Electromagnet Gripping in Iron Foundry Automation Part III: Practice

Rhythm Surén Wadhwa

NTNU Valgrinda, Department of Production and Quality Engineering
Trondheim, 7491, Norway

Abstract

Flexibility can be defined as the ability to respond efficiently to the changing demands of the customer and is different in SMEs (Small-to-Medium manufacturing Enterprises) than the traditional OEMs (Original Equipment Manufacturers). Costs involved in implementing manufacturing flexibility to meet customer demand are more important in the SMEs, especially those that are labor intensive for example foundries. Manufacturing systems with a high degree of flexibility can be rapidly changed to cover a wide range of production requirements. In this paper, we present a methodology enabling part handling flexibility, which has been incorporated in an iron foundry SME framework.

Keywords: *Foundry Automation, Part Handling, Machine Flexibility.*

1. Introduction

The need and rationale for flexible manufacturing arises from unpredictable market changes that are occurring with increased pace in the recent years. [4] These changes include:

- Increasing frequency introduction of new products.
- Changes in parts for existing products.
- Large fluctuation in product demand and mix
- Changes in governmental regulations (safety and environment)
- Changes in process technology

An element of flexibility is needed to cope with the large fluctuations in product demand and mix caused by the new market conditions. A flexible manufacturing system which can adjust the production capacity to fluctuations (internal / external) and can adapt functionality to new products, is needed. In order to cover a wide range of manufacturing requirements, production systems must be flexible in several fields.

The analysis of the literature regarding the topic of manufacturing flexibility, in high volume production environments, highlights the presence of four main categories of scientific works. [3] The publications in the first group deal with the analysis of the interpretation of manufacturing flexibility and their relationships with manufacturing problems. The second group of publications deal with classification of existing flexibility forms through conceptual frameworks. The third category focuses on the development of approaches and models, both qualitative and quantitative, to support the system design while considering the given system flexibility forms. The fourth group of research aims at systemizing the higher number of flexibility definitions related to the real implementation of various forms of flexibility in a manufacturing system. The work presented in this paper belongs to the third category. We present a methodology to support machine and part handling flexibilities by developing an experimental study for the holding forces in for handling of iron foundry parts using an electromagnet gripper. The experimental results obtained were verified with finite element model and were found to be within 10% accuracy. [1]

The flexibility definitions presented could have different interpretations in different organizational contexts. The following example illustrates how a promising flexibility form can lead to different results. When using changeover to evaluate the system flexibility different foundries [2] defined its components of product modularity, volume and product mix, differently according to their individual manufacturing environments (sand casting, aluminium die casting etc.), and associated it differently with different levels of difficulties in implementation. The essential spheres of flexibility are shown in Figure 1.

Machine flexibility refers to the various types of operations that the machine can perform without requiring a prohibitive effort in switching from one operation to another and part handling flexibility is its ability to move different part types efficiently for proper positioning and processing through the manufacturing facility it serves. The use of magnets for iron part handling has a long history. Permanent magnets in the form of metal oxides (Fe203) have existed since the Paleozoic. The first

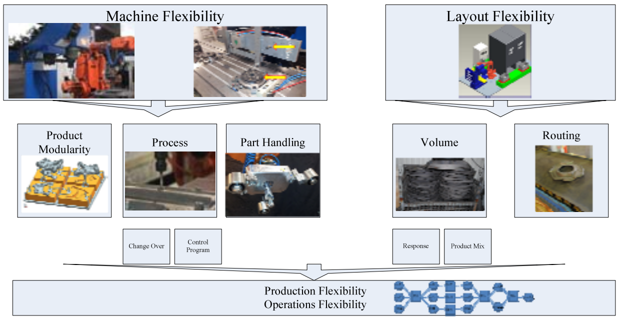


Fig.1. Essential spheres of foundry manufacturing flexibility

application is known in China around 2000 BC with compasses for direction orientation.In Europe, probably the Vikings were the first users magnets for navigation. The first patent for the use of an electromagnet was granted nearly 130 years ago. [Allen, 1919].

The key parameters that affect the holding force of electromagnet are the part pick up surface charaterestics, the dimensions of the part and the weight of the part. Several approaches have been reported in literature to prove that a particular grasp mode is stable [2]. Kinetic analysis of a particle or a system of particles is governed by Newton's second law of motion, which can be mathematically represented as follows:

$$\Sigma F = ma$$

where ΣF is the resultant of the total forces , m is the mass, and a is the resultant acceleration.

