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EFFECT OF TECHNOLOGICAL PARAMETERS ON THE ROTARY COMPRESSION PROCESS

WPŁYW PARAMETRÓW TECHNOLOGICZNYCH NA PRZEBIEG PROCESU OBCISKANIA OBROTOWEGO*

The paper presents results of a numerical analysis of the rotary compression process for producing extreme steps of a multi-step hollow shaft. The numerical simulations of the process were conducted by the finite element method (FEM), using Simufact Forming version 11.0. Applications of hollow parts in industry are discussed and benefits of their use are presented. With numerical modeling, the effect of basic rotary compression parameters (deformation ratio δ, wall thickness g_o*, billet initial diameter D, advance speed v and rotary speed n of the tools) on shape of the produced parts are determined. Also, force parameters of the process, tool thrust force and torques are determined. The presented numerical analysis results confirm the possibility of producing multi-step hollow shafts using tube sections as billet material by metal machining methods.*

Keywords*: rotary compression, multi-step hollow shafts, FEM.*

W artykule przedstawiono wyniki analizy numerycznej procesu obciskania obrotowego skrajnych stopni odkuwki wielostopniowego wałka drążonego. Symulacje numeryczne procesu przeprowadzono metodą elementów skończonych (MES), przy zastsowaniu komercyjnego pakietu oprogramowania Simufact Forming w wersji 11.0. Omówiono obszar wykorzystania elementów drążonych w przemyśle i przybliżono korzyści płynące z ich stosowania. Poprzez modelowanie numeryczne określono wpływ podstawowych parametrów obciskania obrotowego (stopnia gniotu δ, grubości ścianki go, początkowej średnicy wsadu D, prędkości postępowej v i obrotowej n narzędzi) na kształt otrzymanych wyrobów. Wyznaczono parametry siłowe procesu siły nacisku narzędzi i momenty obrotowe. Opisane rezultaty badań numerycznych potwierdzają możliwość wytwarzania odkuwek wielostopniowych wałków drążonych ze wsadu w postaci odcinków rury metodami obróbki plastycznej.

Słowa kluczowe*: obciskanie obrotowe, drążone wałki wielostopniowe, MES.*

1. Introduction

Rotary compression is a modern process for forming metals and their alloys. Nowadays it is mainly used to produce local reduction in cross section of hollow parts (pressed semi-finished products, tubes, bushings, and many more). The process has a number of advantages owing to the tool motion [5, 8]. For this reason, research studies have been undertaken to investigate technological applications of the rotary compression process. Also, it has been proposed that the process be used to produce more complex machine parts such as multi-step shafts and hollow axles.

These days a growing demand for hollow parts can be observed in the global industry; given a general trend to lower production and machine maintenance costs, such parts are more and more often used instead of their solid counterparts [4, 11]. One of the ways to lower production costs is to use tubular parts in place of commonly used solid elements, as in this way material and labor consumption can be decreased. Strength properties of hollow elements of machine parts are similar to those of solid ones (under bending and torque shaft loads), while their weight is considerably lower compared to their solid counterparts. In effect, machines that are equipped with hollow parts have a lower total weight and, in consequence, consume less energy and are more eco-friendly (lower fuel consumption and lower gas emissions). For these reasons, hollow parts are more and more often used in both automotive and aircraft industry, as the decreased weight of vehicles and aircraft helps enhance their performance (power, speed, load capacity, maneuverability etc.) and, at the same time, lower their maintenance costs [1, 10, 12].

When investigating rotary processes for forming metals and their alloys, an innovative method for rotary compression was developed at Lublin University of Technology. This method can be used to produce axisymmetric hollow shafts and axles [6, 7]. The proposed method allows for forming parts from sections of commercial tubes or bushings as billet material, using tools with a simple geometric design.

A series of numerical simulations of rotary compression were performed in order to determine the process stability in terms of such disturbances as uncontrolled slipping (loss of rotary motion capability by a workpiece being formed) and collapse of a tube as well as to determine relations between individual process parameters.

