Investigating Alternative Rotor Materials to Increase Displacement and Efficiency of Screw Compressor While Considering Cost and Manufacturability

A. Kumar, K. Patil, A. Kulkarni, and S. Patil

Abstract Screw compressor, a rotary positive displacement machine, has gained popularity and is one of the most commonly used types of compressors across the globe due to better efficiencies and high reliability. The most vital component on which the screw compressor functions are the screw rotors, enclosed inside the housing with minimal clearances. Hence, the design of the rotors plays a significant role in affecting the thermodynamic performance. Also, it is found that profiles with a greater depth deliver a larger flow with higher volumetric and adiabatic efficiencies than their counterparts of the same size with a smaller profile depth [1]. In this paper, structural analysis of the screw compressor block is carried out to examine the effect of stresses, thermal gradients and deformation for different rotor materials for a 4/5 lobe combination. This alternative material investigation further influences the rotor profile depth for the same main rotor outer diameter, enhancing displacement and efficiency by 5.01% and 1.1%, respectively. Factors such as manufacturability and production cost of screw rotors have also been considered to fairly evaluate the commercial feasibility of alternative materials. Besides enhancing performance, the selected materials improve other essential properties, such as corrosion, bio-compatibility and wear resistance. The future study proposes a 3/6 lobe combination screw rotors to be considered for a significant amount of improvement in performance with smaller root diameter for numerical analysis and to be validated experimentally.

Keywords Screw compressor · Structural analysis · Materials · Rotor profile depth · Manufacturability · Cost

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1 Introduction

1.1 Exploring Lightweight Materials and Innovative Manufacturing Techniques for Screw Compressor Rotors

In the age of high-power requirement applications that have gained widespread usage and demand, a lot of research is currently going into reducing the weights of the moving components, thus reducing their specific power consumption. The research on lightweight moving components have helped various industries including but not limited to the aerospace, automobile, power, and production to improve fuel efficiency, reduce cost of manufacturing as well gaining desirable mechanical properties for the components. Thus, researchers are focusing on finding suitable alternative materials to conventional types which include research on a wide range of alloys, plastics, composites, polymers, etc. Along with materials, the performance, manufacturing feasibility and production cost associated with the materials are also researched for optimum results.

According to the report on the compressor market by Mordor Intelligence [2], the global compressor market value is supposed to be valued at USD 50.45 billion by 2027 from USD 38.28 billion in 2020, with a CAGR of 4.47% for the period 2022–2027. The rotary screw compressor, a type of positive displacement machine, has a wide range of applications including but not limited to refrigeration, petrochemical, HVAC, and pharmaceuticals, and are classified as oil-injected, water-injected, and oil-free based on the quality of air requirement. The screw rotors being an integral part of the screw compressor, are responsible for the compression of the fluid in exchange for power consumption. To cope with this power requirement demand and achieve sustainability, researchers are focusing on alternatives to existing manufacturing and material used due to the limited scope of optimising screw performance from profile and design point of view.

The current manufacturing technique used for these screw rotors is the conventional method of milling and grinding using a numerically controlled machine. Screw rotor having a complex shape, even with the precision machine tools, the associated manufacturing cost and cycle times are relatively large. According to the market survey [3], medium carbon steels are the most widely used materials in manufacturing screw rotors for screw compressors. EN8 is also a type of carbon steel that is widely used in most of the screw compressors. The current research focuses on alternatives to the currently widely used material with a purpose to enhance the displacement and efficiency of screw compressor, taking into account manufacturability and production cost. To find the best suitable material for the application, structural analysis is done using ANSYS Mechanical, followed by SCORPATH (Screw Compressor Optimal Rotor Profiling And THermodynamics) analysis for performance enhancement.

