. Additionally the magnetic pressure acting on the workpiece $p_{m,W}$ is considered.

$$\max_{t_D} \frac{p_{m,D} + p_{m,W}}{p_{p,D}} \tag{2}$$

In case of the results given in Table 2 the parameter $p_{m,W}$ can be neglected as the electrical conductivity of the workpiece material is sufficiently small. Thus the optimum driver thickness is defined by the following condition:

$$\left|\frac{\partial p_{m,D}}{\partial t_D}\right| = \left|\frac{\partial p_{p,D}}{\partial t_D}\right| \quad (3)$$

According to the eddy current distribution obtained by WERDELMANN [15] given in Eq. (4), the current density $J(z)$ is decreasing monotonically along the driver thickness. This means that the current is concentrating in the surface-near region of the driver sheet.

$$J(z)/J(z=0) = cosh\left[(1+i)\frac{z-t_D}{\sigma_s}\right] \Big/ cosh\left[(1+i)\frac{t_D}{\sigma_s}\right] \quad (4)$$

Consequently, an asymptotic course as shown in Figure 3a can be assumed for the magnetic pressure $p_{m,D}(t_D)$. This, in turn, means that the function $f(t_D) = \partial p_{m,D}/\partial t_D$ is decreasing monotonically (see Figure 3b).
Referring to JONES [16], the yield pressure for the circular driver plate $p_{p,D}$ is proportional to its yield stress $k_{f,D}$ and to the square of its thickness t_D. Regardless of the detailed definition of $p_{p,D}$ the derivate of this function with respect to the driver thickness is consequently a straight line, as shown in Figure 3b. Assuming a modification of the driver yield stress $k_{f,D}$, a shift of the intersection point as shown in Figure 3b occurs. Consequently, a higher yield stress causes a decreasing optimum driver thickness and vice versa.

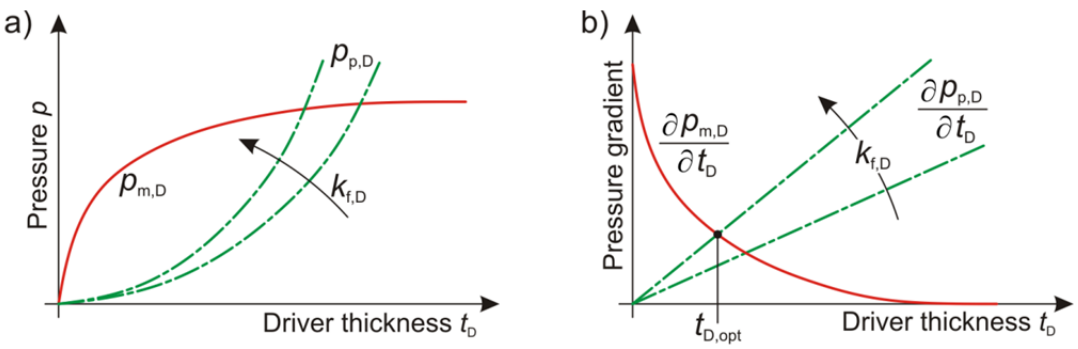


Figure 3: *Effect of driver material yield stress $k_{f,D}$ on the optimum driver thickness $t_{D,opt}$*

These results prove that recommendations for the optimum thickness always need to refer to a specific driver material. General recommendations as given by TILLMAN ET AL. [Til08], SANO ET AL. [San86], and BELYY ET AL. [Bel77] can only be a rough rule of thumb.
The results in Figure 2 show that the optimum driver thickness is not affected by the charging energy E_C, but that it is a crucial parameter when it comes to the choice of the driver material. In case of the smallest charging energy E_C = 1 kJ copper and aluminum drivers reach nearly identical maximum workpiece heights. In case of increased charging energies (E_C = 1.8 kJ and 2.4 kJ) the driver made of aluminum gives higher maximum values. This effect can be attributed to the increasing effective strain $\bar{\varphi}$ in workpiece and driver caused by the higher charging energy. This higher strain, in turn, entails an increase of the forming energy consumed by the driver sheet. Owing to the higher yield stress (see Table 2) the additional energy consumed by the driver sheet is higher in case of copper compared to aluminum. Accordingly, aluminum should be favored as driver material for forming operations with high effective strains. In case of calibration or coining

processes copper should be preferred instead as the negative effect of the higher yield stress is not that pronounced because of the small effective strains. In case both driver materials give identical forming heights (here: E_C = 1 kJ) the decision about the driver material should be based on economic considerations. In this case aluminum should be preferred as the costs for a copper driver are on average by factor 7 higher.

4.2 Effect of workpiece thickness and workpiece material

A variation of the workpiece thickness t_W was conducted for the three low conductive workpiece materials 1.4301, 1.4509, and DC04. To reach similar bulge heights h_W, the charging energy E_C was increased when increasing the workpiece thickness and vice versa. The results are summarized in Figure 4a.

