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Contactless Sheet Metal Feeder for Metal-forming Machines

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Abstract **-** This paper deals with the investigation of a contactless sheet metal feeder for metal forming machines. The concept is based on an asynchronous linear motor in which the sheet metal is used as the eddy currents runner. First numerical analyses were performed by means of a parameterized finite-element (FE) - model of the feeder. The focus was on the investigation of the operational characteristics in dependence on the material and geometrical properties of the sheet metal. The simulation results were validated by experiments using a demonstrator of the feeder. The results show that the feeding forces of partially above 1,000 N using the electromagnetic feeder can be doubled in comparison to mechanical roll feeders.

Keywords**:** Metal-forming machine, Sheet metal, Feeder, Asynchronous linear motor.

1. Introduction

To produce sheet metal workpieces in high quantities within a short time mechanical roll and gripper feeders are used for the automatic feeding of sheet metals from a coil into the press [Schuler, 1998; Behrens and Doege, 2010]. However, in press lines with high stroke rates of about 1000 min^{-1} primarily servo motor powered roll feeders are used (Web-1). To ensure a resource efficient production the sheet metal has to be positioned precisely with an accuracy below 50 µm (Web-2). Thereby the sheet metal is clamped with a high contact pressure of several kN to achieve a slip-free operation during high accelerations for a high position accuracy. A considerably problem of present mechanical roll feeders are represented in the damage of the sheet metal surface due to the high surface pressures in the almost linear contact region (Fig. 1b).

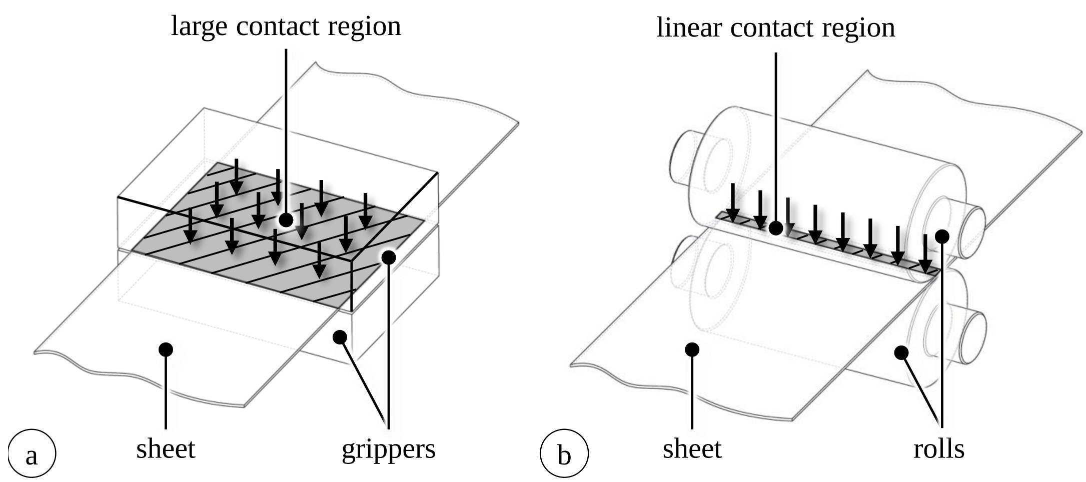


Fig. 1. Contact region in mechanical feeding systems: a) gripper feeder, b) roll feeder.

Common resulting errors are rolling marks and pit formations on the surface. In practice, therefor, preferable gripper feeders are used for feeding thin or sensitive sheets, since here comparatively low pressures arise due to relative large contact region (Fig. 1a). If sensitive materials, such as aluminium or copper, or polished sheet metals are fed with roll feeders the mechanical contact has to be limited to avoid a damage of the sheet surface. In these cases the maximum acceleration forces have also to be limited for a slip-free operation result in higher feeding times and therefor in a reduced production rate. Another problem is that contamination such as metal particles on the sheet metal may cause a permanent damage of the rollers and grippers which leads to downtimes of the press line and maintenance costs for renewing the feeder's elements.

2. Solution Approach

To solve these problems a novel method has been developed at the IFUM providing a completely contactless feeding by means of electromagnetic forces (Behrens et al., 2009; Teichrib, Krimm, 2013). The major advantage is that no mechanical components are required to initiate the feeding forces to the sheet metal. Therefor surface damages are avoided and sensitive sheet metals can also be fed with high feed rates. Due to the fact that just the sheet metal itself has to be accelerated higher dynamics can be achieved in comparison to conventional feeders

The feeder is based on the asynchronous linear motor wherein the sheet metal is used as the moving secondary part. It consists of two stators, which consist of a laminated iron package and a three-phase winding, as illustrated in Fig. 2.