2. Description of the rotary compression process

Rotary compression consists in forming a billet material by means of three cylindrical rollers which rotate in the same direction and, simultaneously, move radially towards the axis of the element being formed. The billet material (a tube or bushing section) is placed between the rollers and then rotated by the tools around its own axis during compression. Due to the tool action, the billet external diameter

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** changes and, at the same time, the billet wall thickness increases. The increase in the billet wall thickness of formed parts can be considered positive owing to strength reasons. Parts formed by this method have an axisymmetric shape. Compared to the presently employed methods for producing hollow parts, rotary compression has a number of advantages such as enhanced strength properties of a part, higher production efficiency, lower implementation and production costs, as well as relatively simple process mechanization and automation.

An example of forming a multi-step shaft (with two extreme neckings) by the rotary compression method is shown in Figure 1.

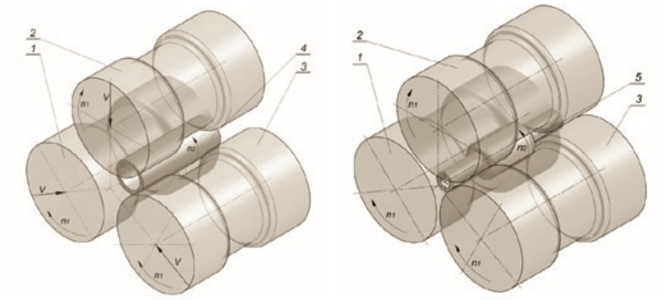


Fig. 1. Design of the rotary compression process for producing axisymmetric hollow part in which three tools perform rotary motion, moving simultaneously towards billet axis: 1, 2, 3 – forming rollers, 4 – billet (tube section), 5 – part; a) process start, b) process end

One characteristic of the rotary compression process is a gradual reduction in the billet diameter (Fig. 2) by the rotating tools, which can be defined by the deformation ratio:

$$\delta = D/d, \tag{1}$$

where D is the external diameter of the billet before the process, d is the external diameter of a journal after the compression process.

Owing to the billet diameter reduction, the material flows radially, in effect of which the wall thickness increases by Δg compared to the initial value of the tube (billet):

$$\Delta g = g - g_o, \tag{2}$$

where g is the thickness of the formed part, g_o is the thickness of the billet wall.

In the course of forming, the metal also moves along the billet axis, which results in an increase in the part length by Δl compared to the initial billet length:

$$\Delta l = l - l_o, \tag{3}$$

where l is the part length, l_o is the billet length.

Obviously, the increase in the wall thickness and length of the part depends on the compression parameters used. The most important ones are: value of the deformation ratio δ, the ratio of initial wall thickness g_o to initial billet diameter g_o/D and the ratio of advance speed v of the tools towards the billet axis to their rotary speed n.

3. Numerical analysis of rotary compression for producing an extreme step of the axisymmetric hollow part

In order to determine the effect of the selected rotary compression process parameters (δ, g_o/D and v/n) on the wall thickness increase Δg and workpiece length Δl, a series of numerical simulations of forming a hollow part with extreme journals were performed. A geometric model of one of the analyzed rotary compression processes, with

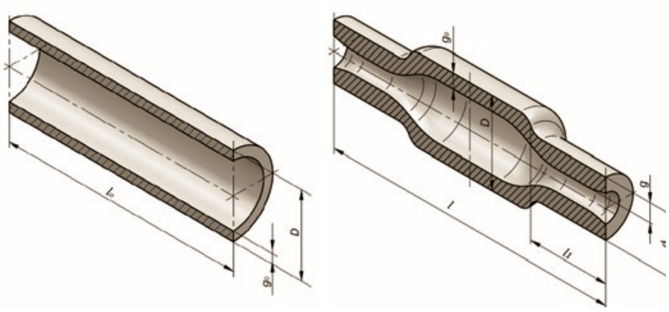


Fig. 2. Shape and dimensions of the billet used in rotary compression – a) and of the formed part with two extreme journals – b)

forming symmetry applied to reduce the computation time, is shown in Figure 3. The simulations were conducted by the finite element method (FEM), using Simufact Forming version 11.0, a metal forming simulation program that has been used by the authors many times to analyze rotary processes for forming metals and alloys, and the results have been positively verified in the experimental tests [2, 9, 3].

