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Progressive Die Cost Estimation Based on Lamination Design and Production Scenario in the Electric Traction Motor Application

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Abstract

In the booming market of electrified mobility, product cost plays a crucial role for the competitiveness of electric vehicles. Approximately 70% of the product costs are determined in the product development phase [1]. Therefore, an early cost evaluation is necessary to check the achievement of cost target and if needed to modify the design as early as possible. To get a holistic view, as one part of the manufacturing cost for lamination stacks, the stamping tooling cost should to be taken into consideration.
This work investigates the cost of progressive die in the lamination stack production. By following design of the lamination and the production scenarios selected for stamping, the tooling cost can be estimated based on the dimension and complexity of the stamping part. Besides design parameters, the production scenario also influences the tooling design and its cost. The area of the stroke station is very different while applying segmenting technology for stator stamping process compared with stamping the stator ring. The proposed model also presented an approach to evaluate the complexity of the stamping part design, which is crucial for determining the number of progressive die stations.

Keywords: Progressive die; Lamination production; Segmented stator; Lamination design; Cost model; Design concept; Electric traction motor;

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1. Introduction

In the concept design phase, where the final product design is not fixed, there are many possibilities to reduce the cost e.g. by changing dimensions. However, the product cost is not only influenced by the design parameters, but also by the production, which affects both the material utilization and the manufacturing cost including tooling cost.

Besides changing design parameters, the designers are looking for the most cost-efficient production solutions like changing manufacturing technology or scenario to adapt the design to lower cost. Especially in the booming market of electrified mobility, where the development cycle is more and more shortened in duration, an early cost estimation based on those changed parameters becomes more and more important.

This paper focuses on estimating stamping progressive die cost based on design parameters and different production scenarios, which would be helpful to find a cost-efficient solution.

Nomenclature

D	Outer diameter of work piece (mm)
d	Inner diameter of work piece (mm)
R	Outer radius of work piece (D/2) (mm)
r	Inner radius of work piece (d/2) (mm)
a	Scrap bridge (mm)
b	Circle distance (mm)
α	Segment radian (radian)

2. Literature review

There are many approaches developed to estimate the die cost. Tang, Eversheim, Schuh and Chin [2] described an approach to estimate the die cost for sheet metal stamping parts from the tooling design point of view. The number of stroke stations, the complexity and size of die is already defined for the cost estimation. Similar approach can be found in [4]. Bouaziz, Younes and Zghal presented a model to predict the manufacturing cost of die based on the given tooling features, which are important for estimating the machining time of the machining features.

Fagade and Kazmer [5] described an automated costing methodology for die cost estimation for injection dies. This model enables an evaluation of part's complexity at the early stages of its life cycle using the number of dimensions from its geometric model. However, it is only applied for plastic parts. Ravi and Mukherjee [6] also presented a good framework for die and mold cost estimation by dividing the mold cost into three categories: mold base cost, functional elements cost and secondary elements cost. However, this model is valid for injection and die casting molds.

There are also some ANN-based (Artificial neural networks) method [7][8] developed specifically for estimating the stamping die cost and injection die cost. However, the drawback of ANN is that the performance of this method highly depends on the quality and quantity of training samples. If no enough design and cost information of samples are available, the plausibility of this method is to be questioned.

In summary, a method for estimating the progressive die cost in the application field of lamination stack production for electric machine, which also takes both the lamination design and production scenarios in to consideration, has not been discussed yet.

3. Structure of progressive die

For production of the lamination stacks, the electric steels should then be cut to shape to profiled laminations and built into stacks by different joining technology.

There are several manufacturing technologies available for the cutting process, like laser cutting, waterjet and stamping [9]. Due to its automatic process and its economics in raw material saving, the progressive stamping is the most commonly used cutting method for highly automated mass production. In this process, the material steel strip is inserted into the progressive die stroke by stroke and profiled laminations are punched out in continuous punching strokes.

In general, tooling invest costs will be driven by size of tool [10]. To investigate the change of tooling size according to part design parameters and production scenarios, the structure of progressive die is first to be understand.

Fig. 1 shows the main parts of a progressive die. The punch- and die holder, which support other system elements, are the biggest parts of a progressive die. Inside the holder, the stripper, punch- and matrix retainer are mounted. The stripper is used to remove the work piece from punches and to ensure the steel strip stay flat on the matrix retainer. The punch- and matrix retainer are the part, where the punch and matrix are mounted. The punches and matrix are working parts of the progressive die, which helps to punch out the required profile.