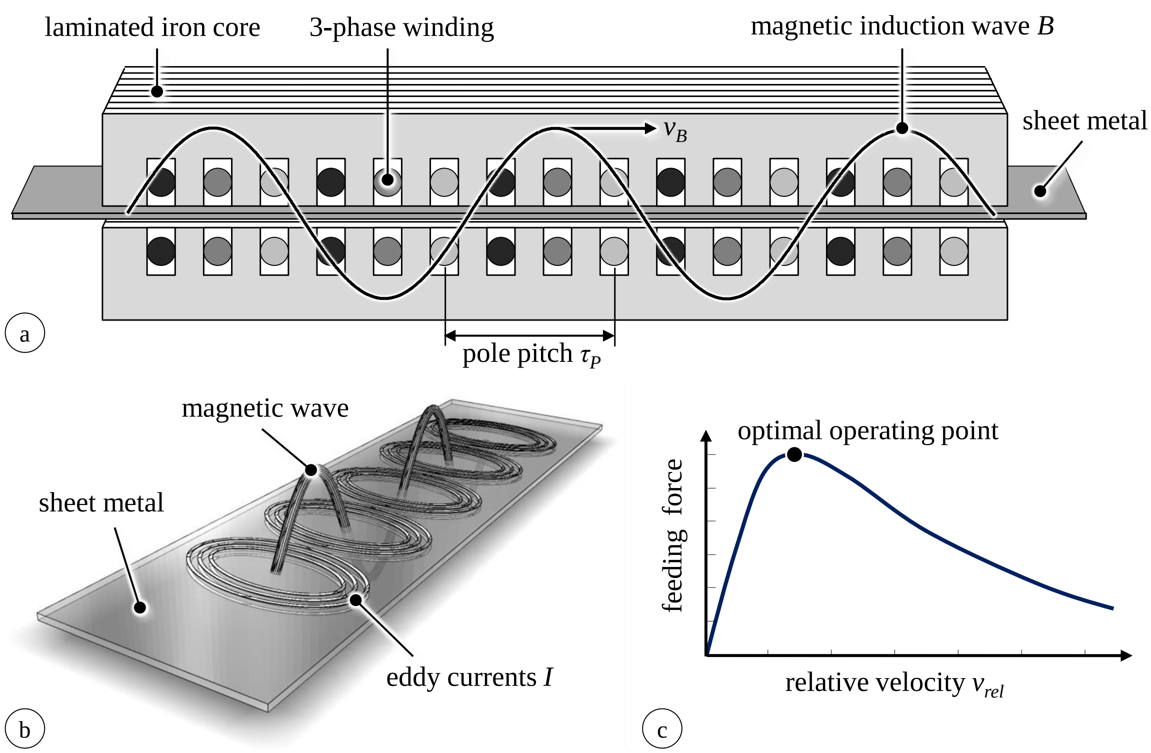


Fig. 2. Feeders structure and operational principle.

The stators are symmetrically positioned above and below the sheet to compensate the forces of attraction in ferromagnetic materials as well as the repulsive forces in non-magnetic sheet metals such as aluminium. By means of the three phase winding in the stators a transient sinusoidal magnetic wave *B* is induced in the air gap according to equation 1 (Budig, 1983).

$$B(x,t) = B_0 \cdot \cos\left(\frac{\pi}{\tau_P} x - 2 \cdot \pi \cdot f \cdot t\right). \quad (1)$$

The velocity v_B of the magnetic wave is controlled within the frequency f of the phase voltage or the phase current applied to the stators. In addition, the wave velocity depends on the pole pitch τ_P (Eq. 2) (Boldea, 2013), which defines the distance between two coil sides of inverse polarity of the same phase (Fig. 2a). The wave's amplitude B_0 and velocity is regulated via a frequency converter.