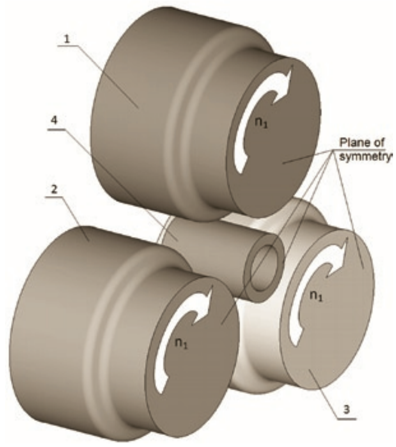
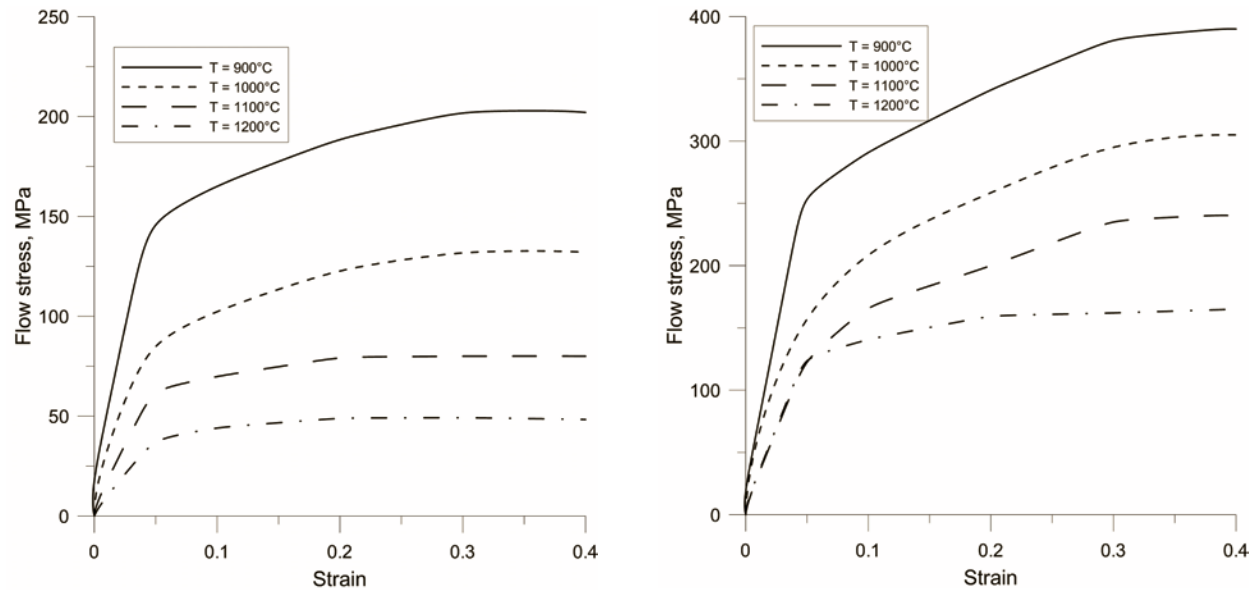


Fig. 3. Geometric model of the rotary compression process for producing extreme steps of a hollow shaft (its description provided in the paper)

The model consists of three identical multi-step rollers – 1, 2, 3 and a billet – 4. The tools (rollers) rotate at a constant speed n_1 of 60 rpm in the same direction and move towards the billet axis at constant speeds v. The billet material was a tube with 42.4 mm external diameter, length l_o = 120 mm and wall thickness g_o. The tube was modeled using 8-node hexahedral first order elements. The value of initial tube wall thickness g_o depended on the tube dimensions available on the market, and it was 3 mm, 5 mm, 7 mm, 9 mm and 11 mm, respectively. Also, it was assumed that the tube was made from constructional carbon steel (C45). This material is commonly used to produce all kinds of gears, shafts, axles, toothed shafts, connecting rods, and other average loaded machine elements. The material model of steel C45 was taken from the material database of Simufact Forming, and examples of flow curves are shown in Figure 4. Other parameters used in the computations included: initial billet temperature −1150°C, rigid tool model with a constant temperature of 150°C, friction factor on metal-tool contact surface m = 1, material-tool heat exchange coefficient – 10 kW/m^{2}K and material-environment heat exchange coefficient – 0.2 kW/m^{2}K.

