Investigation of interaction between forming processes and rotor geometries of screw machines

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ABSTRACT

In the course of the minimization of production costs in the automotive field of screw machines, like superchargers, the issue of further manufacturing methods applies to the entire machine and especially to the complicated close-tolerance geometry of the screw rotors. Manufacturing must meet high precision standards in the case of the complex geometry of the rotors, because tolerance deviations during manufacture will significantly influence the energy efficiency and also the operating reliability.

1   INTRODUCTION

Due to the complex interaction between manufacturing processes and component properties in the case of superchargers, investigations are being carried out on promising deformation processes, in order to determine their suitability for screw rotor production. One of these procedures consists of twisting straight semi-finished products manufactured by extrusion or rolling. The processing of a production-specific rotor profile is carried out via numeric approaches and finite element. In current processing methods the intermesh clearance and the blowhole are the main performance-influencing factors of screw machines along the actual geometries parameters. In the course of evolving new processing methods, a compulsory reduction in the wrap angle of screw rotors reveals further performance-influencing factors which can affect operational behaviour significantly.

At this point the question arose whether the properties of a formed component could meet the strict tolerance and accuracy requirements of screw machines, and whether the technique is generally applicable in this field. High-cost conventional processing methods such as moulding, milling and grinding make the widespread use of screw rotors impossible at present. Thus the cost factor also plays a significant role when considering production methods involving forming.

## 2   MANUFACTURE AND COMPONENT PROPERTIES

2.1   Alternative manufacturing procedures for screw rotors

Concerning the manufacturing of helical profile construction units, various different procedures have been developed and studied intensively over the last few years. The company ASEA, for example, has manufactured steel bars with helical gearing by a hydrostatic extrusion process [1]. The company Hydro also produces helical aluminium screw rotors by extrusion. In the range of cold extrusion the manufacture of diagonally-interlocked gear wheels has been investigated [2,3]. All the procedures mentioned above are characterised by the use of press dies with internal twist.

Thus, the conventional twisting of extruded aluminium profiles provides a promising alter-native for the manufacturing of screw rotors and for achieving adequate results. So far this procedure has been used mainly for the production of, for example, crankshafts or marine propellers [4]. The main focus is on examining the suitability of this procedure for the manufacturing of screw rotors.

A clamping device is fixed on the profile side of the machine as well as a rotary drive on the opposite side in order to cause the twisting, **figure 1**. The main topic of the theoretical and experimental investigations is to determine the component properties that can be obtained in this way. It is essential to achieve outline accuracy as well as an accurate lead angle along the entire profile length.

The theoretical investigations of the twisting process were accomplished by means of the finite element methods with the program MSC super form. For these basic studies a close-to-application rotor geometry was specified. As material the aluminium alloy EN-AW 6060 was selected because it can be extruded smoothly. The outline deviation and the lead angle error along the profile length were examined at the reference lead angles 90°, 120°, and 150°, related to 100 mm of component length. The target of the analysis was to determine a suitable twisting angle to minimise deviation of the geometry outline and the lead angle.
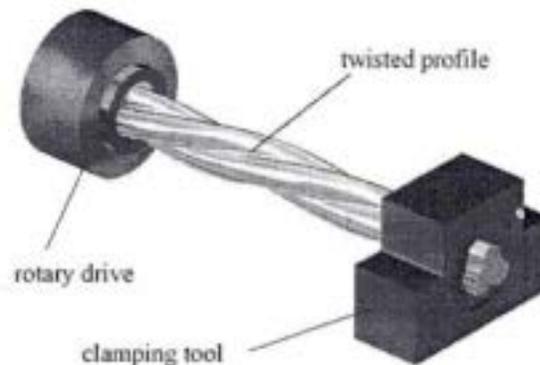
Figure 1.   Principle of conventional twisting

The outline deviation increases as expected as the lead angle rises. Since a large lead angle is desired in the case of smaller deviation, a main aspect is to analyse what maximal tolerances which can be obtained without milling are generally permissible. In this case the averagee deviations calculated here approx. 0.25 mm at a lead angle of 90°, 0.4 mm at 120 °, and less than 0.7 mm at 150°.