Multiple recent studies have explored the additive manufacturing of screw rotors. Additive manufacturing (AM) has been a breakthrough in the manufacturing industry due to its feasibility to manufacture complex shapes without wasting material in the form of chips as in the conventional methods, with little to no human involvement and high accuracy. Bailas [4] presented an innovative way and researched the effect of injecting epoxy resin into the specially designed voids of additively manufactured parts by manufacturing specimens of varying infill using the FDM (Fused Deposition Modeling) process and injecting epoxy into the voids and concluded that the stiffness of the specimens could be enhanced by about 90 percent. The Eaton Intelligent power limited presented its additively manufactured screw rotors [5] and showcased the flexibility of various Additive manufacturing techniques by manufacturing them in vivid ways. Techniques such as 3D printing, Fused deposition modeling, Selective laser sintering can create internal voids in the rotors, which are unlikely to be formed using conventional ways. The advantage of creating internal voids is the reduction in the overall mass of the screw rotors, thus reducing their moment of inertia or providing possibilities to internally cool them to achieve near isothermal compression.

Svenska Rotor Maskiner AB [6] successfully manufactured screw rotors using a metal shaft such as steel and polymeric body of lobes using polyurethane and inorganic filler silicate-containing fibers and demonstrated that they were able to eliminate drawbacks associated with conventional manufacturing. Do Suh [7] also implemented a unique way of manufacturing the screw rotors by implementing the resin transfer molding process. They used carbon fiber in chopped form with a tensile strength of fibers corresponding to 3528 MPa and epoxy resin (IPCO 2434/2310, National starch and chemical, USA). The publication demonstrated that short fibers suit complex products and shapes such as screw rotors. A mold of a helical shape resembling the screw rotor of material aluminum 6061T6 and manufactured using CNC machining was used. They successfully manufactured the composite screw rotor, weighing 52% as compared to the aluminum screw rotor. However, the publication didn't demonstrate the testing part of the composite rotor, thus leaving scope for further investigation and research. Vacuum casting is also a type of additive manufacturing in which silicon molds are used to manufacture fully polymeric screw rotors. Thus with the technological advancements in manufacturing, additive manufacturing can be a breakthrough considering its innovative adaption and a wide variety of production techniques apart from 3D printing.

1.2 *Metal Additive Manufacturing and Alternative Materials for Different Screw Compressor Applications*

The additive manufacturing of screw rotors for compressors is suitable, but a decision for shortlisting the correct type of AM and the suitable material for manufacturing plays a significant role. Materials like polymers for screw rotors are suitable for lower-pressure applications due to their lower yield strength and temperature resistance. However, the applications where the inner casing temperature exceeds (100–125) °C and pressure varying 7–13 bar, higher yield strength materials are suitable. According to the literature survey, materials other than metals have no significant practical advantage. The metals, however manufactured using Powder bed fusion, a

Table 1 Tabular column showing alternative materials and their mechanical properties

Material name	UTS (MPa)	Yield stress (MPa)	Hardness (HB)	Density (g/cc)
EN8 (normalised)	610	465	180–220	7.85
SS 316L	666	548	183	7.9
AISI10Mg-0403	442	264	114	2.68
Maraging steel M300	1140	1016	342	8.1
Ti6Al4V ELI-0406	1133	1045	380	4.42

type of metal additive manufacturing technique, exhibit mechanical properties at par with conventionally manufactured metals if material properties are compared. As discussed earlier, Eaton Intelligent power limited [5] manufactured the screw rotors using selective laser sintering and stated that various metals like steel and aluminum could be similarly sintered.

The screw compressor can be distinguished as oil-free and oil-flooded [8]. In oil-free compressors, based on the lubrication method used there are two types- water-injected screw compressor and those with purely air in the compressor chamber. Patel [9], in their work on the tribological behavior of materials for compressors, stated that stainless steel has less wear property and suitable for compressor applications. For oil-free and water-injected screw compressors, the material implemented must be highly corrosion resistive and wear-resistant. SS 316L, a grade of stainless steel, is corrosion resistant due to chromium content and due to its lower carbon variation compared to standard SS 316; it can be implemented for water-injected compressors. Removing the heat from the screw rotors for oil-free compressors is vital, so materials with higher thermal conductivity could be used. AISI 10Mg-0403, a type of aluminum alloy which can be additively manufactured, has a thermal conductivity ranging from 130 to 190 W/mK, making it suitable for oil-free compressors. In natural gas compressors, where reactive materials like nickel, brass, or copper cannot be used and high strength is required, Maraging steel (with yield strength around 1000 MPa) can be utilised as it has properties of corrosion resistance. In pharmaceutical applications where biocompatibility is important, titanium alloy (Ti6Al4V ELI-0406) is a suitable option. Table 1 shows the material properties comparison of the materials obtained from additive manufacturing firms and the conventionally manufactured material EN8.