For a system of particles, such as symmetric objects, we need to consider the uniformly distributed mass of the system as a point mass localized at the centre of gravity of the system. The corresponding equations of motion are defined by the, *Principle of motion of the center of mass*, which can be represented as below:

$$R_x = \Sigma F_x = m(a_G)_x$$
$$R_y = \Sigma F_y = m(a_G)_y$$
$$R_z = \Sigma F_z = m(a_G)_z$$

An analysis of forces that come into action during the different movements of the robot arm can be broadly classified as prehension and retention.

Prehension of a part involved vertical motion of the gripper towards the part, and grasping the part using the electromagnet end. The forces that come into existence during this process are the electromagnetic force through the gripper F_e, the weight of the part *w*, and the force generated due to the movement of the robot arm, *ma*. The equilibrium forces can be represented as follows:

$$F_e - w = ma$$

A grasp during prehension is stable if the electromagnetic force generated during pickup is large enough to overcome the effect of weight of the part, and the forces due to the acceleration of the gripper, towards or away from the object.

Thus, the following condition can be established for grasp stability.

$$F_e > ma + w \tag{1}$$

A grasp could be considered stable during prehension if it satisfies the condition shown in expression (1).

Retention of the object during material transfer involves a force due to the acceleration of the robot arm when translating from the 'pick' position to the 'place' position, and an opposing shear force which acts against the direction of motion of the gripper, aside from the forces perceived during the prehension motion of the gripper. The shear forces serves to resist the slipping of part, once picked.

During translation in the horizontal plane, every line in the body of the gripper remains parallel to its initial position in the x-z plane. The equations of motion of the body can be represented as follows:

Horizontal Component:

$$\Sigma F_{x-z} = F_h - F_f = m(a_G)_{x-z}$$

The force generated due to the movement of the robot in horizontal direction F_h, tends to cause the material to slip. The frictional force F_f, must be at least large enough to prevent this slippage, by serving as the limiting value.

It is known that:

$$F_f = \mu N$$

where μ is the coefficient of friction between the object and the gripper material, and *N* is the normal component of the force. The value of *N* may be determined by computing forces in a vertical plane.

Vertical Component:

$$\Sigma F_y = (F_p - w - N) = m(a_G)_y = 0$$

Since there is no vertical movement when moving the object in a horizontal plane the LHS of the equation is equated to zero, which makes the calculation of the normal force N possible.

A grasp is considered to be stable during retention, if the shear force due to friction and suction through the robot gripper is at least as large as the horizontal force generated due to the motion of the robot. Thus, the following condition may be established for grasp stability.

$$F_f > F_h$$

In summary, a grasp is considered stable during retention if it satisfies the above inequality. The experiments that follow help in a better understanding of the performance of the grippers.

2. Experiments

A setup was built to measure the normal force required to pull a part from the electromagnet normal to its surface. Figure 2.0 shows the experimental setup and indicating its main components. The actuator used to pull the part was a Deckel FP3L (Type 2271) three axis lathe. The electromagnet was attached to the lathe spindle axis via a strain gauge load cell with a capacity of 5000N (Kistler 5011, Hottinger Baldwin Messtechnik Gmbh Spider 8; Accuracy +-0.01%). A fixture was designed to connect the loadcell directly to the spindle of the lathe. The procedure followed for normal holding force measurements is described below.

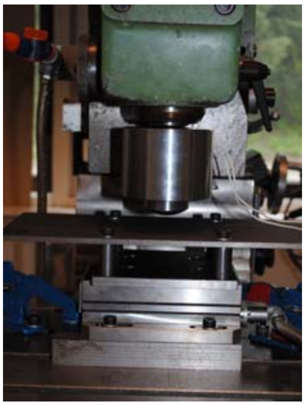


Fig. 2. Magnet holding force estimation setup

A cast iron plate with thickness equal to the iron foundry part thickness was held by a fixture on the milling machine bed, and the normal forces were applied to the electromagnet, through the machine spindle. The data was acquired through a 3 –axis Kistler load cell. The normal force was applied gradually starting at zero and moving the lathe spindle along z-axis, until the part was pulled off the surface of the electromagnet. The normal force was defined as the applied force at the moment when the two bodies break contact. A computer based data acquisition system was used to acquire and store the data.