The numerical simulations were based on the assumption that the tools (forming rollers) would rotate at a constant speed in all process variants. The only parameter that would vary in the process would be the speed at which the rollers move towards the billet axis. Other parameters that were being changed in the process included: the deformation ratio δ (in the range from 1.2 to 2.1) and the billet wall thick-



a) b)

Fig. 4. Flow curves of steel C45 at strain rates of: a) 0.1 s^{-1}, b) 100 s^{-1}

Table. 1. Technological parameters used in FEM simulations of rotary compression to produce extreme steps

Rotary speed of tools	n [rpm]	60						
Linear speed of tools [mm/s]	v [mm/s]	0.5	1	2	4	6	8	10
Advance speed-to-rotary speed ratio	v/n [mm/r]	0.46	0.92	1.84	3.69	5.54	7.38	9.23
Billet external diameter	D [mm]	42.4						
Wall thickness	g_o [mm]	3	5	7		9	11	
Wall thickness-to-billet diameter ratio	g_o/D	0.07	0.12	0.16		0.21	0.26	
Deformation ratio	δ	1.2		1.5		1.8	2.1	

ness. The main parameters applied in rotary compression to produce extreme steps of a hollow shaft are listed in Table 1.

As a result of the performed computations, material flow kinematics in the rotary compression process for producing hollow parts could be analyzed. Figure 5 illustrates changes in the product shape depending on progress of the process for one of the analyzed compression cases. It can be observed that the material begins to move towards the workpiece axis due to the reduction in the billet external diameter, which leads to an increase in the wall thickness. Also, it can be observed that the material moves along the workpiece axis, particularly at the surface regions, which results in an increase in the workpiece length compared to the initial billet length and leads to the occurrence of concave (funnel-like) frontal surfaces. In the final stage of compression, the advance motion of the tools is stopped, and they only perform the rotary motion. In effect, the workpiece shape undergoes sizing and the surface irregularities that occurred in the initial process stages are removed.

Figure 5 illustrates the distributions of effective strain both on the surface and in the cross section of the workpiece being formed. In the region of the tool action, the material is deformed inside-out, which makes it flow towards the billet axis, and the strains are not homogenous in the cross section of the steps being compressed. At the surface, the material is subjected to higher deformation relative to the central regions (located in the vicinity of the internal wall).

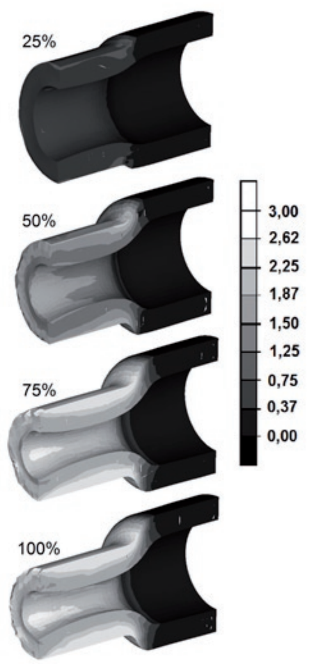


Fig. 5. Numerically determined hollow shaft shape changes with effective strain

This is characteristic of rotary metal machining processes, as it results from the process kinematics as there are considerable differences in the circumferential speeds of the workpiece being formed (due to the variable tool radius). As a result, slipping between the material being formed and tools occurs and considerable circumferential strains are generated (by the action of friction forces).

In the numerical simulations, the effect of the basic forming process parameters (δ, g_o/D and v/n) on the wall thickness increase Δg and workpiece length Δl was determined. Based on the performed simulations, the following could be observed:

- an increase in the deformation ratio δ in the range between 1.2 and 2.1 leads to an increase in both the wall thickness Δg and workpiece length Δl (Fig. 6),

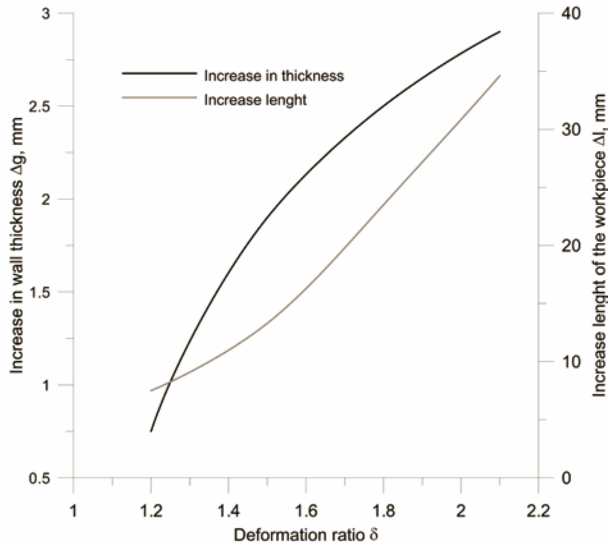


Fig. 6. Effect of deformation ratioδ on increase in wall thickness and length of the workpiece, determined at: g_o = 5 mm, v = 6 mm/s

