TOOL WEAR AND ITS COMPENSATION IN SCREW ROTOR MANUFACTURING

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ABSTRACT

Since screw compressor rotors are of a helical shape and tool points engaged in their manufacturing pass different cutting length, the tools do not wear uniformly along the rotor profiles. The non-uniformity depends on a difference between the rotor point angle and pressure angle and on the rotor helix angle. A difference in relative movement between the tool and the rotors with and without the cutting stock is used to quantify a relative wear of the tool. This is now in counterpart used as a basis for calculation of a variable rotor stock distribution, which results in a uniform wear of the finishing tool when it is applied. Finally, the roughing or semi-finishing tool is generated which cuts the rotors with such a variable distributed stock. Application of this procedure can substantially improve the overall tool economy.

1 INTRODUCTION

Screw compressors are positive displacement rotary machines comprising a meshing pair of helical rotors contained in a casing forming a chamber which volume depends on their rotation.

Compressor efficiency depends on the rotor profile and clearances between the rotors and between the rotors and compressor housing. For such machines to perform effectively the rotors must meet the meshing requirements and should maintain a seal along the entire rotor contact.

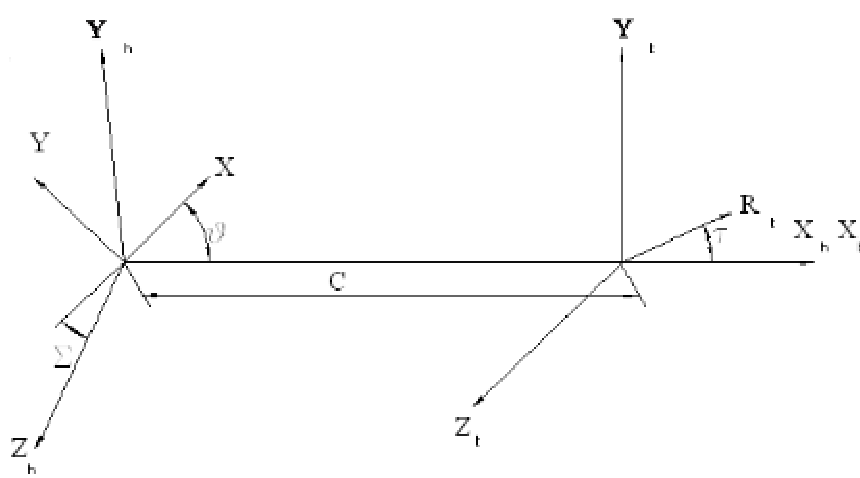

Fig 1. Rotor and tool coordinate systems

The rotor and tool coordinate systems are presented in Fig 1. Rotors are today mainly manufactured by the use of formed, milling or grinding tools. This means that tools suitable for screw rotor production must be calculated by an appropriate meshing procedure. The envelope method, which states that two surfaces are in mesh if each envelops the other under a specified relative motion, is suitable for such a purpose. The procedure starts with a given surface (1) with its derivatives (2) and (3), where x(t) and y(t) are the rotor (Fig 2) coordinates in the transverse plane in the X,Y coordinate system for which a meshing tool surface is to be determined. A family of such surfaces is given in parametric form (4) and their derivatives in $X_hY_hZ_h$ rotor and $X_tY_tZ_t$ tool coordinate system respectively are given in (5) as presented in Fig. 1, where C represents the axis distance, Σ shaft angle and indices h and t are rotor and tool. The envelope equation of such surfaces in respect of the rotation angle ϑ is (6).