The proposed study focuses on the finite element analysis of an industrial screw compressor block by varying the screw rotor's material. Further, the SCORPATH analysis using the high-strength material is carried out to increase the displacement and efficiency by increasing the rotor profile depth keeping in account the rotor deflection and minimum shaft size requirement for bearings and seals fitment. The proposed materials can be manufactured additively and are widely accepted by metal additive manufacturers. For a clear understanding the cost breakdown structure of manufacturing screw rotors using the conventional machining method is presented along with a comparison table with the additive manufactured rotors. In the future study, the prototype of the additive manufactured rotors is to be produced in-house, followed by the performance validation.

2 Numerical Simulation

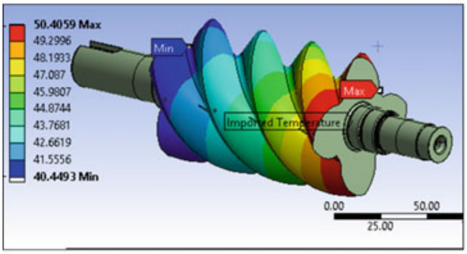
Before implementing any new system or material in industrial applications, validating numerically and experimentally with the latest alternative has become critical. Finite element analysis has become the backbone of research and development in almost all industrial applications. As discussed in the previous sections, the materials EN8, SS 316L, AISI 10Mg-0403, and Maraging steel M300 are suitable for the screw rotors depending on the applications. The static structural analysis of the screw rotors incorporated into the compressor block has been carried out by varying the screw rotor materials mentioned. The Ansys static structural solver has been used to evaluate results like principal stresses, penetration, and clearance after deformation between the rotor and the casing.

2.1 Modelling Methodologies

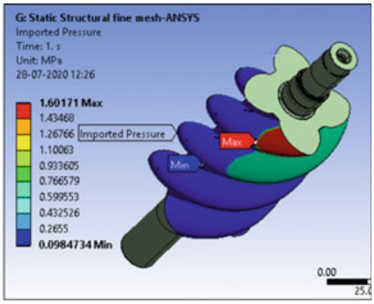
The machine considered in this work is KAS-100 oil-flooded air screw compressor (belt-driven) with built-in volume ratio of 4.6 operated at a pressure ratio of 8.5 and a tip speed of 20 m/s, manufactured at Kirloskar Pneumatic Company Limited, Pune (India). Since this is a commercial screw compressor product, information about the size and profile cannot be disclosed. Experimental testing has been conducted for this compressor, whose data will be used for modelling the screw compressor in the SCORG (Screw Compressor Rotor Grid Generation) software from the PDM Analysis [10].

2.2 Rotor Grid Generation ($SCORG^{TM}$)

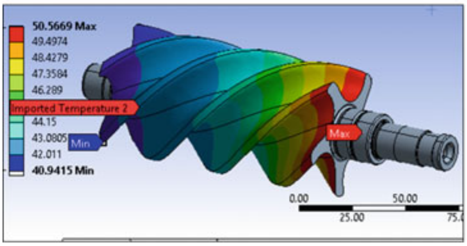
The SCORG is an industry leading grid generation and performance software for positive displacement screw machines. It performs the thermodynamic calculation based on the multi-chamber model using conservation equations of mass and internal energy to control volumes [11]. SCORG is used for the grid generation of temperature and pressure domains for the screw rotors, which is used as an input in the Ansys structural analysis as shown in Fig. 1 for reference. The procedure of analytical grid generation of screw machine working domain is explained in Kovacevic [12].