As shown in Fig. 1, the size of holder, retainer, and stripper are mainly driven by the cutting area (area of raw material usage for one stroke, calculated by Bs*Lh) and the number of stroke stations ($k_{station}$). The number and size of punches and matrixes are usually determined by the number and size of holes to be stamped out of the work piece. The cutting area and the number of stroke stations depends on the lamination design parameters as well as the production scenarios, which are explained in the following sections. Detailed illustration of geometric parameters in Fig. 1 is presented in section 6.

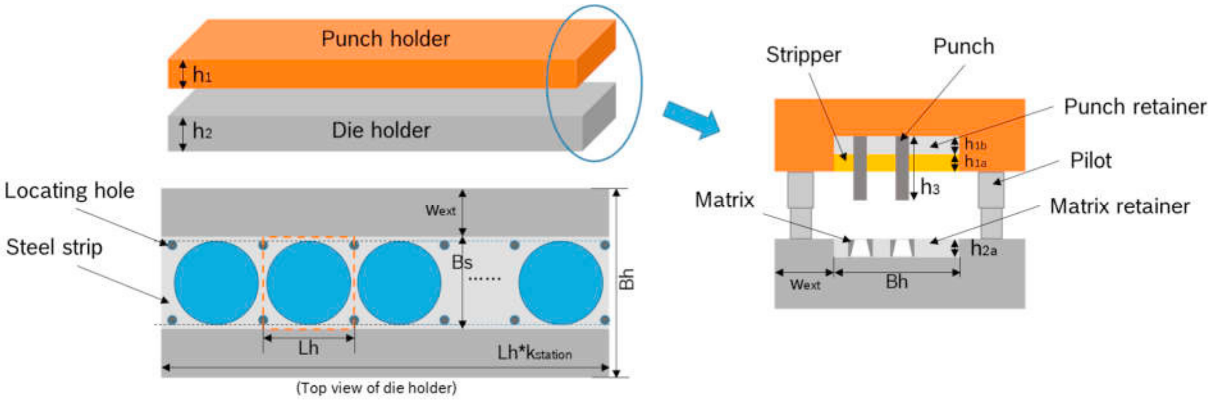

Fig. 1: Rough sketch of the progressive die (in accordance with [3])

4. Lamination design

To investigate the influence of lamination design parameters on the progressive die cost, an example of PSM stator- and rotor core design is illustrated in Fig. 2, which presents all design parameters of the lamination stack.

For the progressive die, not the design of stack, but the design of single stator- and rotor sheet is crucial information for the tooling design and its cost estimation. In general, the outer diameter of stator and rotor affect the size of steel strip as well as the area of each stroke station of die. The number and size of holes to be punched out of the steel strip as well as the distance between holes determine the complexity of the work piece. The more complex the design is, the more stations are needed for stamping, therefore, the bigger the progressive die will be.

As mentioned in the previous section, not only the lamination design, but also the production scenario of lamination stacks have influence the progressive die design and its cost.