Since a generating surface is defined by the parameter t, the envelope can be used to calculate another parameter ϑ, which is the rotor rotation angle, as a condition to generate a meshing surface. The cross product in the envelope equation represents a surface normal while $\partial\rho/\partial\tau$ is a relative velocity of two surfaces in the common point, τ is a tool rotation angle and p is a rotor lead defined for a unit rotation angle.

$$\mathbf{r}(t,\vartheta)=[x_h,y_h,z_h]=[x\cos\vartheta-y\sin\vartheta,x\sin\vartheta+y\cos\vartheta,p\vartheta] \qquad (1)$$

$$\frac{\partial\mathbf{r}}{\partial t}=\left[\frac{\partial x_h}{\partial t},\frac{\partial y_h}{\partial t},0\right]=\left[\frac{\partial x}{\partial t}\cos\vartheta-\frac{\partial y}{\partial t}\sin\vartheta,\frac{\partial x}{\partial t}\sin\vartheta+\frac{\partial y}{\partial t}\cos\vartheta,0\right] \qquad (2)$$

$$\frac{\partial\mathbf{r}}{\partial\vartheta}=[-y_h,x_h,p] \qquad (3)$$

$$\begin{aligned}\boldsymbol{\rho}(t,\vartheta,\tau)&=[x_t,y_t,z_t]=[R_t\cos\tau,R_t\sin\tau,y_h\sin\Sigma+z_h\cos\Sigma]=\\&[x_h-C,y_h\cos\Sigma-z_h\sin\Sigma,y_h\sin\Sigma+z_h\cos\Sigma]\end{aligned} \qquad (4)$$

$$\frac{\partial\boldsymbol{\rho}}{\partial\tau}=[-y_t,x_t,0],\quad \frac{\partial\boldsymbol{\rho}}{\partial\tau}=[p\vartheta\sin\Sigma-y_h\cos\Sigma,(x_h-C)\cos\Sigma,-(x_h-C)\sin\Sigma] \qquad (5)$$

$$\left(\frac{\partial\mathbf{r}}{\partial t}\times\frac{\partial\mathbf{r}}{\partial\vartheta}\right)\cdot\frac{\partial\boldsymbol{\rho}}{\partial\tau}=0 \qquad (6)$$

$$(C-x_h+p\cot\Sigma)\left(x_h+y_h\frac{\partial y_h}{\partial x_h}\right)+p\left(p\vartheta\frac{\partial y_h}{\partial x_h}-C\cot\Sigma\right)=0 \qquad (7)$$

Evaluated from (6) a condition of meshing is presented in (7), which can be solved by application of a numerical method. For a given parameter t, the point coordinates and their derivatives are known. A guessed value of parameter ϑ is then used to calculate x_h, y_h and $\partial y_h/\partial x_h$ from (1) and (2) for given x, y, $\partial x/\partial t$ and $\partial y/\partial t$. A revised value of ϑ is then calculated from equation (7) and the procedure repeated until the difference between two consecutive values becomes sufficiently small.

For given transverse coordinates of the rotor profile and their derivatives, contact angle ϑ, determined from (7) may be used to calculate the x_h, y_h and z_h coordinates of the rotor helical surface from equation (1). The tool surface and finally the tool transverse point coordinates Rt and z_t may then be calculated from (4) as:

$$R_t=\sqrt{x_t^2+y_t^2}=\sqrt{(x_h-C)^2+(y_h\cos\Sigma-z_h\sin\Sigma)^2},\quad z_t=y_h\sin\Sigma+z_h\cos\Sigma \qquad (8)$$

Although derived here for a screw rotor tool generation, the meshing condition, as shown, may be conveniently employed in general gearing practice. Reference textbooks on gears consider this application too complex and only a case of straight-sided tools for involute generation is reported there. However, Andreev 1961, [1], and recently Xing 2000, [5] in their books on screw compressors give its full derivation specifically for screw compressor tools. A similar approach has been published in Tang, 1995, [4], Zhang, 1997, [6] and in Stosic, 1998, [2] where additionally a reverse tool to rotor transformation (10) was given, which was latter used in Stosic, 1998, [3] to calculate influences of setting errors upon the screw rotor manufacture.

