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Research on the Lifting Forces of Industrial Plastic Vacuum Cups

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Abstract: *Industrial vacuum cups are used for lifting, holding and moving a wide variety of automated applications for handling semi-finished products and parts made of a wide range of materials - metal, glass, plastic, paper, wood, etc. and are used in a variety of industries. This paper presents some of the authors' theoretical and experimental research on the maximum lifting force that different types of vacuum cups can achieve. The study was carried out on the basis of sizing recommendations made by manufacturers and dealers of these types of vacuum cups. The specially designed experimental stand was installed on the universal material testing machine LBG 100 kN and allowed the practical determination of these lifting forces provided by various types of industrial vacuum cups. Lifting force measurements were carried out with the AXIS FB 1k digital dynamometer attached to the machine. Vacuum cups of 3 different shapes and made of 3 different materials were used, using different vacuum depressions - 0.3 bar, -0.5 bar, -0.7 bar and -0.9 bar. The research aimed to determine by measurement the maximum lifting force of these types of vacuum cups applied to steel parts. The results obtained for these forces were compared with the calculated theoretical values, with the manufacturer's recommended dimensioning values, and comparative conclusions were also drawn on the maximum lifting force provided by the different types of industrial vacuum cups studied.*

Keywords*: silicone rubber, urethane rubber, NRB, vacuum cups, vacuum, lifting force*

1. Introduction

Industrial vacuum cups are also known as rubber vacuum cups or silicone vacuum cups.

Industrial vacuum cups have the function of lifting, suction, holding and moving for a wide variety of automated applications for handling semi-finished products and parts made of a wide variety of materials such as: metal, glass, plastics, paper, food, wood, etc. These vacuum cups are used for different fields and industries [1-3].

Basically, these vacuum cups are made of various types of plastics and are driven by a vacuum pump that generates a depression at the vacuum cup-workpiece contact. This allows the vacuum cup to develop a lifting force that enables the safe transport of the part/workpiece to the desired destination [4, 5].

Initially, the materials handled with vacuum cups were bottles - a rigid material with a flat, low roughness, watertight surface.

Gradually, through the industrialization of many different types of materials, the vacuum cups were adapted in correlation with the material of the part to be lifted and handled. The increasing robotisation of handling has led to the emergence of different types of vacuum cups, variable both in terms of the material from which they are made and their shape.

The materials from which industrial vacuum pads are made are: nitrile butadiene rubber (NBR), silicone rubber, urethane rubber, conductive NBR, conductive silicone rubber, etc.

The construction shapes of industrial vacuum cups are: flat, flat with ribs, flat with groove, thin flat, bellows, bellows with ribs, etc.

Figure 1 shows a flat type vacuum cup made of NBR material, the upper part of which shows the steel base that secures the vacuum cup and ensures coupling to the vacuum source. Vacuum is generated in the space between the vacuum cup and the workpiece to be lifted, which develops a force that presses the vacuum cup against the surface to be handled and lifts the workpiece.

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Figure 1. Industrial vacuum cup NBR flat

The frictional force that occurs at the vacuum cup-workpiece contact will allow the development of a lifting force that will be used to transport and manipulate the workpiece. This lifting force depends on the following factors:

- the material of the part to be lifted-handled and the surface roughness of the part;
- the material of the vacuum cup;
- the shape of the vacuum cup;
- the area of the vacuum cup-workpiece contact surface subjected to the vacuum created (directly proportional);
- the pressure of the vacuum to drive the vacuum cup.

The influence of the following parameters was studied in this research: vacuum cup shape, vacuum cup material and vacuum pressure used. The following quantities were determined Figure 2:

- theoretical lifting force;
- the lifting force recommended for sizing by the manufacturers;
- the maximum lifting force measured by experimental investigations.