The deviations of the lead angle along the component length were also determined. The smallest deviation of the lead angle, approx. 1.4° on 100 mm or 0.014 °/mm, was obtained at a lead angle of 120°. In comparison to the 90° lead angle (deviation 0.037 °/mm) or to the 150° lead angle (0.03 °/mm) a reduction in deviation of more than 50% can be observed. This tendency was also confirmed by the analysis of the other rotor geometries. The reason for this lay in the uneven forming from the edge up to the profile centre. Within the 120° range the lead angle was relatively constant. Starting from this angle, the profile begins to rotate in the middle more than at the sides, as shown in the diagram in **figure 2**. In this diagram it can also be observed that the development of the lead angle at the reference angle of 120° resembles the qualitative development at 150°. This indicates that the optimal twisting angle with the smallest deviation is, for instance at 115°.
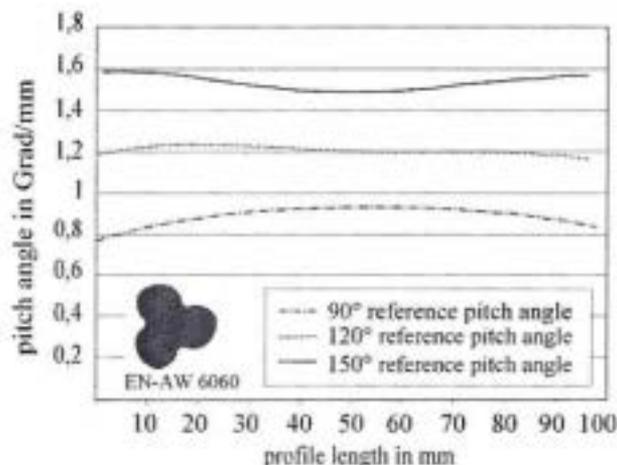

Figure 2.   Development of lead angle along the profile

In order to verify the simulation results, experimental investigations were carried out. Extruded semi-finished aluminium alloys (Material: EN-AW 6060) were twisted with a conventional rack up to an angle of, for instance, 160°. The results showed the emergence of a swirl surface on the components manufactured (orange peel effect), which was a result of tensile stresses at the surface.

Concerning the lead angle, the tendencies determined by the theoretical investigations could be qualitatively proved: The deviation of the lead angle along the profile depends on the twisting angle, and the errors at a twisting angle of approx. 120° are qualitatively less than at other angles. This applies, however, only to the solid profiles. Rotors with 4 hollow chambers were also twisted, **figure 3**.

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Here the twisting process could only be achieved at approx. 60° without visible cross section deformation. The profile geometry clearly deformed more strongly with further twisting.

approx. 60°   approx. 120°
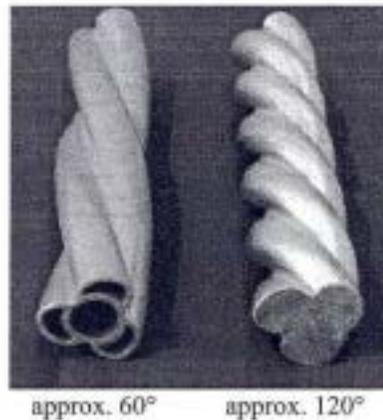
Figure 3.   Example of rotors manufactured by conventional twisting