From the known tool coordinates, R_t and z_t and their derivative $\partial z_t/\partial R_t$, the rotor profile points x and y can be used to calculate the rotor transverse coordinates x_n and y_n of the rotor with given stock from inverse of the equation (1) as:

$$\left[x_n, y_n\right] = \left[x_{hn}\cos\vartheta_n + y_{hn}\sin\vartheta_n, -x_{hn}\sin\vartheta_n + y_{hn}\cos\vartheta_n\right] \qquad (9)$$

for the angle parameter ϑ which is obtained from:

$$\left(R_t + z_t\frac{\partial z_t}{\partial R_t}\right)\cos\vartheta + \left(p + C\cot\Sigma\right)\frac{\partial z_t}{\partial R_t}\sin\vartheta + p\cot\Sigma - C = 0 \qquad (10)$$

Once calculated, the distribution of ϑ along the profile may be used to calculate the coordinates of meshing tool and rotor points, as well as to determine the contact lines and paths of contact between the rotor and tool. The sealing line of screw compressor rotors is somewhat similar to their contact line. Since there exists a clearance gap between rotors, the sealing line is a line consisting of points of the most proximate rotor position. The most convenient practice to obtain a clearance gap between the rotors is to consider the gap as the shortest distance between the rotors in a cross section normal to the rotor helicoid. A transverse clearance gap can then be obtained from the normal one by an appropriate transformation.

It is interesting that a manufacturing stock, a surplus of material which is to be removed by a tool action, may be considered as a negative clearance. In such a case all transformations derived for clearances can be applied and are valid for the stock calculation.

2 CALCULATION OF THE ROTOR AND TOOL COORDINATES

2.1 Rotor Coordinates for a Given Stock

If a stock, which is to be cut of the rotors, δ is given in the plane normal to the rotor helicoids surface, the first part of the relation (6), the cross product of the **r** derivatives, which define the normal direction, can be used to calculate the coordinates of the rotor helicoids with the stock from the transversal rotor coordinates without the stock and the stock itself as:

$$x_{hn} = x + p\frac{\delta}{D}\frac{dy}{dt}, \quad y_{hn} = y - p\frac{\delta}{D}\frac{dx}{dt}, \quad z_{hn} = \frac{\delta}{D}\left(x\frac{dx}{dt} + y\frac{dy}{dt}\right) \qquad (11)$$

where the denominator D is given as:

$$D = \sqrt{p^2\left(\frac{dx}{dt}\right)^2 + p^2\left(\frac{dy}{dt}\right) + \left(x\frac{dx}{dt} + y\frac{dy}{dt}\right)^2} \qquad (12)$$

These serve to calculate the new transverse coordinates x_n and y_n of the rotor with stock from equation (11) for the angle $\vartheta_n = z_{hn}/p$. The x_n and y_n and original rotor coordinates x and y serve now to calculate the tool coordinates, which will cut the rotors with the stock, or roughed or semi-finished rotors and rotors without the stock, or final rotors respectively. A difference between these two will somewhat give a relative measure of the tool wear.

2.2 Tool Wear

A relative movement between the rotor and tool contains a simultaneous sliding and rolling action, because both components and not only a tangent one count for the tool wear. Cutting process is determined by the tool speed and advance. However, if only a relative measure of the tool wear is considered, these parameters will simultaneously be contained in both, the rough and fine cutting. Therefore, the tool wear will be dependent only on the difference between the coordinates either of two tools, two rotor helical coordinates or two rotor transverse coordinates. Either the rotor or tool motion equally well determine cutting through the stock. As the simplest, a difference of rotor transverse coordinates x_n, y_n and x, y is, thereby, presented here as relative measure of the tool wear.

$$s = \sqrt{(x_n - x)^2 + (y_n - y)^2} \qquad (13)$$

A rotor pair in configuration of 5 - 6 lobes on the main and gate rotor is used as an example here. The main rotor diameter is 128 mm. The rotor helix angle is 40^o. Rotor centre distance is 90 mm.