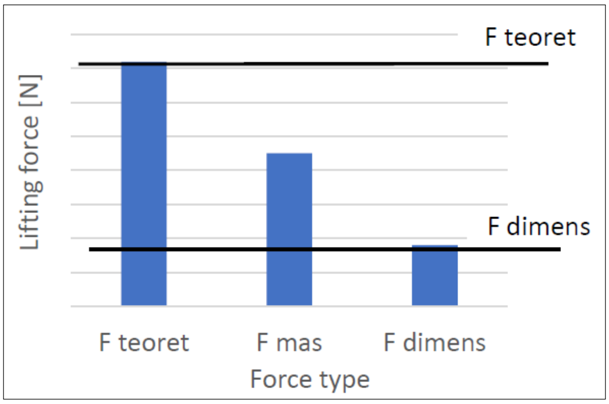

Figure 2. Comparison of the values of the forces studied

The theoretical lift force (F_{teoret}) is calculated as the product of the vacuum cup area (A) and the vacuum depression (p) (1).

$$\boldsymbol{F_{teoret} = A \cdot p} \quad (1)$$

The dimensioning force (F_{dimens}) is the theoretical force decreased by a super unit safety factor (k) recommended by the vacuum cup manufacturer [6, 7].

$$F_{dimens} = \frac{F_{teoret}}{k} = \frac{A \cdot p}{k} \quad (2)$$

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In order to be safe when handling parts, the measured lifting force (F_{mas}) must always be greater than the dimensioning force.

Research was carried out on steel parts using 3 different shapes of vacuum cups (flat, flat with ribs, bellow) of 3 different materials (NBR butadiene nitrile rubber, silicone rubber, urethane rubber) and 4 different vacuum levels -0.3 bar, -0.5 bar, 0.7 bar and -0.9 bar.

2. Materials and methods

2.1. Types and materials for vacuum cups

Seven of the most commonly used ZPT vacuum cups were used for the research, each cup having a diameter of 32mm, manufactured by SMC company, with the corresponding codes [6].

The systematisation of these vacuum cups is shown in Table 1.

In the case of urethane vacuum cups, flat and flat with ribs shapes were not available because the manufacturer only produces them to special order.

Table 1. Types of industrial vacuum cups studied

No.	Vacuum cup material	Sucker shape		
		Flat	Flat with ribs	Bellow
1	NBR	 ZPT32UN-B01	 ZPT32CN-B01	 ZPT32BN-B01
2	Silicon	 ZPT32US-B01	 ZPT32CS-B01	 ZPT32BS-B01
3	Urethane	At the time of the experiments, they were not in production. They were made to order. ZPT32UU-B01	At the time of the experiments, they were not in production. They were made to order. ZPT32CU-B01	 ZPT32BU-B01

2.2. Material of the piece

The part on which the determinations were made was made of non-alloy structural carbon steel S355JR (1.0045): EN 10025-2-2004.

The used specimen has a parallelepiped shape with dimensions 250x200x30 with the upper surface machined by grinding to a roughness of Ra=0.8µm. The specimen is fixed to the table of the testing machine with 4 hexagonal head screws inserted in the cylindrical recesses according to Figure 3.

2.3. Technological system used for experiments

A Figure 3 technological system consisting of the following equipment was used for the experimental research:

- universal material testing machine LBG 100 (1); the machine was set to the pull function with a travel speed of 20mm/min;
- digital dynamometer with external sensor FB1k (2) with a measuring accuracy of 0.1N; it was used to ensure a higher measuring accuracy than the universal material testing machine;
- vacuum cup fixing device (3); its purpose is to ensure the connection between the dynamometer and the vacuum cup under study as well as the connection to the vacuum pump;
- vacuum generating system consisting of
  - -a vacuum pump (4) VP 2200N, free air displacement 12 CFM, power 1 HP;
  - -a pressure regulator (5);
  - -a vacuum gauge (-1 ... 1.5) bar (6), accuracy class 1.6;
  - -tubing.
- vacuum pad (7).