$$v_B = 2 \cdot f \cdot \tau_P . \quad (2)$$

In case of a relative velocity v_{rel} between the magnetic wave and the sheet eddy currents are induced in the electrically conductive sheet metal (Rajput, 2005). Due to their interaction a translational force is applied to the sheet metal according to the Lorentz law (Budig, 1983). The generated Lorentz force is proportional to the cross product between the induced eddy current I and the magnetic induction B multiplied with the sheet width w_s:

$$F_L = (B \times I) \cdot w_s . \quad (3)$$

As known from the asynchronous motors the Lorentz forces strongly depend on the relative velocity. Thereby an optimal operating point exists as shown in Fig. 2c (Toliyat, Kliman, 2004; Rajput, 2005). This is inversely proportional to the electrical resistance (Budig, 1983):

$$v_{rel,opt} \sim \frac{1}{R_s} . \quad (4)$$

Since the sheet metal acts as the secondary part of the feeder, its magnetic and electrical properties have a decisive influence on the operational performance of such a feeder (Budig, 1983; Boldea, 2013). These properties vary significantly for different metals (Table 1). Consequently other feed characteristics result in dependence on the sheet material which have to be investigated.

Table 1. Electrical and magnetic properties of typical sheet metals (Gobrecht, 2006; Bargel, Schulze, 2008)

Material	*Electric Conductivity [S/m]*	*Relative Permeability [-]*
Copper	*62*	*< 1*
Aluminium	*35*	*~ 1*
Brass	*15*	*~ 1*
Steel	*10*	*300 – 10,000*
Stainless Steel (1.4301)	*1.37*	*≤ 1.3*

3. Numerical and Experimental Investigations

3. 1. Feeder Design

To analyse the fundamental mechanism of the contactless feeder a parameterized finite-element (FE) – model was developed using the software tool Ansys (Fig. 3). The aim was to determine the operational performance of such a feeder in dependence on the material and geometrical properties of the sheet metal. For a realistic determination of the eddy currents in the electrically conductive sheet metal and the influence on the achievable forces, a three-dimensional model was built. Due to the symmetry properties the feeder was modelled as a ¼ model to reduce the computing time.

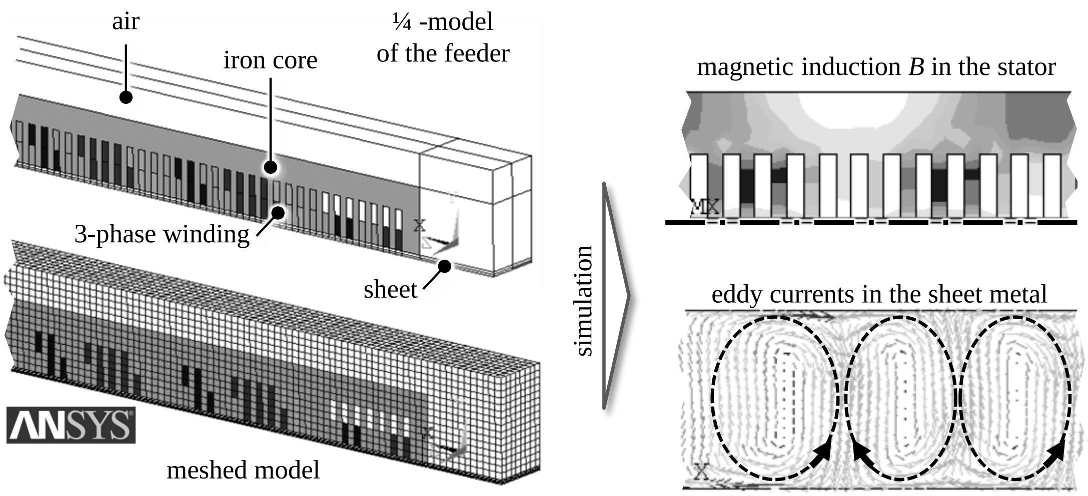


Fig. 3. FE modelling and simulation of the contactless feeder.

On the model symmetry and boundary planes the corresponding conditions for the eddy currents in the sheet metal and the magnetic field distribution were set. To take into account the magnetic leakage field near the stator, the surrounding air space with its magnetic properties was also modelled. The virtual coils were simplified as single conductor bars. The material properties for the sheet metal, the iron core (ThyssenKrupp Steel, 2009) and the coils were considered as viable parameters. To take into account the eddy currents as well as the nonlinear B/H-curve of the iron core and ferromagnetic sheet metals transient simulations were performed.