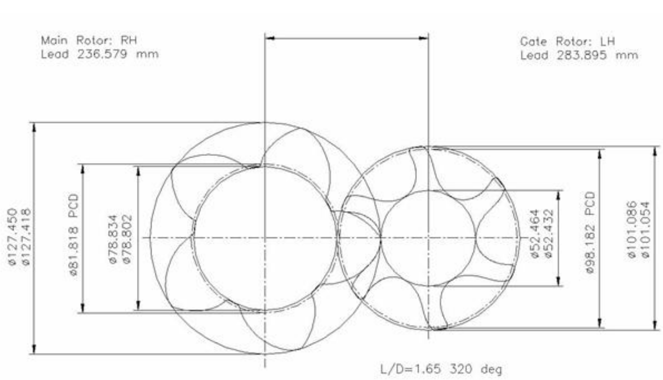

Fig 2. N Rotors 5/6-128 mm

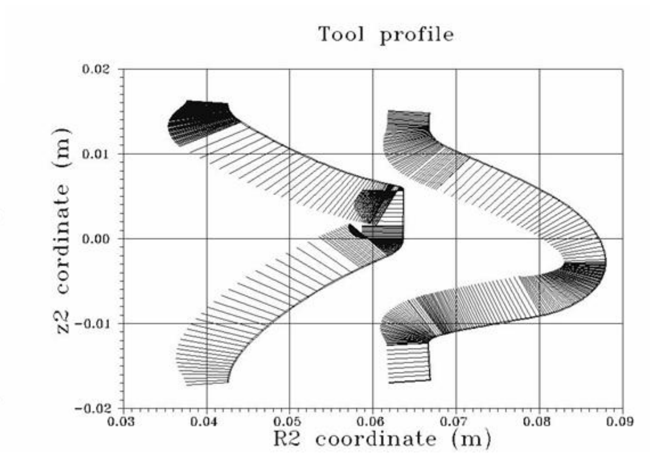

Fig 3. Tool wear to cut uniform stock

The meshing rotors in transverse cross section are presented in Fig 2. A screw compressor rotor and its formed tool are meshed on non parallel and non intersecting axes. Due to their axes not being parallel, there is only point contact between them. This point is a cutting point. The need to satisfy equation (7) leads to the rotor - tool meshing requirement for the given finished rotor transverse coordinate points x and y with $\partial y/\partial x$. The rotor helical coordinates x_h, y_h and z_h are obtained from (1). These are sufficient to get the tool transverse point coordinates R_t and z_t from (8). The identical procedure is applied for the x_n, y_n rotor coordinates with 100 μm stock to obtain their cutting tools. In both cases the rotor-tool centre distances were 105 and 125 mm for the main and gate rotor respectively. A shaft angle was 45^o.

Both the tool coordinates R_t and z_t are plotted in Fig 3 as R_2 and z_2 to visualize the tool wear which is scaled 50 times. It is obvious that the tool wear is not uniform along the tool profile. It is minimal and equal to the stock applied in all points where the rotor profile and pressure angle are the same, and it is larger in all other cases.

A distribution of a relative tool wear resulting from such a cutting is presented in detail in Figs 4 and 5 for the main and gate rotor respectively. The tool point number in Figures 4 and 5 represents the coordinate point position along the profile. For the rotors presented in the example the maximal tool wear was about twice of the minimal one for the main rotor and about 50 % in excess for the gate rotor.