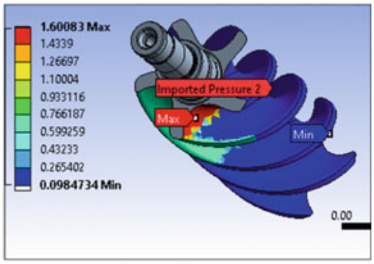
Male: SCORG imported temperature (50^oC max)



Male: SCORG imported pressure (16 bar)



Female: SCORG imported temperature (50^oC max)



Female: SCORG imported pressure (16 bar)

Fig. 1 Thermal and pressure boundary conditions on rotors using SCORG

2.3 Structural Analysis Boundary Conditions

Temperature and pressure range are two essential factors in the analysis. Here two solvers have been used in the Ansys workbench environment. First is steady-state thermal, where the temperature input is given. The properties like thermal conductivity and coefficient of thermal expansion are specified in the engineering material section. The solution of the steady-state thermal is connected to the setup of the static structural. In static structural, the properties mentioned in Table 1 and other mechanical properties are specified in the engineering materials section. The temperature and pressure 3D grids of screw rotors generated from SCORG are imported into the Ansys mechanical as inputs. The design pressure considered for this structural analysis is 16 bar (g) at an ambient temperature of 30 °C and operating temperature of 50 °C. The KAS-100 compressor block is a belt driven screw, so the belt tension force of 1200 N is applied on the male rotor shaft. Other boundary conditions, such as gravity force, load, displacement and fixed supports, are then specified.

The mesh size is 3 mm, generating 1186339 nodes and 759047 elements. Figure 2 shows the cross-sectional view of the meshing with the screw rotor visible.

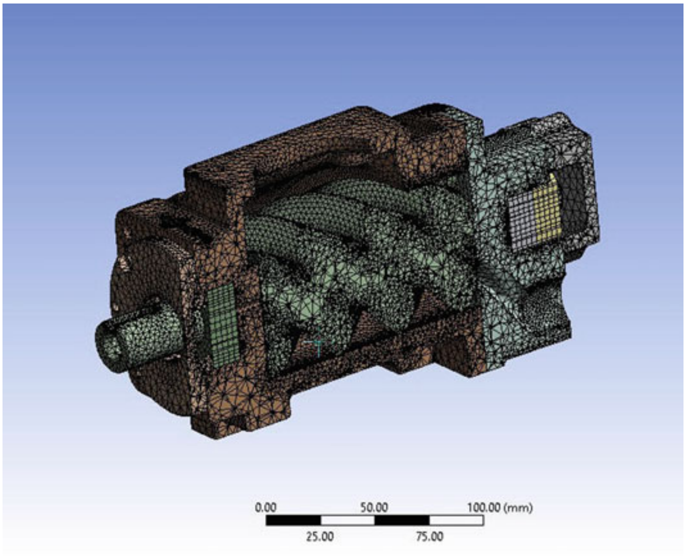


Fig. 2 Cross-sectional view of the meshing

2.4 SCORPATH Modelling

The software developed for the conceptual and preliminary design of screw machines is called SCORPATH (Screw Compressor Rotor Profiling and Thermodynamics) [13]. It is used for the performance enhancement analysis of the same oil-flooded screw compressor with 4/5 lobe combination. The rotor profiles with both nominal and deeper profiles was designed for comparison. The deeper profiles were generated by reducing the centre distance keeping all other parameters constant except the main rotor profile addendum, that is being tweaked to maintain the main rotor outer diameter constant. Since the main rotor outer diameter is constant, which results in the same length of the rotors, i.e., same relative length ratio (L/D). The nominal centre distance was reduced by 3.5 mm to increase the rotor profile depth. The purpose is to show how the increased strength of rotor can be used to design deeper profiles and enhance their energy efficiency; a principle already known and presented in [1].

The influence of the changing of the distance between the centres of the rotors are the same for all materials of the rotors, even though the influence of centre distance is known and realised that at smaller centre distance a more efficient profile is achieved. This effect cannot be utilised fully for designing more efficient profiles unless higher strength materials are adopted. For existing rotor materials generally used, profile depth cannot be increased beyond a certain point without compromising the rotor rigidity and deflections. Hence from this point of view it is important to stress here how change of rotor materials with higher strength can be utilised to improve the efficiency of the machine (Fig. 3).