Based on the simulation results a real demonstrator of the feeder was manufactured to validate the FE model and to test the functional ability in practice (Fig. 4). The feeder can be controlled via a standard frequency converter with which the magnetic wave is modulated concerning the magnitude and velocity. Therefore the feeding forces as well as the sheet metal position are controlled. The rated voltage of the converter is 400 V at a maximum current of 50 A. To achieve the required low phase inductance of only 2.4 mH preformed coils were installed. With this winding a rated frequency range of 140 Hz can be achieved. In comparison, conventional electrical motors feature rated frequencies of 50 to 80 Hz. Due to a wire cross-section of 5 mm² an electrical resistance of 0.5 Ω results. An additional benefit is the reduced heating losses.

Table 2. Technical parameters of the feeder

parameter	***value***
rated voltage / current	400 V / 50 A
rated frequency	140 Hz
Poles	7
pole pitch	63 mm
resistance/phase	0.5 Ω
inductance	2.4 mH
length x width x height (feeder)	780 x 250 x 150 mm³

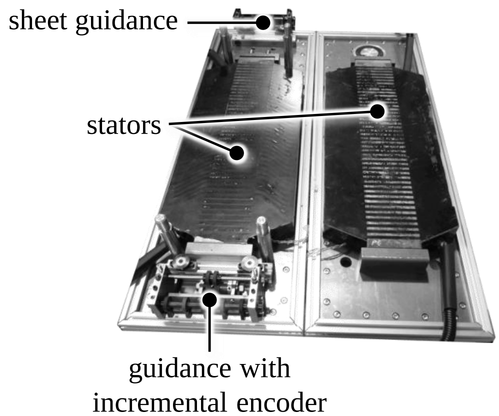


Fig. 4. Demonstrator of the feeder.

3. 2. Results

A main focus of the numerical analyses was the identification of the optimal control voltage frequencies of the feeder, referred to as slip frequencies, depending on the sheet material and geometry. With the voltage frequency the magnetic wave can be controlled in its velocity (Eq. 2). The simulation results indicate that a major dependence of the slip frequency exists with regard to the sheet metal material as well as to the respective cross section. In Fig. 5 the simulation results for the optimal slip frequency are shown. Within the simulations the cross sections for steel, aluminum and copper are varied.

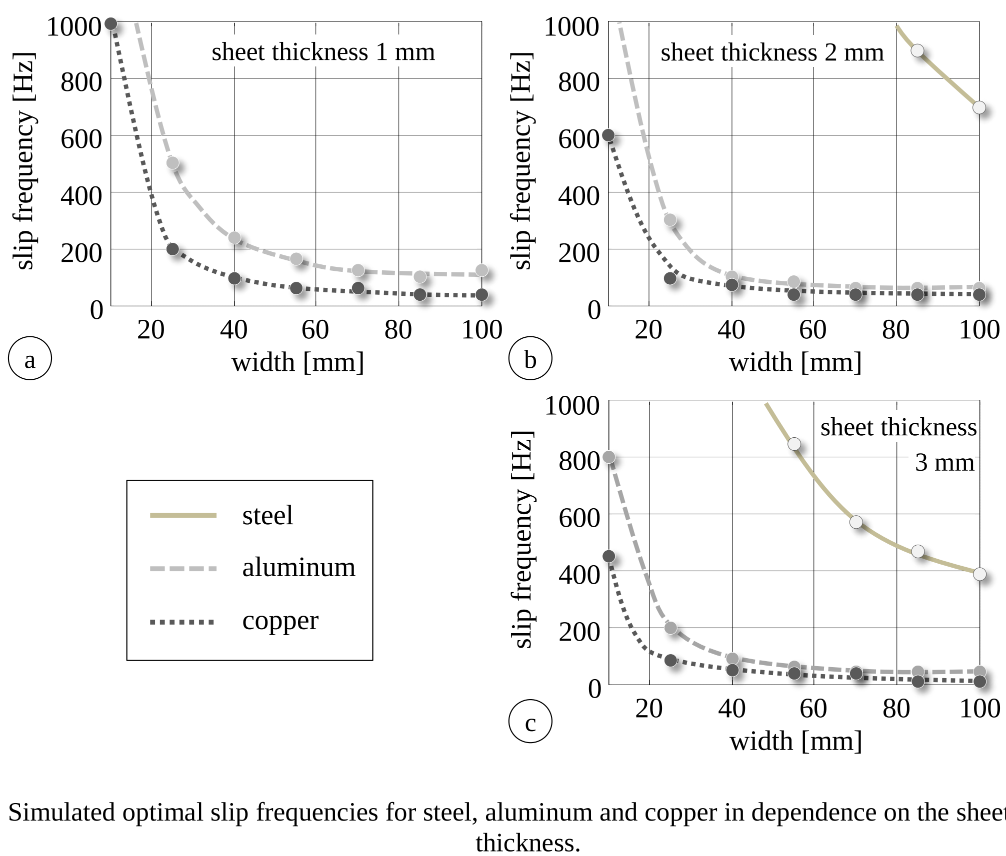


Fig. 5. Simulated optimal slip frequencies for steel, aluminum and copper in dependence on the sheet width and thickness.