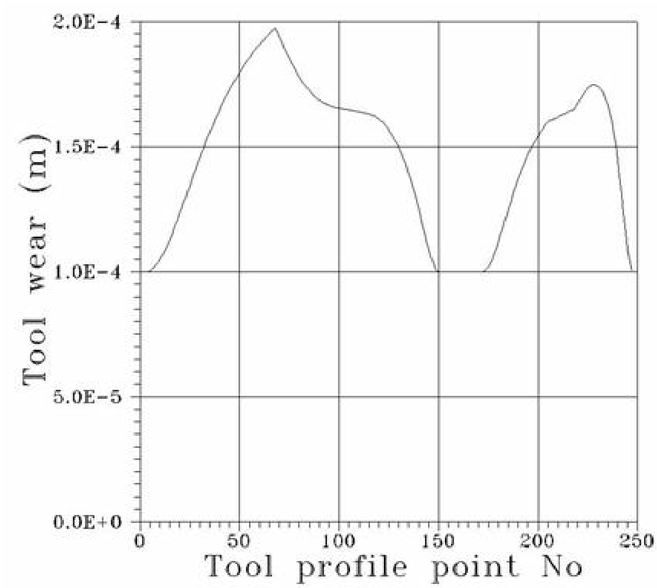

Fig 4. Tool wear, main rotor

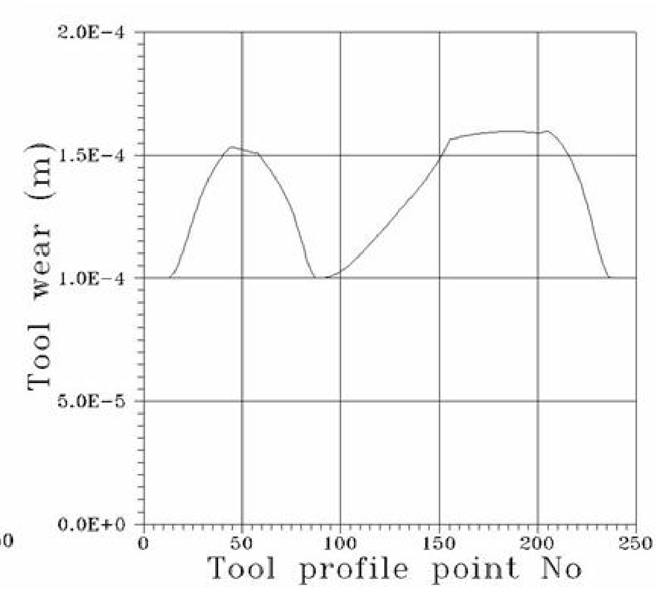

Fig 5. Tool wear, gate rotor

3 APPLICATION OF VARIABLE CUTTING STOCK TO MINIMISE WEAR

It is quite logical to expect that a variable stock applied around the rotor profile will cause a different tool wear along the tool profile compared with the uniform one. If a distribution of a stock is chosen to be reciprocal to the wear caused by the uniform stock, a uniform tool wear can be obtained. This is proven here by application of such a stock to the rotors, which leads to the new rotor coordinates x_n, y_n. The new coordinates are compared with the old ones, x, y and presented in Fig 6. The scale of the rotor coordinate differences is again 50 times. The new coordinates are now used to calculate the tool coordinates R_t and z_t, presented in Fig 7 as R_2 and z_2 which are compared with the finishing tool and their difference scaled 50 times. This wear is presented separately for the main and gate rotors in Fig 8 and 9. It is visible that the tool wear is uniform now. The rotor point number in Figures 8 and 9 represents the coordinate point position along the profile.