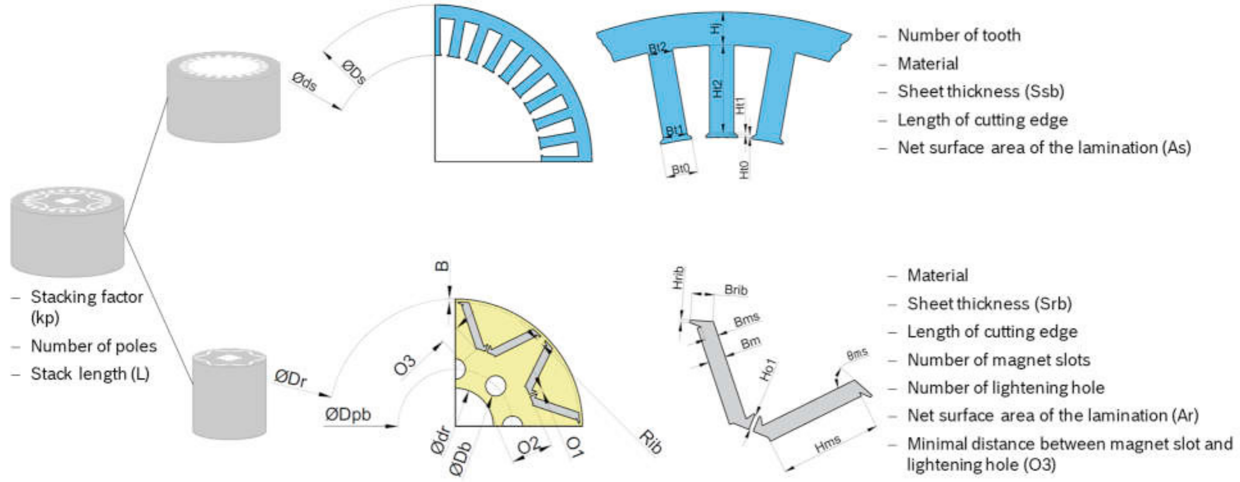

Fig. 2: Design parameters of a PSM stator- and rotor core

5. Production scenario of lamination stacks

In this present paper, production scenario means the way to produce the lamination stacks: it can be the usage of different manufacturing technologies as well as various way to apply them. For example, the progressive die size and cost would be very different while applying different strip layouts for the stamping process. This will be explained in the next section.

5.1. Material utilization and strip layout

During progressive stamping the rotor and stator laminations are usually punched out of the same blank sheet material, the rotor out of the inner part of the sheet, the stator out of the outer part. However, it is also possible to punch them separately. The reason will be clarified in the following paragraphs.

Due to the raising requirements on performance of the electric motors, more magnets are being designed to increase the magnetic field strength and the rotational speed becomes higher. This results in a higher requirement on the yield strength of rotor. Fig. 3 (a) shows the relationship between flux density and yield strength of a set of non-oriented electrical steel sheets produced by BaoSteel. B-50 means the flux density of the materials showed in the table are measured by a magnetic field strength of 5000A/m.

As shown in Fig. 3 (a), for both normal and high-performance non-oriented electric steel sheets, the flux density decreases when the yield strength goes up. That means the flux density has to be sacrificed for reaching a high yield strength, which is not beneficial for a high-performance electric motor. Therefore, a new idea comes up to use electric steel with high yield strength for rotor and electric steel with high flux density for stator. Because for the stator, it is not the yield strength, but the flux density, which is one of the most important properties to be considered. It is clear that under this consideration, rotor and stator material can be different and thus, cannot be punched out of the same sheet.

Because of the above-mentioned reason, both possibilities (use the same material for rotor and stator; use different materials for rotor and stator) will be considered in this paper. For both of them, there is more than one solution to arrange the rotor and stator laminations on the strip material for progressive stamping. Since lamination stack cost is largely decided by material cost, it would be advantageous to increase the material utilization by optimizing the strip layouts. Fig. 4 shows seven different strip layouts. The orange frames with dotted line are the cutting areas for one stroke. For each layout, the material utilization by increased number of segments is shown in Fig. 3 (b).