It was identified that for low conductive materials, such as steel, very high slip frequencies result. Which are above 1,000 Hz in most cases. Therefor the optimal operation point (Fig. 2c) cannot be reached due to the limited power output of the converter resulting in a lower efficiency. Even when processing a 100 x 3 mm² steel sheet 400 Hz are required. The higher electrical conductivity of aluminum and copper leads to significantly lower slip frequencies (Eq. 4). For sheet width of 50 mm these amount below 200 Hz. This results in higher efficiency of the electromagnetic feeder and higher feeding forces. It is also shown in Fig. 5 that a general increase of the sheet thickness leads to lower slip frequency due to the reduced electrical resistance of the sheet.

The developed electromagnetic feeder was designed for feeding sheets with a maximum thickness of 3 mm and a width of 100 mm. For this purpose the maximum forces were examined in dependence on the geometry as well as the material by means of simulations and experiments. Here the static forces of the feeder applied to the sheet were measured. The results for aluminium and ferromagnetic steel are shown in Fig. 6. The sheet width was varied between 20 to 100 mm, the thickness between 1 to 3 mm. The experimental investigations show a very good correlation to the numerical studies with a deviation of less than 10 %.

Generally, an increase of the sheet width causes higher feeding forces due to the larger acting area between the magnetic field and the eddy currents according to Eq. 3. Since aluminum has a significantly higher electrical conductivity (Table 1) higher forces can be generated feeding a 1 mm sheet. For a 100 x 1 mm² aluminium sheet about 1,000 N can be achieved. Compared to current mechanical roll feeders of a comparable size the feeding forces could be more than doubled (Behrens, Marthiens, 2011). In contrast, a maximum of just 400 N were achieved by feeding a 1 mm steel sheet. This is caused by the limited power output of the frequency converter. By using a higher performance converter higher slip frequencies could be achieved, and correspondingly the feeding forces could be increased. The results also show that for sheet width of 20 mm and 30 mm low forces can be generated. For such sizes an improvement of the feeder is required.

For aluminum an increase of the sheet thickness leads to decrease feeding forces due to its paramagnetic properties. Thereby the magnetic resistance in the air gap is increased and lower forces result according to the less magnetic magnitude. When feeding steel, a higher sheet thickness results in a reduced electrical resistance. Therefor higher eddy currents are induced in the sheet metal. Since the magnetic field is uninfluenced due to the ferromagnetic material properties, a higher feeding force can be generated. The maximum force was thus achieved with a 100 x 3 mm² steel sheet and is above 1,000 N.