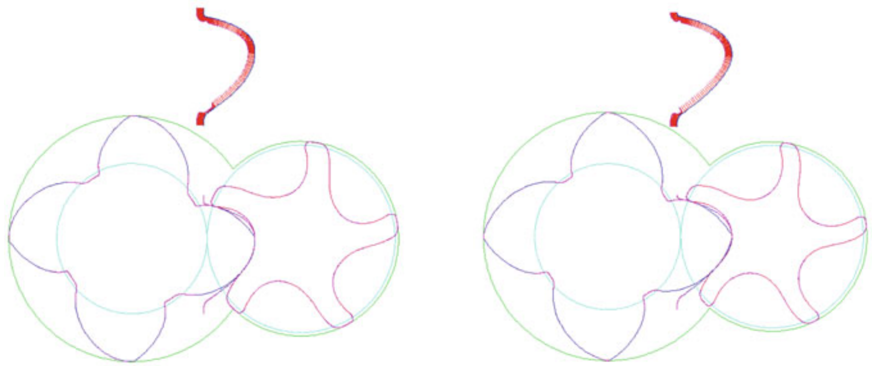


Fig. 3 Screw rotor profile with nominal and reduced centre distance using SCORPATH

Table 2 Tabular column showing structural analysis results for different rotor materials

Materials	Stress (MPa)	Penetration (mm)	Clearance (μ)
EN8 (normalised)	11.621	0	38 (M); 36 (F)
SS 316L	7.7837	0	40 (M); 39 (F)
AISI10Mg-0403	12.538	0	30 (M); 29 (F)
Maraging steel M300	6.5438	0	45 (M); 44 (F)
Ti6Al4V ELI-0406	6.4519	0	47 (M); 45 (F)

3 Result and Discussion

The results from the structural analysis for different rotor materials is presented in Table 2. In this analysis, the casing material is kept constant, FG 260. The current rotor material used for conventional machining manufacturing rotors is normalised EN8. In the Ansys mechanical static structural set up, except the engineering material for screw rotors all others are assumed to be constant.

From the structural analysis, the minimum stresses were found to be in Maraging Steel M300 and Ti6Al4V ELI-0406. Also, these materials show good amount of clearance (between rotors and housing i.e. radial clearance) left after deformation which is obvious as these are high strength materials. The critical point is that no penetration is observed with different rotor materials. All the comparison have been made concerning the currently used rotor material, i.e., normalised EN8. The clearance before deformation is found to be 60 μ.

On the other hand, from the SCORPATH analysis to generate the deeper profiles, the centre distance was reduced by 3.5 mm. The main rotor outer diameter and the relative length is kept constant. The rotor inner diameter decreased, and the rotor profile depth increased. The oil-flooded compressor's average flow and specific power

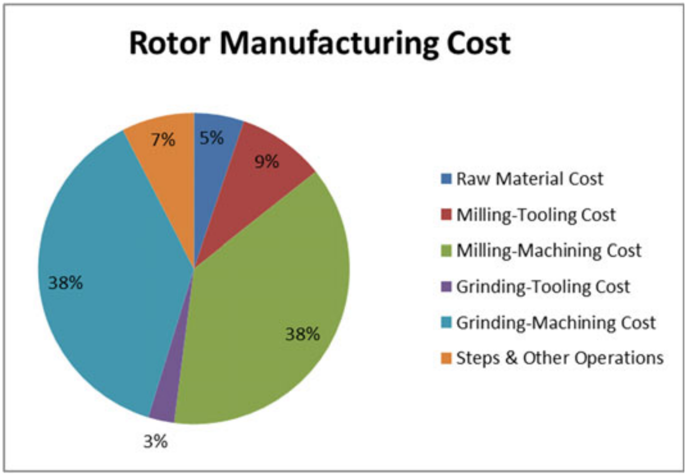


Fig. 4 Rotor manufacturing cost

with these rotors operating between 1 and 8.5 bar were improved 5.01% and 1.1%, respectively.