The electromagnet was used with DC voltage varying between 17.5 and 25V and made of standard steel 1.0035. The B-H curve for the parts were also obtained from an external vendor (Figures 3 and 4). The normal force test was repeated five times for each specimen. Since the permeability of ferromagnetic materials is multi-valued, the specimens were demagnetized (ING System Type MZ04503-1 serial 577, 220 V 50-60 Hz) each time, before bringing in contact with the electromagnet gripper head. This procedure ensured that the specimens will not have any residual flux and their B-H curves would be the same for all replications. The above force estimation experiments were necessary as a special magnet was developed for the specific foundry part curvature (Figure 5) requirements.

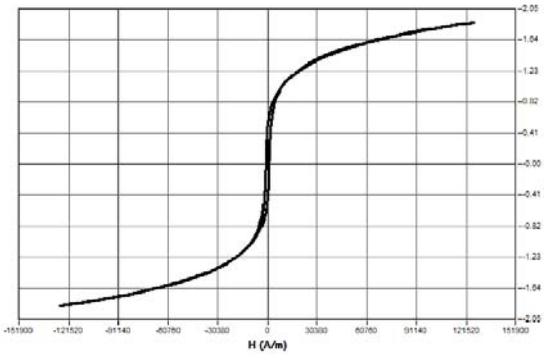


Fig. 3. Magnetization curve of plate

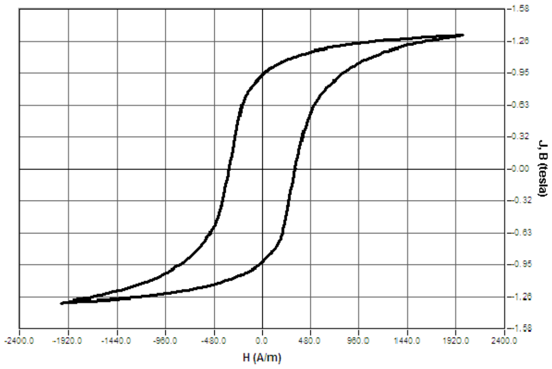


Fig. 4. Magnetization curve of electromagnet core

Fig. 5. Sample curved foundry part in need of handling automation

The strength of the magnetic field produced in the electromagnet depends on the current passing through the coil. For this reason, care was taken to maintain the current at the same amperage for comparative tests, i.e. if two tests were going to be compared to each other, the current in both of them was kept the same.

The permeability of ferromagnetic materials is multi-valued. If an external magnetic field is applied to a ferromagnetic material, it will become magnetized. However, when the external field is removed, the material will maintain some residual flux density. If the external field is applied again, the magnetization curve will be different from the previous time. Because of this, the specimens were demagnetized (ING System Type MZ04503-1 serial 577, 220 V 50-60 Hz) each time, before bringing in contact with the electromagnet gripper head. This procedure ensured that the specimens will not have any residual flux and their magnetization curves would be the same for all replications.

During the measurement of the normal force, an important factor influencing the experiment is the temperature of the electromagnet. The temperature of the electromagnet increases with time, due to the current flowing in the coil. Even though the rise in temperature is not considerable because the electromagnet is not turned on for long periods of time (15 seconds at maximum for our application), the replications were randomized to minimize temperature dependent variations. Each test was repeated (5) times.

The normal force was measured at distance varying from 0-15mm by moving the lathe spindle along z-axis. A computer based data acquisition system was used to acquire and store the data. Figure 6.0 shows a representative normal holding force measurement and illustrates the determining of this force.
.

3. Results

To The results show that the average normal holdig force is higher for the thinner (t ~5,67-5,77)cast iron plate than for the thicker one (t ~7,66-7,82). As the input volatge to the electromagnet was decreased from 25 V DC to 17.5 V, there was a decrease observed in the holding force of the electromagnet. This is because the decrease in the current supplied to the electromagnet and hence the decrease in holding force.