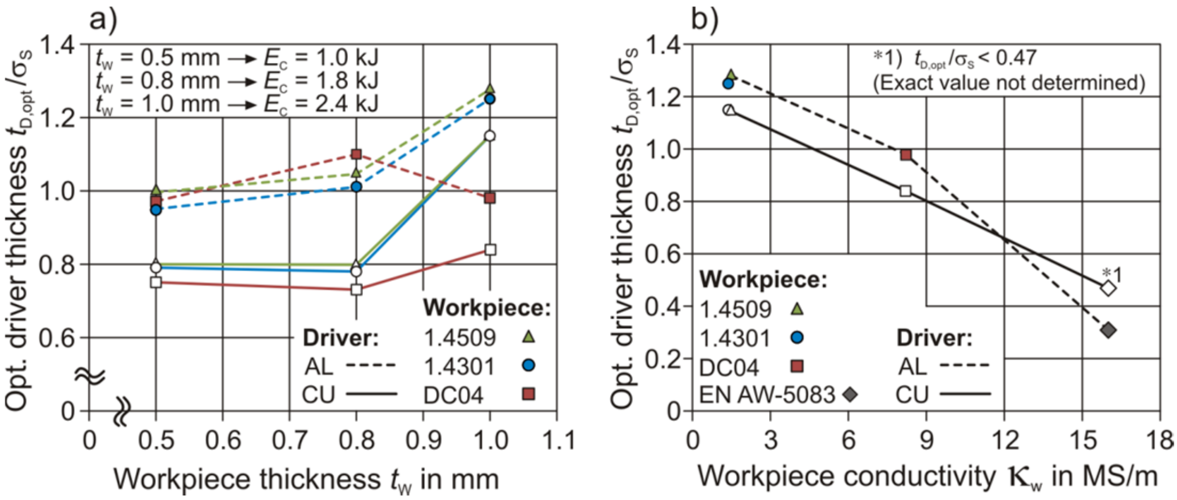


Figure 4: *Effect of a) workpiece thickness t_W and b) electrical workpiece conductivity $\boldsymbol{\kappa_W}$ on optimum specific driver thickness $t_{D,opt}/\boldsymbol{\sigma_S}$*

The results in Figure 4a reveal that the optimum driver thickness $t_{D,opt}$ tends to increase with increasing workpiece thickness t_W. An exception to that is the optimum thickness for DC04 using aluminum drivers. Consequently, no general recommendation for the adoption of the driver thickness in case of a varying workpiece thickness can be derived.
The results of the workpiece material variation are summarized in Figure 4b and show a clear correlation between workpiece material and optimum driver thickness. The optimum driver thickness $t_{D,opt}$ decreases with increasing electrical conductivity of the workpiece, regardless of the driver material. Consequently, the optimum driver thickness for the highly conductive aluminum alloy EN AW-5083 is significantly smaller than the optimum value for the low conductive stainless steels. The optimum thickness for EN AW-5083 using a copper driver is even smaller than the upper bound shown in Figure 4b. The exact value could not be determined due to a minimum copper sheet thickness of 0.3 mm which was not thin enough to reach the optimum. The correlation between optimum driver thickness and electrical workpiece conductivity can be explained considering the maximization problem defined in Eq. (2) by the following line of arguments: If the electrical conductivity of the workpiece is increased the shielding of the magnetic field penetrating through the driver is enhanced. This means that the pressure $p_{m,W}$ increases if all other

parameters remain equal (see Figure 5a). Consequently, the curve describing the sum of the magnetic pressure acting on driver $p_{m,D}$ and workpiece $p_{m,W}$ is shifted, as shown in Figure 5a. Due to this shift the derivate of this function with respect to the driver thickness decreases (see: Figure 5b). As the function $g(t_D) = \partial p_{p,D}/\partial t_D$ is not affected by a change of the workpiece conductivity the intersection point and, thus, the optimum driver thickness is shifted to a smaller value.

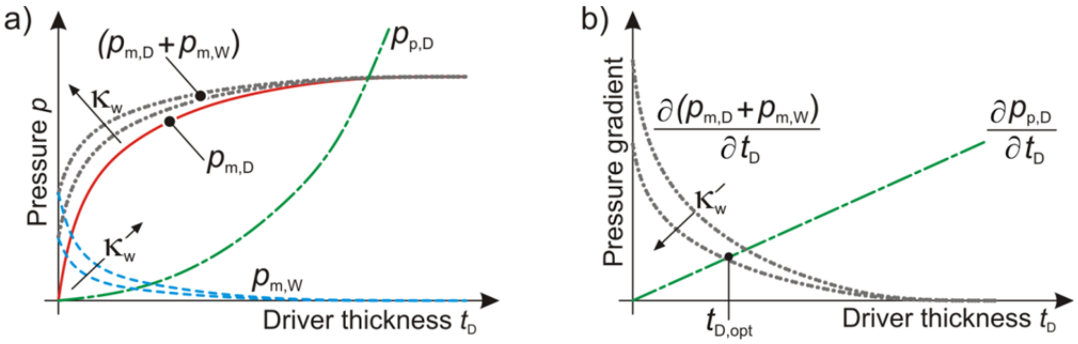


Figure 5: *Effect of electrical workpiece conductivity κ_W on the optimum driver thickness $t_{D,opt}$*

Beside this negative correlation of workpiece conductivity and optimum driver thickness the driver-assisted forming using a workpiece made of EN AW-5083 revealed that a proper driver sheet configuration can even enhance the forming of a workpiece material with high electrical conductivity. Without a driver sheet the bulge height of the aluminum workpiece was measured to be h_W = 27.15 mm in contrast to a maximum value of h_W = 28.18 mm in case of a driver-assisted process.

5 Conlusions

- The optimum specific driver thickness t_D/σ_S depends on the workpiece conductivity κ_W and on the yield stress $k_{f,D}$ of the driver material. Both parameters show a negative correlation.
- In case of forming operations with high effective strains aluminum should be preferred as driver material. In case of low effective strains (e.g. calibration or coining processes) copper drivers should be favored.
- Charging energy E_C and the amount of effective strain $\bar{\varphi}$ do not affect the optimum specific driver thickness.
- Even in case of workpiece materials with sufficiently high electrical conductivity for electromagnetic forming the use of a driver can enhance the forming process.

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