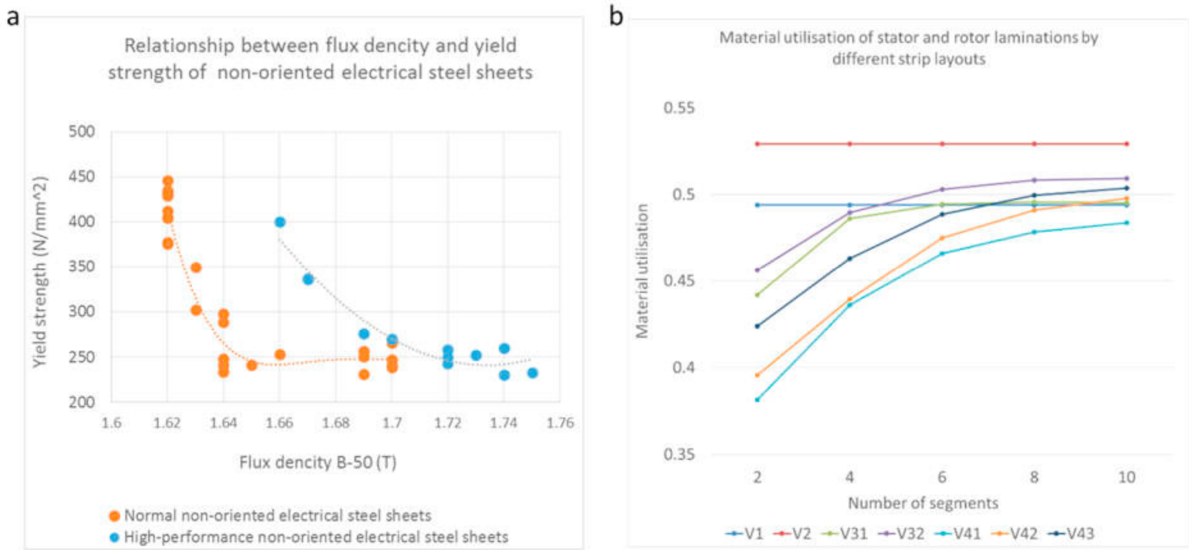

Fig. 3: (a) Relationship between flux density and yield strength of non-oriented electrical steel sheets (according to the steel data sheet in [11], p.13-p.14); (b) Material utilization of stator- and rotor laminations by different strip layout (according to [12])

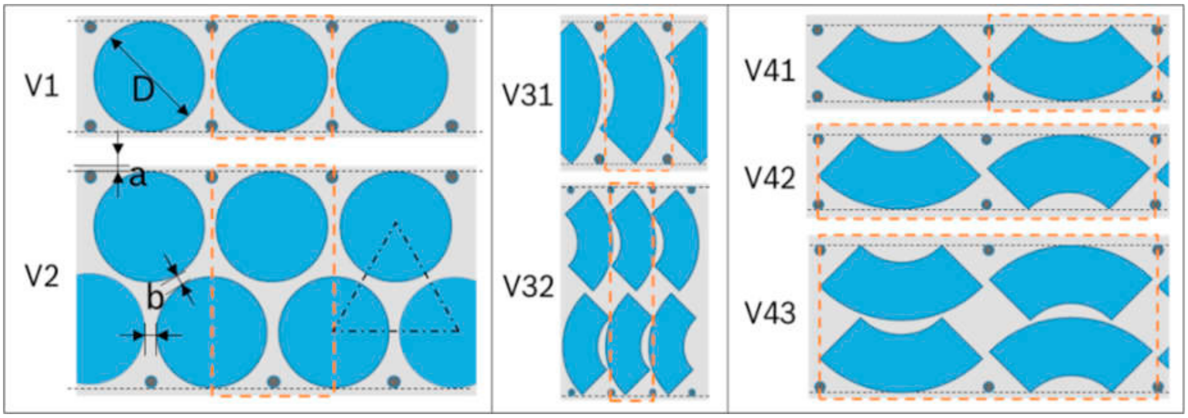

Fig. 4: Examples of strip layouts (according to [12])

As the results are shown in Fig. 3 (b), V2 has the maximum utilization rate among all the strip layouts. If the stator and rotor can be punched together, V2 would be the best solution in terms of material utilization. However, a bigger die and stamping machine should be used for V2. Therefore, it is still a question if the material cost and manufacturing cost in total for V2 would also be the lowest.

For the strip layouts with segmented stator, it can be observed from Fig. 3 (b) that with more segments, a better material utilization can be achieved. Nevertheless, the stator cannot be split into an infinite quantity. Because it increases the difficulty and cost of assembling the segments to a round lamination stack and the roundness is hard to be guaranteed.

As a part of stamping process cost, the progressive die cost by different strip layouts and changed number of stator segments is the focus of this paper. Other cost related issues were discussed in [12].

5.2. Production technology

Beside different strip layouts and changed number of stator segments, the available production technology could also be the changed production scenario for lamination stacks and affect the progressive die cost. Fig. 5 shows the stamping process combined with different joining processes, namely gluing, interlocking and welding. Since gluing and interlocking is integrated in the stamping process, they are classified under the separation process. The letter "R" and "S" inside the green point means, under that condition, this process is only applied for rotor or stator.