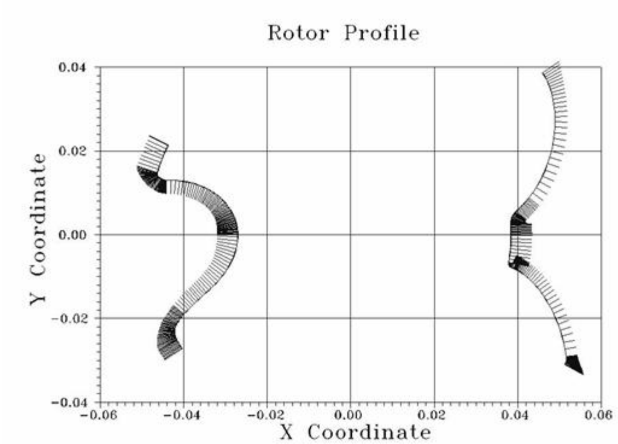

Fig 6. A rotor stock for uniform tool wear

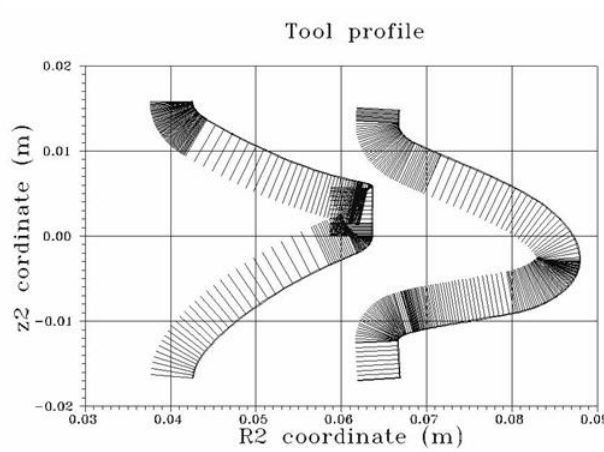

Fig 7. Uniform tool wear

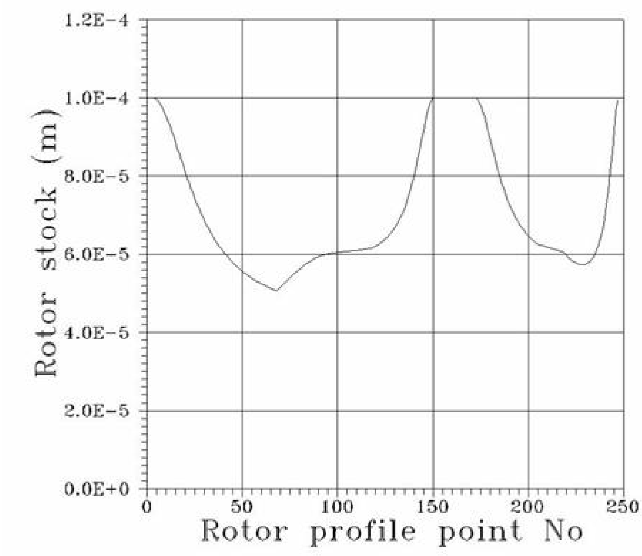

Fig 8. Stock for uniform wear, main rotor

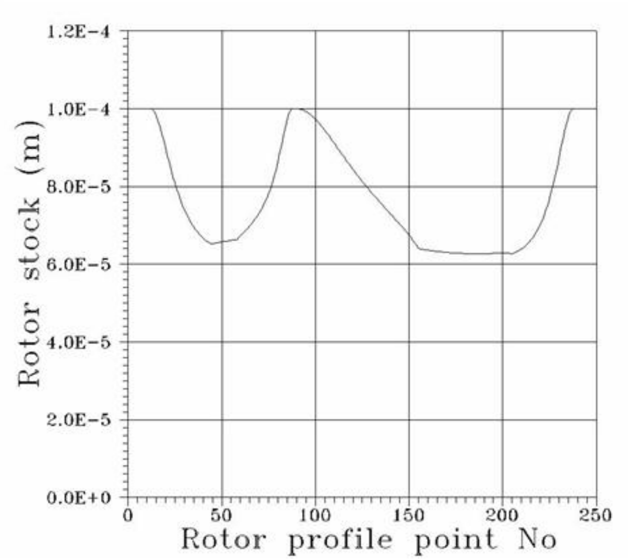

Fig 9. Stock for uniform wear, gate rotor

The uniform tool wear appears to be the optimal one for the tool economy allowing the tool to be used for the longest period between two tool conditionings either by dressings or sharpening.

4 CONCLUSION

A tool wear is always present in manufacturing of screw compressor rotors. It is logical to expect that a variable machine stock which is removed from the rotor will cause a different tool wear along the tool profile compared with the uniform one. If a stock inversely proportional to the wear caused by the uniform stock is to be cut off, a uniform tool wear could be obtained. The envelope theory of gearing has been applied here as a meshing requirement for crossed helical gears to calculate the stock distribution which would result in the uniform wear of a finishing tool.

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