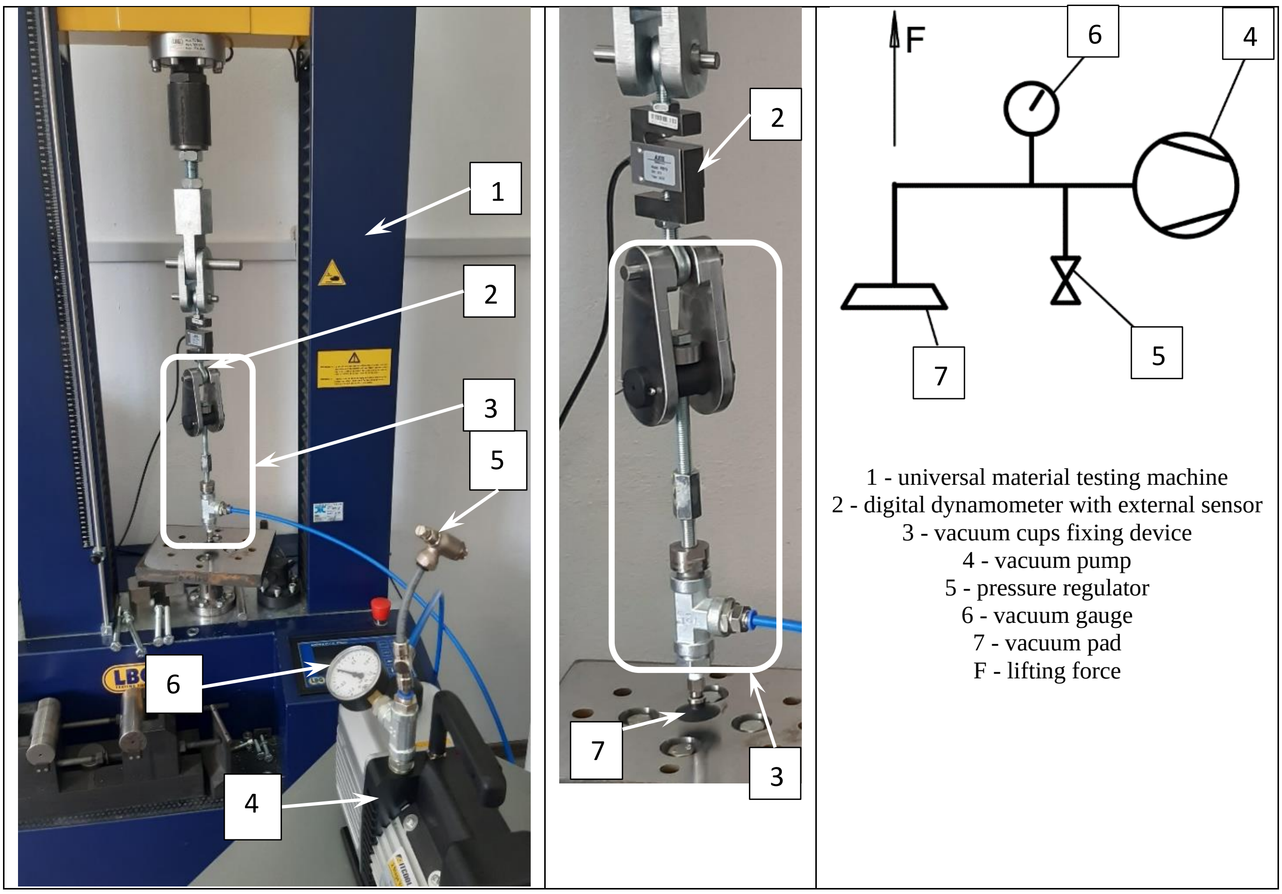


Figure 3. The technological system used for the experiments

2.4. Working method

In order to carry out the experiments, connections were made between the components of the technological system shown in Figure 3.

The 7 vacuum cups were used in turn with mounting in the vacuum cup fixture and with vacuum on the upper surface of the part.

Four vacuum levels were used: -0.3bar, -0.5bar, -0.7bar and -0.9bar.

At each test the maximum lifting force until the vacuum cup detached from the surface of the F_{mas} part was measured with a dynamometer. In some tests the vacuum cup was disassembled from the socket before it was detached from the surface of the specimen, in which case the force indicated at that moment by the dynamometer was considered as the maximum lifting force.