2.2   Integration in supercharger-concept

The production procedure for screw rotors described here must satisfy the high accuracy requirements of a complex geometry of the rotors, **figure 4**. A change in the rotor form influences the meshing of the gearing and consequently the form and position of the clearance limiting gap, as well as the filling of the chambers. These properties have in turn a significant influence on the physical behaviour of the machines, such as efficiency or reliability.
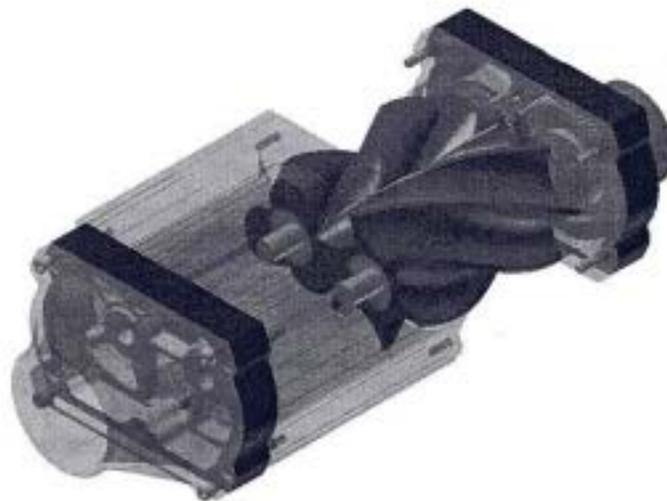

Figure 4.   Supercharger with complex geometry of the rotors

Thermodynamic simulation shows that for example supercharger properties improve significantly if the machine geometry deviates from that currently used in screw compressors. The wrap angle and the length-diameter-rate should be mentioned here as important geometry parameters. The low compression pressures of superchargers compared with the usual compressor pressure-rates allow both a decrease in the length-diameter-rate and a reduction in the wrap angle. Both changes in geometry reduce the length of the relevant gaps inside of the supercharger and so improve the performance.

A reduction in the relevant gap heights always leads to a certain degree of operational unreliability. There are leakage streams resulting from gap length and height as well as the blow hole area, which is determined through the rotor length, wrap angle and especially by the profile form. At the present time the necessary minimum gap heights of screw machines are determined by tolerances in manufacturing as well as by inaccurate knowledge of deformations of the machine through pressure and temperature loads during operation. Coatings used during running-in or dry-running operation can prevent failure if the rotors touch. These coatings can also be responsible for reducing clearances.

Several stages of development were carried out on profile forms with the aim of continually reducing the gap areas and also to incorporate improved manufacturing aspects. These developments are based on a modification of existing profiles [5]. Common profile forms are used from construction catalogues for screw machines. There are profiles which definition curves are predominantly on their female rotors, but this is not necessarily a common practice with the new profiles. The flank profiles of newer screw gearing consist of curve segments. Circles, straight lines, involutes, trochoid and circular forms are generally used as curves.
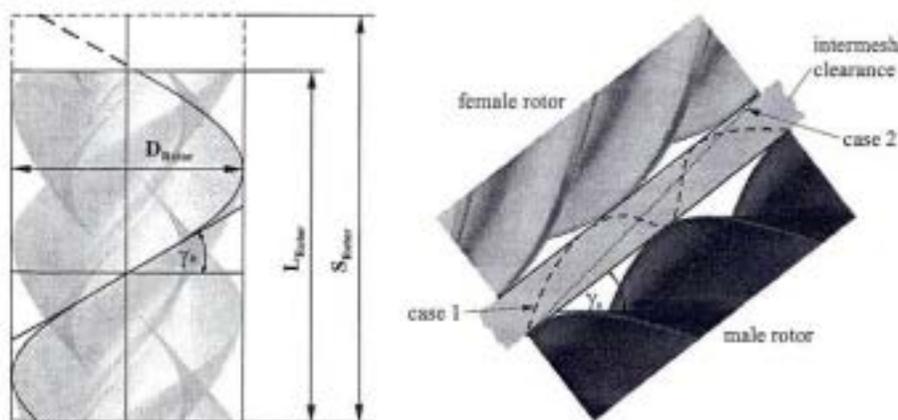
Figure 5.   Thread line / lead angle of a rotor
case 1: variable lead error above rotor length
case 2: constant lead error above rotor length

The assumptions for the thermodynamic appraisal of a screw machine have to be based on production processes. The gap heights of the intermesh clearances used in dry-running screw machines are in the area from about 0,08 to 0,15 mm, depending on the dimensions, the pressure-ratio, rotation speeds and material properties of the machines. The profile accuracy (nominal/actual value comparison) and information about the lead error are needed for a feasibility of the rotors in question, **figure 5**. Failure can be related to the intermesh clearance height selected. Minimization of this gap height can be equated with a reduction in the tolerance zone of manufacturing inaccuracy.