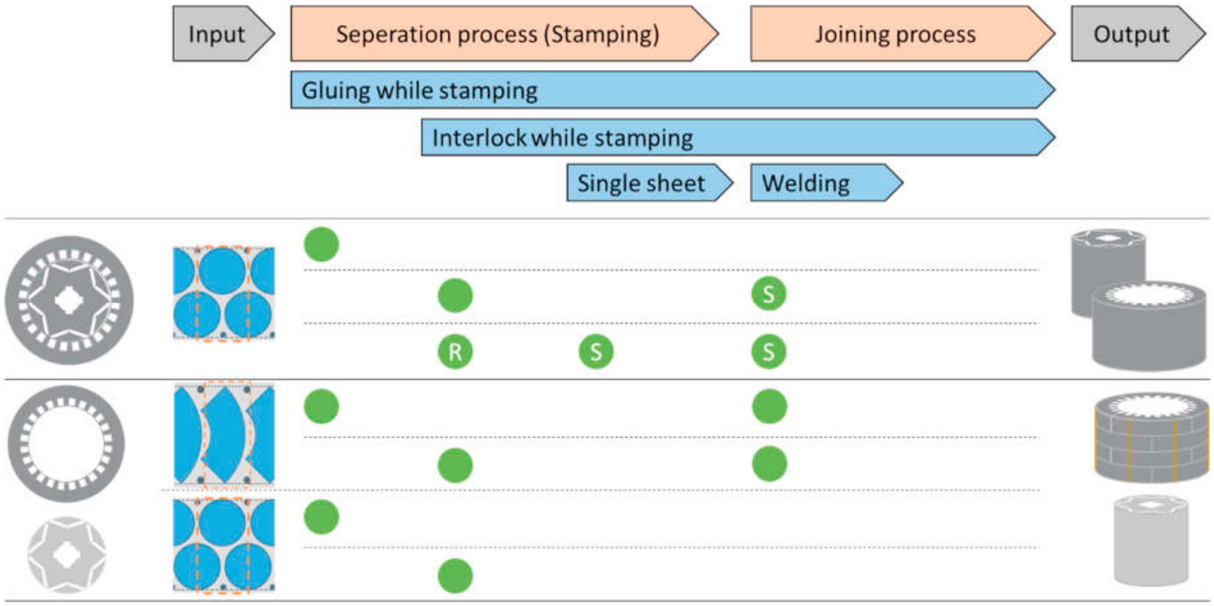

Fig. 5: Mass production technologies for lamination stacks (R: Stator; S: Stator)

If the stator and rotor use the same material, all the listed stamping technologies can be applied. Since the stator core need to be winded later, it is usually welded after stamping to keep its tight structure. Even if the stator sheet is interlocked, the welding process is still necessary. Therefore, the single sheet stamping technology can be applied for stator core. For rotor core, welding is not necessary, because the interlock is already tight enough.

For segmented stator, after it is stamped and glued or interlocked in segment stacks, the segment stacks should be combined and welded (orange line on the stator in Fig. 5) together.

In the following section, all the input parameters for progressive die cost estimation including design parameters and production scenarios will be presented.

6. Progressive die cost estimation

As analyzed from section 4 and 5, the design parameters and production scenarios, which has a direct influence on the design-dependent production parameters and a further influence on the progressive die cost, are summarized in Fig. 6. The standard production parameter are standard values used by the die maker.

According to Fig. 6 and Fig. 1, it is easy to identify, that the size of holder, stripper and retainer is mainly determined by the cutting area and the number of stroke stations (K). In this paper, it is defined that the value of die complexity equals the number of stroke stations. The size of punch and matrix is not dependent on the die complexity, but on the size of profiles to be punched out of the raw material steel strip.

In the following sub-sections, the algorithm for cutting area calculation, complexity evaluation and punch area estimation are to be illustrated. Finally, the progressive die cost estimation equations are given.