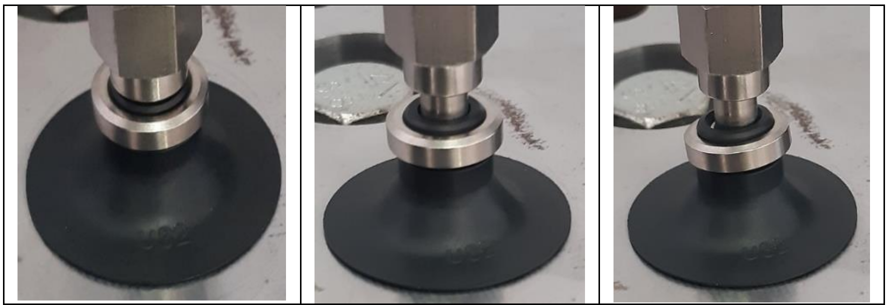
Each test was repeated 3 times and the maximum lifting force was taken as the arithmetic average of the three measured values.

3. Results and discussions

The experimental investigations carried out consisted of measuring the maximum lifting force indicated by the dynamometer at which each type of vacuum cup analysed resisted, until the vacuum cup detached from the surface of the steel piece, as shown in Figure 4.

Figure 4. Detaching the vacuum cup from the piece

However, there have also been situations where the maximum lifting force was not determined at the moment of the vacuum cup detachment from the surface of the steel part, but before this, the phenomenon of "pulling" of the socket from the vacuum cup assembly occurred. In Figure 5 this situation can be seen: in Figure 5a the vacuum cup is still glued to the metal surface after which the vacuum cup-steel socket assembly first gives way. In Figure 5b and Figure 5c the vacuum cup is still adhered to the surface but it can be seen that its socket is already pull out. In these situations, highlighted in yellow and italics in Table 2, the maximum measured lifting force was considered the force at which the vacuum cup - socket assembly failed.



a.	b.	c.

Figure 5. Pulling the vacuum cup out of the steel socket

The values of the maximum lifting forces thus determined have been centralised and are shown in Table 2.

Table 2. Lifting Force measured centralizer table

No.	Industrial vacuum cups	Vacuum [bar]			
		-0.3	-0.5	-0.7	-0.9
		Lifting force [N]			
1	ZPT32BS-B01 (bellows / Silicon Rubber)	13.60	20.53	24.60	31.13
2	ZPT32BU-B01 (bellows / Urethane Rubber)	15.27	26.67	33.00	*35.60*
3	ZPT32BN-B01 (bellows / NRB)	16.47	30.20	36.40	*39.67*
4	ZPT32CN-B01 (Flat with Ribs / NRB)	16.80	28.33	38.20	47.07
5	ZPT32CS-B01 (Flat with Ribs / Silicon Rubber)	15.00	*23.67*	*25.87*	*25.93*
6	ZPT32UN-B01 (Flat / NRB)	16.07	26.07	34.73	*37.93*
7	ZPT32US-B01 (Flat / Silicon Rubber)	15.27	24.73	*29.87*	*30.67*

The values of the maximum lifting forces allowed by each type of vacuum cup level were then plotted as a function of the vacuum level used, Figure 6-9. The theoretical lifting force F_{teoret} and the manufacturer's recommended dimensioning lifting force F_{dimens}, respectively, were also shown for each level and calculated with relations (1) and (2). The safety coefficient k was taken as k=4, as recommended by the vacuum cup manufacturer [6] for vertical lifting of a part in a horizontal position of the cup.