The centre distance was reduced to its optimum point of 3.5 mm to achieve the maximum rotor profile depth. It is possible to further reduce profile depths or design rotors with smaller root diameters with lower number of lobes by taking advantage of the high strength materials. The only limitation could be in selecting suitable bearings and other components over the rotor shaft which is too small (practically rotor shaft diameter has to be smaller than root diameter of the rotor).

In order to improve performance by increasing profile depth, one of the practical challenges is regarding the rotor deflection at high discharge pressures. If the current material (Normalised EN8) was used for this reduced centre distance profile, the deflection was beyond the optimum range and would lead to seizure of the compressor block. Therefore, using the high strength material from the above structural anlaysis, which gives minimum stress and has an optimum clearance left after deformation could be used. The deflection could be reduced by a significant amount of 32%. With the rotor deflection in check because of the high strength material, an improvement in performance is also achieved with 5.01% higher flow and and 1.1% lesser specific power.

Thus, it is evident from the structural analysis using Ansys Mechanical and the SCORPATH analysis that high strength alternative rotor materials can lead to improved displacement and efficiency with minimum stress and optimum clearance after deformation. But this cannot be the only factor in using this alternative materials for the screw rotors without considering the manufacturability and cost.

The pie chart in Fig. 4 presents the rotor manufacturing cost for the exact size of rotors using the conventional machining, i.e. milling and grinding process. The main cost is the milling and grinding machining cost, including the jigs and fixtures.

Table 3 Tabular column showing comparison of normalised manufacturing cost for a single pair of screw rotors

Materials	Conventional manufacturing cost	Additive manufacturing cost
EN8 (normalised)	1.00	–
SS 316L	–	1.83
AISI10Mg-0403	–	1.50
Maraging steel M300	–	3.00
Ti6Al4V ELI-0406	–	4.12

The alternative materials mentioned above are high strength materials which can be manufactured conventionally using high strength tools, but in regards to this study, additive manufacturing is considered for comparison. Manufacturing the screw rotors using the metal additive manufacturing technique eliminates the milling tooling and machining cost, which requires a considerable investment in the jigs and fixtures. The surface roughness obtained after additive manufacturing is in the range of (5–10) Ra, which needs to be further ground using the conventional grinding operation. The comparison of production cost of screw rotors (both male and female) for the given compressor block using the conventional machining for the currently used material and the additive manufacturing for the alternative materials are presented in Table 3. All the cost have been normalised; and the cost of manufacturing screw rotors using the conventional machining is taken as reference.

From the table, it is evident that the currently costlier AM is suitable over conventional method only if the advantages such as improved energy efficiency (achieved by reliably realising deeper profiles) cover the extra initial cost of manufacturing by saving in energy cost throughout the life cycle of the machine.

4 Conclusion

A comparative analytical study was carried out to determine the effect of alternative rotor materials on screw compressor performance. The structural analysis was conducted to find the efficient material with minimum stress, zero penetration and optimum clearance left after deformation through Ansys Mechanical. In the SCORPATH analysis the effect of high strength material with deeper rotor profile by reducing centre distance improved average flow and specific power consumption by 5.01% and 1.1%, respectively. The female rotor deflection using this high strength material got reduced by 32%, thereby maintaining the optimal clearances and avoiding seizure. The manufacturability and production cost of screw rotors using additive manufacturing and conventional machining has also been presented. The selected materials not only improves the performance of the screw compressor but also improves other properties such as corrosion, wear resistant and biocompatabiliblity.

5 Further Study

In the current study a 4/5 lobe combination and deeper profile by 3.5 mm; the improvement observed is not very significant. However, considering a 3/6 lobe combination, the effect of smaller root diameter can be more strongly realized. 3 lobes on main rotor would reduce its root diameter significantly and the 6 lobes on gate rotor would allow for enough gate rotor shaft diameters for bearing fitments along with relatively deep profiles. In the future study, a 3/6 lobe combination screw rotors made of high strength materials proposed hereby are to be considered for further analysis.

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