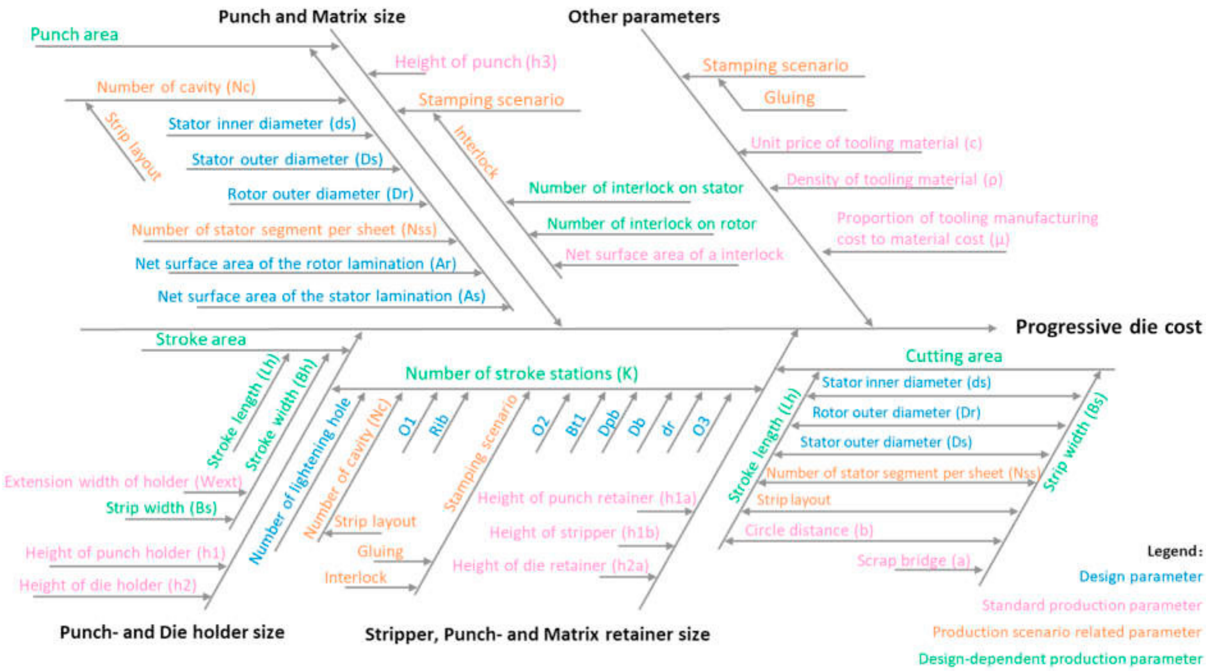

Fig. 6: Influence parameters on the progressive die cost

6.1. Cutting area calculation

The cutting area (Ac) for one stroke can be calculated by equation (1).

$$A_C = B_s \cdot L_h \tag{1}$$

The strip width (Bs) and stroke length (Lh) varies by different strip layouts. According to the strip layouts presented in Fig. 4, the strip width and stroke length can be calculated as below. The strip layout V1 and V2 are used for stamping round laminations. The strip width and stroke length for V1 and V2 can be calculated by equation (2) to (4). Meanings of the following parameters can be found in nomenclature.

$$B_{S,V1} = (\mathrm{D} + 2\mathrm{a}) \tag{2}$$

$$B_{S,V2} = (D + 2a) + \frac{\sqrt{3}}{2} \cdot (D + b) \tag{3}$$

$$L_{h,V1} = L_{h,V2} = D + b \tag{4}$$

If the stator and rotor are to be stamped in separate steps, it is recommended to split the stator in several segments to increase the material utilization.

Strip layout V1 and V2 can still be used for rotor stamping. V3 (include V31 and V32) and V4 (include V41, V42 and V43) are the strip layouts for segment stator stamping. Since the material utilization of V4 is significantly lower than V3, the three layouts of V4 will not be discussed later because of their uneconomicalness. The strip width and stroke length for V31 and V32 can be calculated by equation (5) to (9).

$$B_{S,V31} = \left(\mathrm{D} \cdot \sin\frac{\alpha}{2} + 2\mathrm{a}\right) \tag{5}$$

If $R\,(1 - \cos\frac{\alpha}{2}) \geq (R - r) \cdot cos\frac{\alpha}{2}$, then: $B_{S,V32} = \left((D + b) \cdot \cos\left(sin^{-1}\frac{R + r \cdot cos\frac{\alpha}{2}}{D+b}\right) + D \cdot \sin\frac{\alpha}{2} + 2a\right)$ (6)

Otherwise: $$B_{S,V32} = \left(\frac{3}{2}\mathrm{D}\cdot\sin\frac{\alpha}{2} + \left(r\cdot\cos\frac{\alpha}{2} + R\left(1-\cos\frac{\alpha}{2}\right)\right)\cdot\tan\frac{\alpha}{2} + \frac{b}{\cos\frac{\alpha}{2}} + 2a\right) \tag{7}$$

$$L_{h,V31} = L_{h,V32} = r\cdot cos\left(\pi - \frac{\alpha}{2}\right) + \sqrt{r^2\cdot\cos\left(\pi-\frac{\alpha}{2}\right)^2 - r^2 + R^2} + b \tag{8}$$

With: $$\alpha = \frac{2\pi}{Number\ of\ segments\ Nss} \tag{9}$$

6.2. Complexity evaluation

The complexity evaluation algorithm of progressive die for stator- and rotor lamination is shown in Fig. 7. Parameters in the blue diamonds are design parameters and parameters in the orange diamonds are production scenario related conditions. “K” refers to the value of complexity. The production parameter O_{min} refers to the allowed minimal distance between matrixes, it is often given by the manufacture.