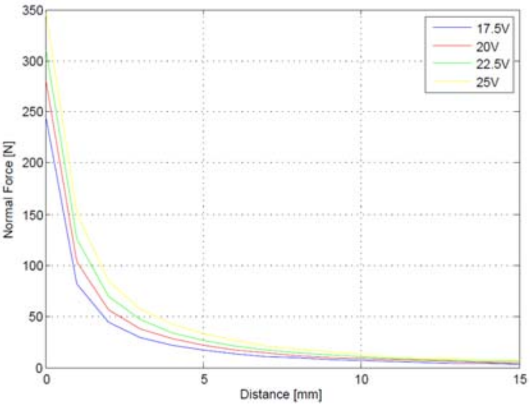


Fig. 6.0 Variation of normal holding force for cast iron plate thickness (t ~7,66-7,82), at different electromagnet volatges

Table 1: Average Normal Force for Varying Electromagnet Voltage for Cast Iron Plate thickness (t ~7,66-7,82)

Airgap (mm)	***17,5V***	***20V***	***22,5V***	***25V***
15	3,696	4,640	5,744	6,864
14	4,032	5,120	6,400	7,696
13	4,592	5,824	7,088	8,800
12	5,072	6,576	8,288	8,890
11	5,904	7,552	9,376	10,016
10	6,888	8,720	10,848	13,212
9	7,888	10,176	12,576	15,344
8	9,440	12,016	14,720	18,084
7	11,264	14,208	17,664	21,416
6	13,680	17,542	21,488	26,368
5	17,024	21,824	26,880	32,896
4	21,920	28,256	34,672	42,352
3	29,984	38,400	47,024	57,440
2	44,656	57,152	70,112	84,736
1	81,648	103,856	126,512	151,152
0	243,680	279,488	309,928	345,376

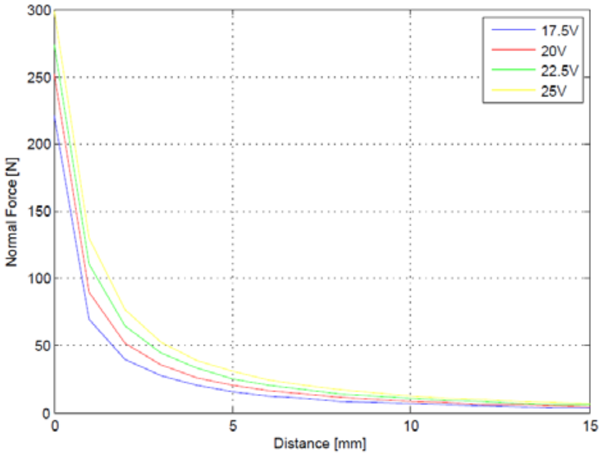


Fig. 7.0 Variation of normal holding force for cast iron plate thickness (t ~5,67-5,77), at different electromagnet volatges

Table II: Average Normal Force for varying electromagnet Voltage for Cast Iron Plate thickness (t ~5,67-5,77)

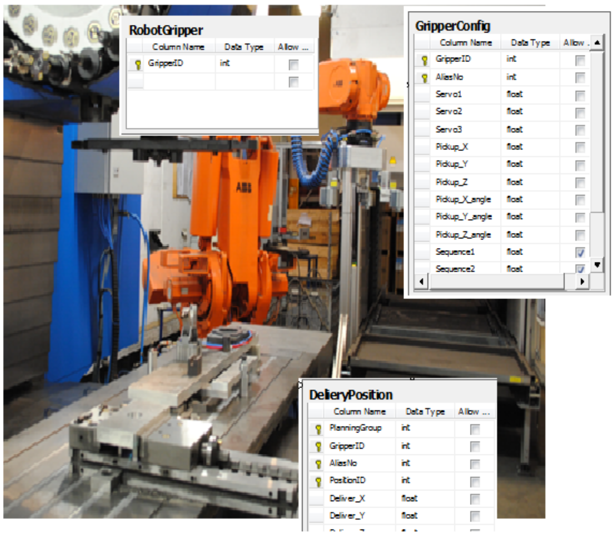
Airgap (mm)	*17,5V*	*20V*	*22,5V*	*25V*
15	3,536	4,608	5,760	6,880
14	3,820	5,072	6,324	7,496
13	4,284	5,716	7,136	8,516
12	4,864	6,432	8,048	9,680
11	5,642	7,420	9,228	10,932
10	6,452	8,416	10,538	12,588
9	7,392	9,858	12,214	14,544
8	8,784	11,534	14,368	17,154
7	10,504	13,758	17,120	20,432
6	12,736	16,704	20,704	24,748
5	15,878	20,758	25,676	30,706
4	20,346	26,526	33,046	39,404
3	27,366	35,816	44,384	52,784
2	40,048	52,156	64,560	76,816
1	69,792	89,92	110,412	129,952
0	220,448	252,208	274,048	298,560

The holding force also increases with the decreasing airgap between the electromagnet and part, which among other factors could be because of decreasing airgap reluctance. The airgap term applies to the flux lines crossing the magnet-part interface. In reality, the airgap length varies at each point in the interface because of surface roughness and form errors. A simplified assumption could be to consider the cross-sectional area of the air gap is equal to the magnet-part contact area.