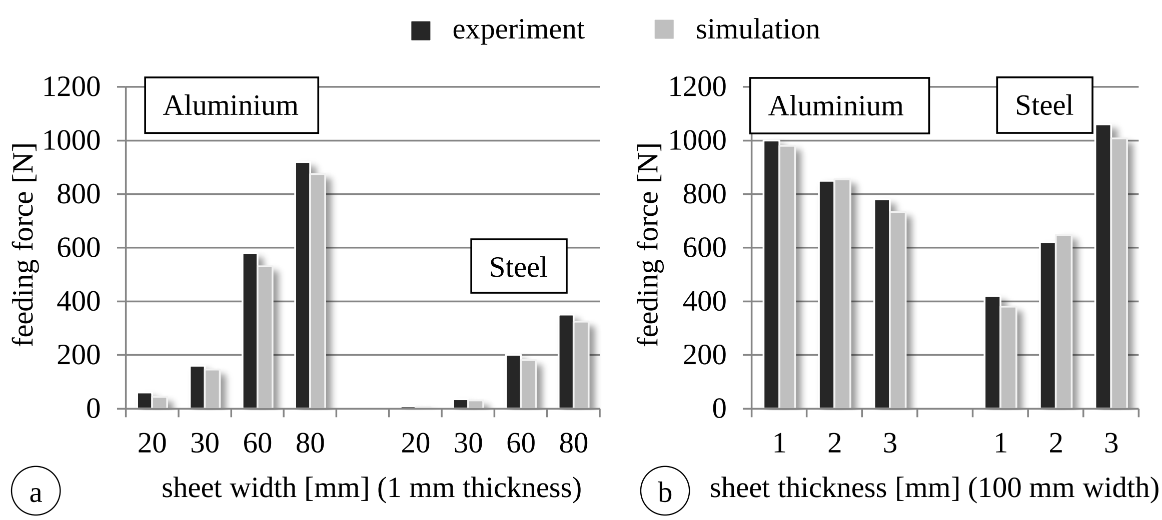
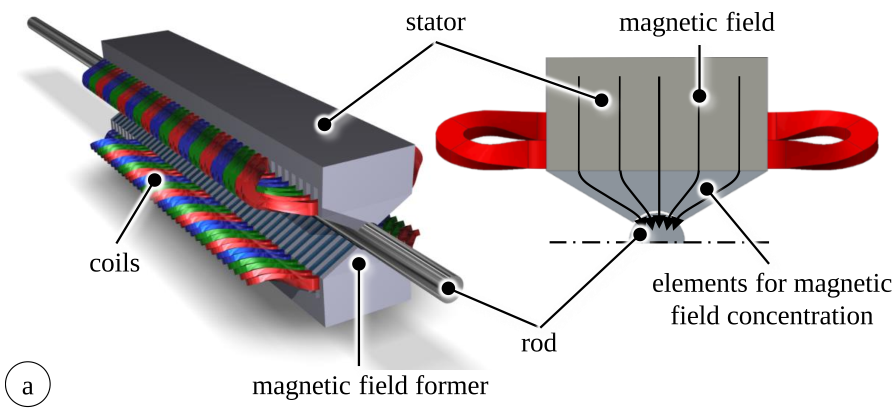


Fig. 6. Feeding forces for ferromagnetic steel and aluminum depending on the sheet width (a) and thickness (b).

4. Contactless Feeder for Complex Workpieces

Further research activities are planned to investigate the electromagnetic feed principle for complex workpiece geometries such as tubes, rods and profiles. A major problem is the uneven workpiece contour. For an efficient performance of the feeder the air gap should be as low as possible. Ideally, the stators should have the contour of the workpiece. To reduce the costs and to increase the flexibility of such a feeder, a modular system should be investigated. An approach is a feeder consisting of two static stators and variable iron core elements to concentrate the magnetic field. These field formers are adapted to the respective contour of the workpiece which have actually to be fed (Fig. 7a). The mounted field formers consist of a stack of electric sheets to suppress eddy currents and retroactively the heat losses. This is a comparable cheap construction and can be produced inexpensively. Thereby the magnetic field form elements can be flexibly interchanged. With these elements the magnetic field is focused and directed onto the workpiece. The magnetic field leakage can be reduced and the feeding forces can be increased significantly. First numerical analyses indicate that advantage feeding forces of more than 2000 N can be achieved using this feeder concept (Fig. 7b)



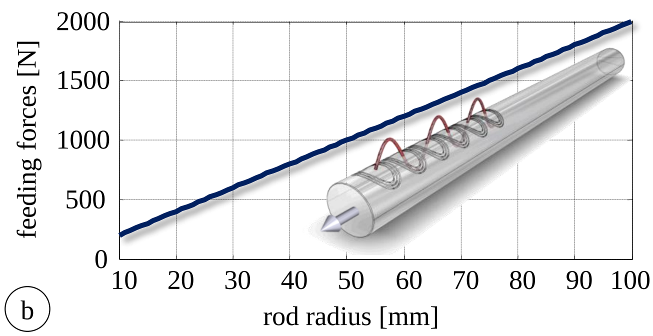


Fig. 7. Structure of a contactless feeder for rods or tubes (a) and simulated feeding forces in ferromagnetic steel depending on its radius (b).

5. Conclusion

The feeding system of a press line has a significant influence on the output rate. An innovative system has been developed at the IFUM which provide a contactless feeding of electric conductive sheet metals by means of electromagnetic forces. Numerical simulations have been performed and were validated by experiments using a demonstrator. In comparison to mechanical roll feeders the feeding forces were doubled. Future works are aimed at the investigations of such electromagnetic feeding system for complex workpiece cross-sections such as rods, tubes or other profiles.

Acknowledgements

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