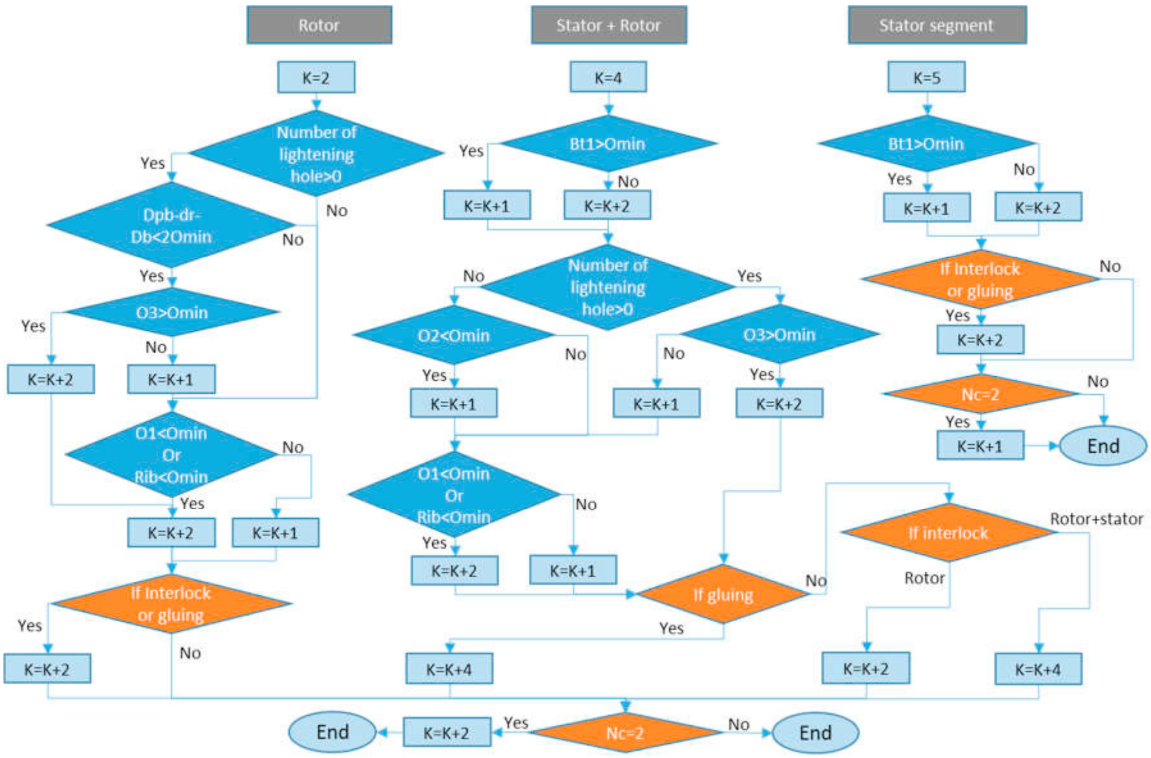

Fig. 7: Complexity evaluation of progressive die for stator- and rotor lamination stamping

The start value of K for single rotor stamping is 2, because 2 stroke stations are definitely needed to punch the inner (including lightening hole) and outer round profiles of rotor.

If the rotor and stator are using the same material and can be stamped with the same die set, the inner round profile of rotor can be punched out together with magnet slots, because in this case, the structure of steel strip is much more firm. The start value of K for stator-rotor stamping is 4, because 3 stroke stations are needed to punch the inner and outer round profile of stator as well as the outer profile of rotor. The other one station is set idle to leave enough place for mounting matrix and rotational mechanism for rotor blanking.

For stator segment stamping, the start value of K is 5. Because 2 stations are needed for stator segment blanking and fit slot (slot on stator yoke for stator segment combination) punching. Another 2 idle stations are necessary before and after stator segment blanking to leave enough place for mounting matrix. At least one idle station is needed before or after the station for fit slot punching, because the matrix for fit slot is mounted on the edge of that station, which conflicts with the matrix on the former or later stations.