- an increase in the tool advance speed v relative to their rotary speed n results in an intensive increase in the wall thickness Δg and a decrease in the workpiece length Δl (Fig. 7),

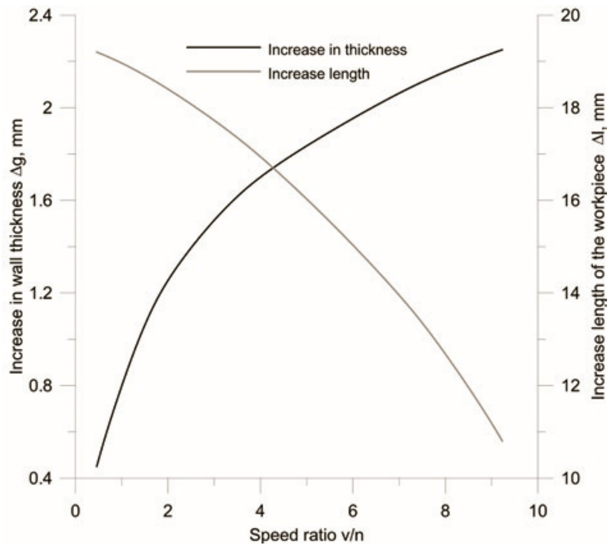


Fig. 7. Effect of the tool radial motion relative to their rotary speed on changes in the wall thickness and workpiece length, determined at: δ = 1.5, g_o = 7 mm

- an increase in the ratio of initial wall thickness g_o to billet diameter D (g_o/D) leads both to a decrease in the wall thickness Δg and to an increase in the workpiece length Δl (Fig. 8).

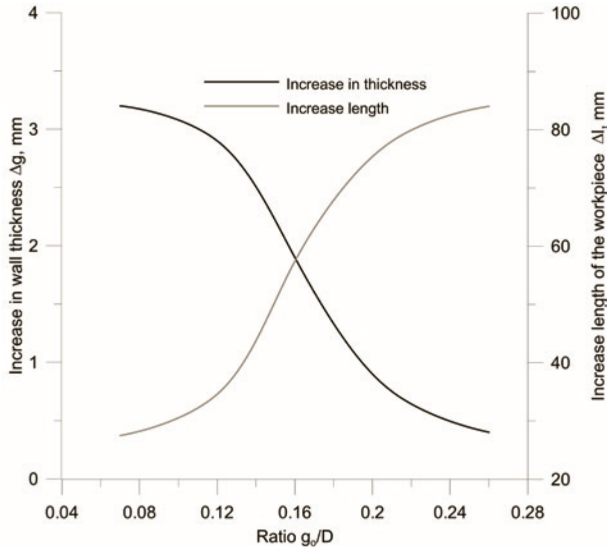


Fig. 8. Effect of the initial wall thickness relative to billet diameter on changes in the wall thickness and workpiece length, determined at: δ = 2.1, v = 8 mm/s

The variations of forces and torques were also analyzed in the conducted numerical simulations. If maximum values of these parameters are estimated accurately, both the technology and design of tools and forging unit can be developed in a suitable manner. Additionally, the information about the force variations helps control the process in terms of predicting phenomena that could disrupt its stability. Examples of the force parameters (tool thrust force and torque) determined by the FEM simulations of rotary compression are shown in Figures 9 and 10.