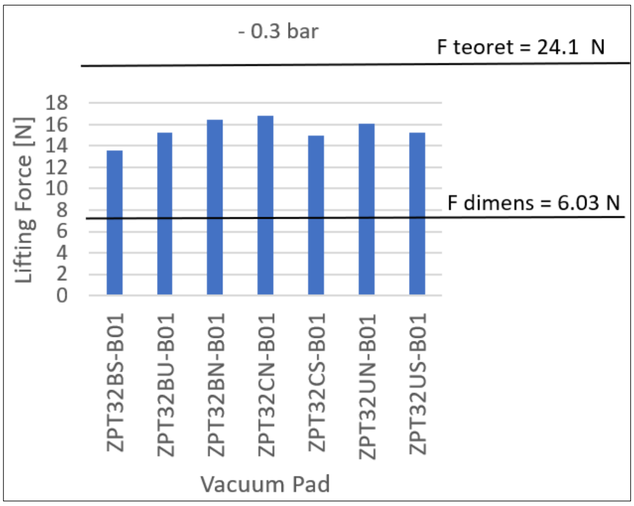


Figure 6. Measured lifting force variation as a function of vacuum cup type at vacuum - 0.3 bar

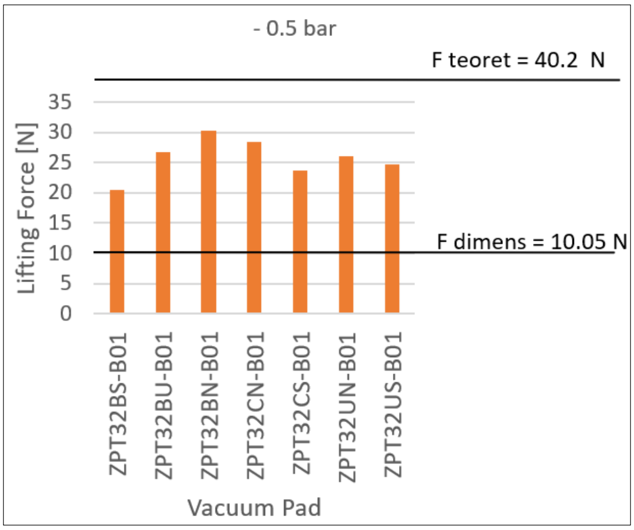


Figure 7. Measured lifting force variation as a function of vacuum cup type at vacuum - 0.5 bar

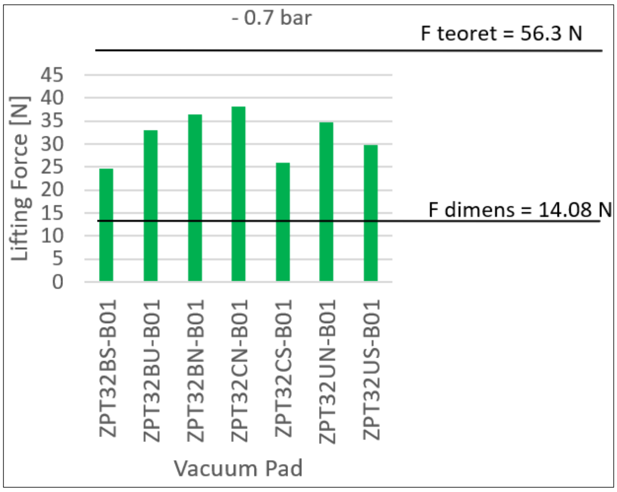


Figure 8. Measured lifting force variation as a function of vacuum cup type at vacuum – 0.7 bar

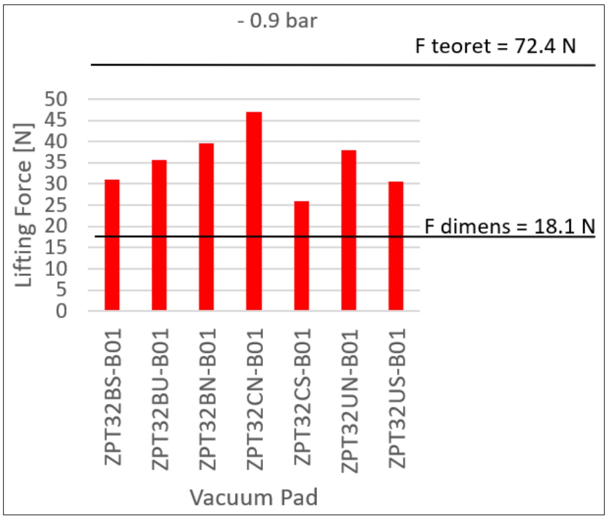


Figure 9. Measured lifting force variation as a function of vacuum cup type at vacuum – 0.9 bar

The main finding is that, for all tested vacuum cups, the maximum lifting force measured is between the manufacturer's recommended design force and the theoretical lifting force.