After the start value is defined, the algorithm will check the distance between holes on the design part, as shown in the blue diamonds. If distance between two kinds of holes is smaller than O_{min}, these two kinds of holes must not be punched out in the same station.

As mentioned before, the production scenarios are also considered while estimating the complexity as shown in the orange diamonds. If interlock or gluing is integrated while stamping, normally two more stations are necessary for one part (rotor or stator). As the cavity is increased from one to two (as shown in V2 and V32 of Fig. 4), the number of stations should also be increased.

6.3. Progressive die cost estimation

In this section, the estimation for punch area is first given to simplify the progressive die cost estimation equation. The punch area (A_P) for single rotor stamping ($A_{P,R}$), rotor-stator stamping ($A_{P,SR}$) and stator segment stamping ($A_{P,SS}$) can be calculated by equation (10) to (12). The meaning of the parameters can be found in Fig. 6.

$$A_{P,R} = (\frac{\pi}{2}\mathrm{D}_r^2 - A_r) \cdot N_c \tag{10}$$

$$A_{P,SR} = (\frac{\pi}{2}\mathrm{D}_s^2 - A_r - A_s + \frac{\pi}{4}\mathrm{D}_r^2 + \frac{\pi}{4}\mathrm{d}_s^2) \cdot N_c \tag{11}$$

$$A_{P,SS} = (\frac{\pi}{2}\mathrm{D}_s^2 - \frac{\pi}{2}\mathrm{d}_s^2 - A_s)/N_{ss} \cdot N_c \tag{12}$$

As mentioned in section 3, tooling invest costs can be estimated by size of tool, which drives the material cost of tool. Therefore, in this paper, the cost of the progressive die (C_{PD}) is estimated by the raw material density (ρ), the unit material price (c), the size of each part of progressive die, and the proportion of tooling manufacturing cost to material cost (μ).

Because of different functional requirements on holder, retainer, stripper and punch, different raw materials are used for these three parts. Therefore, the unit price and density of these raw materials are also different (ρ_r and c_r for retainer and stripper, ρ_h and c_h for holder, ρ_p and c_p for punch). The equations of raw material cost estimation for retainer (including stripper, $C_{RM,\ retainer}$), holder ($C_{RM,\ holder}$) and punch ($C_{RM,\ punch}$) are given in (13) to (15).

$$C_{RM,retainer} = B_S * L_h \cdot \mathrm{K} \cdot (h_{1b} + h_{1a} + h_{2a}) \cdot \rho_r \cdot c_r \tag{13}$$

$$C_{RM,holder} = (B_S + 2W_{ext}) \cdot L_h \cdot K \cdot (h_1 + h_2) \cdot \rho_h \cdot c_h \tag{14}$$

$$C_{RM,punch} = A_P \cdot h_3 \cdot \rho_p \cdot c_p \tag{15}$$

In equation (16), the estimated cost of progressive die (C_{PD}) is given. Since the hardness, size, precision requirement on retainer, holder and punch are different, their proportion of manufacturing cost to material cost ($\mu_h < \mu_r < \mu_p$) are also different. This can either be given from the manufacture or be estimated from the quotations. If gluing is integrated in stamping process, the total cost of tooling should be increased by f_g (%) for mounting gluing and heating system in the stamping tool, otherwise, f_g equals zero.

$$C_{PD} = \left[C_{RM,retainer} \cdot (1 + \mu_r) + C_{RM,holder} \cdot (1 + \mu_h) + C_{RM,punch} \cdot (1 + \mu_p)\right] \cdot (1 + f_g) \tag{16}$$

7. Conclusion and future work

A cost estimation approach for progressive die based on design parameters and production scenario in the electric traction motor application has been described.

Both the strip layouts and the dimensions can exert influence on the progressive die cost and the resultant manufacturing cost as well as the product cost. This paper describes the design of stator- and rotor lamination, different strip layouts, the appropriate design of tooling size and tooling structure for estimating the tooling invest cost.

An approach to evaluate the complexity of die based on design parameters, strip layouts and production scenarios is presented, which is crucial for determining the number of progressive die stations.

With the proposed approach, an approximate value for the progressive die cost resulted from different strip layouts can be determined. The further work is to develop a method to increase the accuracy of the proportion of tooling manufacturing cost to material cost for a better tooling cost estimation.

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