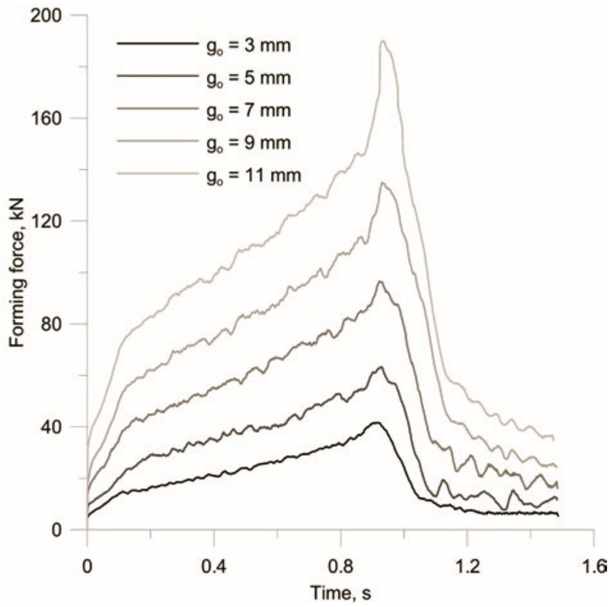


Fig. 9. Numerically determined tool thrust forces in rotary compression at: δ = 1.5, v = 6 mm/s

The distributions have a similar shape, yet with an increase in the billet wall thickness, the values of the tool thrust force and torque increase, too. The compression process can be divided into two basic stages. In the first stage, the radially moving tools reduce the billet

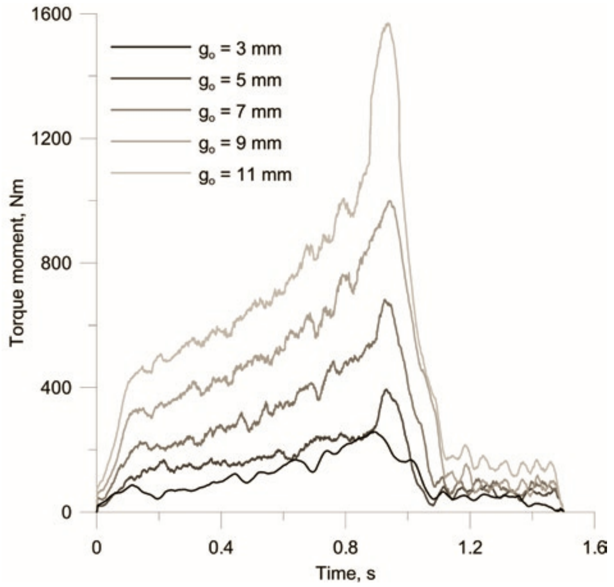


Fig. 10 Numerically determined torques on one tool in rotary compression at: δ = 1.5, v = 6 mm/s

external diameter, which is accompanied by a gradual increase in the force parameters. At the end of the first stage of compression, a sudden increase in the forces and torques can be observed, which results from the contact of the central (undeformed) step with the tools. In the second stage, during sizing (the advance motion of the tools is stopped), the surface irregularities generated in the first stage of the compression process are removed. In effect, a sudden decrease in the force parameters can be observed.

4. Conclusions

The conducted analysis of the rotary compression process confirmed the possibility of using this method to form hollow stepped shafts and axles. The multi-variant numerical analysis of rotary compression was performed using the finite element method (FEM) in spatial state of strain. The simulations positively verified most of the adopted technological and design-related assumptions; also, material flow kinematics was determined and, above all, the effect of the selected compression process parameters (δ, g_o/D and V/n) on shape of the produced parts was determined. It was proved that the tool motion speed has the most considerable effect on increasing the workpiece wall thickness Δg. As the tool speed v increases, a higher increase in the wall thickness can be observed, whereas at lower speeds, the material flows more intensively in the axial direction, which results in an increased workpiece length. The initial wall thickness of the billet used is also of vital importance for the material flow kinematics. The increased wall thickness g_o leads to an increase in radial deformation resistance, which causes a decrease in the workpiece wall thickness and, simultaneously, a sudden increase in its length. The intensity of the thickness and length increase depends not only on the deformation ratio, but it is also affected by the other two parameters (g_o/D and v/n).

Summing up, it can be stated that the developed method can be used to form axisymmetric hollow elements using tubular semi-finished products as the billet material. In effect, the labor and material consumption costs can be significantly lowered, while the strength properties of the formed parts are enhanced. Moreover, the production and machine maintenance costs can be lowered, too. The results are promising, yet in order to fully understand the rotary compression process and phenomena that disturb its stability, a comprehensive theoretical and analytical analysis needs to be conducted.

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