The electromagnet holding force data generated from the above experiment, was utilized in the automated test cell at the iron foundry. (Figure 8)

4. Conclusions and Future Work

Research on the holding force of electromagnet grippers is in its early stages. Many factors influence the force of attraction between a electromagnet and a part, and their effects are not well understood. This chapter presented a methodology that can be used to study the normal holding forces on iron casted plates (obtained from the participating foundry). Efforts towards realization of a mathematical model are presented in [5] and [6]. The COMSOL finite element model was used to obtain estimates of normal holding force for airgaps varying between 0-15 mm.


RobotGripper

	Column Name	Data Type	Allow ...
🔑	GripperID	int	☐
			☐

GripperConfig

	Column Name	Data Type	Allow ...
🔑	GripperID	int	☐
🔑	AliasNo	int	☐
	Servo1	float	☐
	Servo2	float	☐
	Servo3	float	☐
	Pickup_X	float	☐
	Pickup_Y	float	☐
	Pickup_Z	float	☐
	Pickup_X_angle	float	☐
	Pickup_Y_angle	float	☐
	Pickup_Z_angle	float	☐
	Sequence1	float	☑
	Sequence2	float	☑

DelieryPosition

	Column Name	Data Type	Allow ...
🔑	PlanningGroup	int	☐
🔑	GripperID	int	☐
🔑	AliasNo	int	☐
🔑	PositionID	int	☐
	Deliver_X	float	☐
	Deliver_Y	float	☐

Figure 8.0 Automated test cell framework utilizing the data from the experiments

The error was within 10% for most cases. [7] It was noticed that the BH curve of the materials is critical for obtaining meaningful results when a model is used to predict the normal force. However, obtaining this curve is a by itself a difficult task because magnetic properties depend on a large number of factors.

It was observed from the model validation experiments that the normal holding force increases with current until it reaches a maximum and then it starts to decrease with further increments in current. This is attributed to the leakage flux and saturation of the workpiece material that doesn’t produce any force in the normal direction. This observation could suggest that using maximum available current doesn’t always produce maximum holding force.
Some recommendations for future to further improve our understanding of the electromagnet gripping characteristics, to help improve their performance, are as below:

- Surface flatness is an important factor, and it is recommended that a method to characterize it be developed.
- Since most models capable of computing force of attraction assume a constant airgap between the two bodies, a correlation between flatness characterization and an equivalent airgap length is desirable.
- The effect of other factors that can influence the holding force, such as temperature (BH curve is temperature dependent), lubricants (cutting fluids) etc. is also recommended.

Acknowledgments

Financial support from the AutoCast Consortium and the Norwegian Research Council is gratefully acknowledged.

References

[1] Wadhwa, R.S., Lien,T. Electromagnet Gripping in Iron Foundry Automation Part I: Principles and Framework **,** IJCSI, Vol 6, Issue 6, Nov 2011

[2] Wadhwa, R.S, Lien, T.K., Monkman, G.J., Robust Prehension for ferrous metalcasted product families, Proceedings of MITIP 2011

[3] Sethi, A.K., & Sethi, S.P. (1990). Flexibility in manufacturing: A survey. International Journal of Flexible Manufacturing Systems, 2, 289–328.

[4] Koren, Y. 2010. Reconfigurable manufacturing systems: Key to future manufacturing. Journal of Intelligent Manufacturing.

[5] Wadhwa, R.S. "*Iron Foundry Automation*", Proc. High Tech Die Casting 2012 (HTDC 2012), Vicenza, Italy

[6] Wadhwa, R.S., Robust Part Handling in Foundry Automation, 37th International Matador Conference 2012, University of Manchester.

[7] Wadhwa, R.S. Electromagnet Gripping in Iron Foundry Automation Part II: Simulation**,** IJCSI, Vol 6, Issue 6, Nov 2011

First Author Rhythm Suren Wadhwa is a researcher at the department of production and quality engineering, NTNU. She has worked in the Manufacturing Automation industry for five years. Current research interests include assembly automation, optimization techniques, assembly simulation and industrial robotics. She was the president of Society of Women Engineers at the University of Michigan. She has a Masters Degree in Mechanical Engineering from University of Michigan, and Bachelors degree in Manufacturing Processes Automation Engineering.