This indicates that the manufacturer's recommendations are correct, with the recommended maximum lifting force being ensured.

Of course, as expected, the maximum measured lifting force is higher the higher the vacuum depression. These aspects are clearly shown in Figures 6…9.

In Figure 10, all the results of the maximum lifting forces obtained in all the tests carried out, on all the types of vacuum cups and at all the vacuum pressure analysed, have been presented synthetic.

The tests show that some vacuum cups can only be used at certain vacuum pressure to avoid disassembling the vacuum cup from the vacuum socket:

- ZPT32CS-B01 (Silicon Rubber) type vacuum cup up to -0.5bar;
- ZPT32US-B01 (Silicon Rubber), vacuum cup type up to -0,7bar.

In case of vacuum cups made from NRB material the dimensioning coefficient may decrease. In the case of vacuum cups of this material we identify, based on Figure 8 and the data in Table 2, a 3 times difference between the measured lifting force and the dimensioning lifting force F_{dimens}.

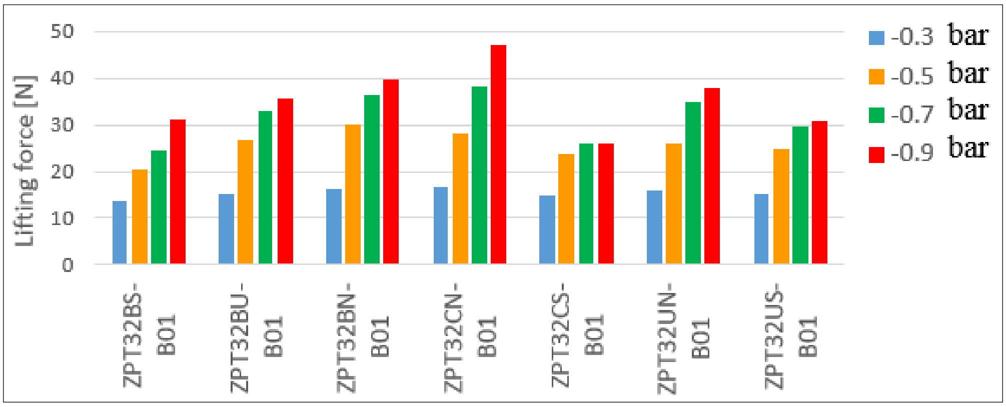


Figure 10. Centralised graph of measured lifting forces as a function of vacuum cup type and vacuum pressure

4. Conclusions

In the case of the industrial plastic vacuum cups studied, the research identified a variation in lifting force depending on the material and shape of the vacuum cups:

- depending on the material of the vacuum cups, the highest lifting forces were determined for NRB material and the lowest for Silicon Rubber material;

- depending on the shape of the vacuum cups, the highest lifting forces were determined for the "Flat with Ribs" shape followed by "Bellows" and the lowest for "Flat".

For all types and materials of vacuum cups, the maximum lifting force measured is higher the higher the vacuum pressure, that it has the lowest values at a vacuum of -0.3 bar and the highest values at a vacuum of -0.9 bar.

It was also found that for all vacuum cups studied and for any vacuum value, the maximum lifting force measured, is between the limits between the manufacturer's recommended dimensioning force and the theoretical lifting force, so the manufacturer's recommendations are correct.

However, it was noted that in terms of the safety coefficient k recommended by the vacuum cup manufacturer, for vacuum cups made from NRB material this could decrease by a minimum of 25% with safe operation of the vacuum cups.

In order to achieve material savings this safety factor k should also be differentiated according to the vacuum cup material. Therefore, either fewer vacuum cups or vacuum cups with smaller contact area could be used.

As further research in this field of industrial vacuum cups the authors propose to study the variation of the lifting force as a function of the material of the lifted part and as a function of the wear condition of the vacuum cups.

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