The lead error is defined above a certain length, so different variants can be considered, figure 5. Case 1 above does not lead to an earlier contact of the rotors with a higher lead error than in the case of 2. Here the sum of the individual lead errors can differ strongly if the overall length is taken into account.

In order to guarantee reliable running of the machine, the distance between the rotors must be increased constantly with increasing profile and lead error. Thus inaccuracies that have occurred through transforming manufacturing processes have to be compensated for by enlargement of the respective gaps. The effects of a rise in the gaps, especially the intermesh clearance, on the volumetric efficiency of a machine are described in [6]. The influence of the individual gaps on the volumetric efficiency depends on the respective geometry parameters of the supercharger and cannot therefore be formulated universally. The intermesh clearance and the housing gaps have a decisive influence on the volumetric efficiency of superchargers, where the male rotor housing gap influences efficiency considerably more than the housing gap of the female rotor. The comparison between the housing gaps and the intermesh clearance shows that with smaller gap heights the intermesh clearance affects efficiency more than the female housing gaps. So higher profile accuracy and a smaller gradient for conventional twisting are desirable.

Rotor profiles can be classified according to their feasibility for production by means of an evaluation of identification statistics related to the efficiency of the machine in question. These statistics currently allow a comparative appraisal of different end-profiles, ignoring either the parameters of rotor length and wrap angle or giving them set values which are treated as constants.

Final properties of a rotor pair result first from the end-profile in connection with further parameters. A three-dimensional appraisal of the leaks between rotors and profiles is the sum of the clearance areas in the sense of evaluation of power related to the swept volume. The areas responsible for energy transformation have to be integrated with the parts responsible for entropy production and the working space seals. In this connection the intermesh clearance, housing gaps, front gaps and blowhole, all depending on the present gap forms, should be mentioned. The rotor variant with the smallest assessed gap area is desirable but not beyond the point where the screw-type machine is still reliable. As the performance-influencing factor of individual gaps changes with the rotation speed and the pressure-ratio, a further characterization as for the gap forms can be carried out. Existing form

factors for front and housing gap areas, intermesh clearance and blowhole, which possess a height-length-ratio, are of assistance in this connection [5].

2.3 Applicability of geometries in superchargers

As well as the effect of gap changes on the efficiency of a machine, the reduction in the mass moments of inertia is very important if the screw machine is used as a mechanical charging unit. The moment of inertia depends primarily on the mass distribution of the contour along with the geometry of the rotors. Roots-chargers with hollow rotor teeth are already state of the art.

The rotor profiles lower the mass moments of inertia through the choice of suitable materials such as aluminium or magnesium, or through the geometry, for example by employing hollow rotors, **figure 6**.

massive profile   strutted profile (hollow shaft)   hollow profile

Figure 6.   **Rotor profiles with different moments of inertia**

The suitability of the rotor profile forms for screw chargers with rotation speeds of up to 30.000 RPM has been examined in terms of centrifugal force and material expansion because the operational reliability of synchronised aluminium-superchargers is restricted by centrifugal force and by thermal extension. A possible contact between the rotors during the operation usually leads to mechanical failure.

Finite element calculations for different rotor profiles at rotation speeds of up to 30.000 RPM show that the radial expansion of massive and hollow rotors is in the area of 0,03 to 0,08 mm, which is uncritical for screw charger operation. However, the results for the variant "hollow rotor" show expansion of several tenths of a millimetre. The rotor was calculated with a section thickness of 5 mm. This section thickness resulted from investigations of the manufacturing procedure. This case is beyond the reliability border. The simplest improvement for hollow rotor geometries is a deliberate increase in the section thickness, which inevitably also increases the moment of inertia. The investigations for massive and braced profiles for conventional twisting show that the use of these profiles in screw chargers is acceptable.