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Manufacturing design of plain milling technology of spline shaft by formed disc-type milling cutter

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Manufacturing design of plain milling technology of spline shaft by formed disc-type milling cutter

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Abstract. The spline fittings are widely used in different mechanical constructions where high load transmission is required from a shaft to a spline plate or a tooth gear or other internal cylindrical element. In many cases a key joint connection can not bear the load that we want to transform. In this case the application of double key could give solution. But sometimes it does not give solution due to the high load that is why spline fitting should be used. This publication focuses for the manufacturing of the spline shaft with plain milling technology. The type of the tool is a formed disc type milling cutter. Since more splines are around the perimeter of the shaft the repetition of the milling process is needed in the function of the number of the splines. All of the manufacturing parameters will be determined that are needed for a complex technological analysis such as cutting forces, machining times, speeds, etc. The chip volume will be approximated by volume constancy since the separated chip volume is a quite complex geometric body. I will prescribe initial technological parameters and define existing shaft geometries for which I will determine the technological parameters to show and analyze the correlations between the technological parameters and the variable for each shaft.

1. Introduction

The spline shaft is inserted to the spline hole that has grooves. They are element pairs together (Figure 1) [1, 2]. High surface pressure can be developed on the connected surfaces in case of application of one or two keys and high moment transmission. Spline fitting is applied in these cases instead of the key joint. The number of teeth is at least 3 on the perimeter of the shaft. Mostly minor diameter fit, rarely major diameter fit or side bearing fit are established for the connection between the elements (Figure 2) [2].

The porperties of the position accuracy and the quality of spline fitting are [3, 4]:

- the centralized diameters has the concentricity and size accuracy,
- the side sizes of the spline width, division accuracy and the paralelism of the side surfaces compared to the center line,
- the surface roughness and hardness,
- the accuracyof fits.

The centralized surfaces are made by narrow tolerances which provide the concentricity of the elements. The other two elements have wider tolerances [3, 4].

Based on Figure 2 the comparison of the three types of fits is the following [1, 2, 3, 4]:

1. The connection on the minor diameter fit: the load distribution and the conneciton is on the root circle diameter of the spline shaft (d_f) and the tip circle diameter of the spline hole (D_a) (Figure 2.a).
   Advantages: the manufacturing of the tip circle diameter of the spline hole (D_a) is simple because there are not obstacles concerning the chip separation process so continuous grinding is applicable, grinding technology provides the concentricity of the root circle diameter of spline shaft, the shaft and the hole can be hardened.
   Disadvantage: the grinding process of the root circle diameter of the spline shaft (d_f) is difficult and complex due to the chip removal in the tooth spaces.

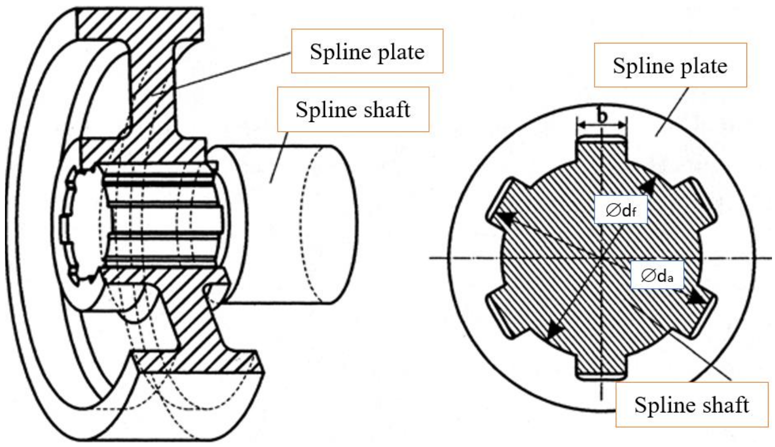
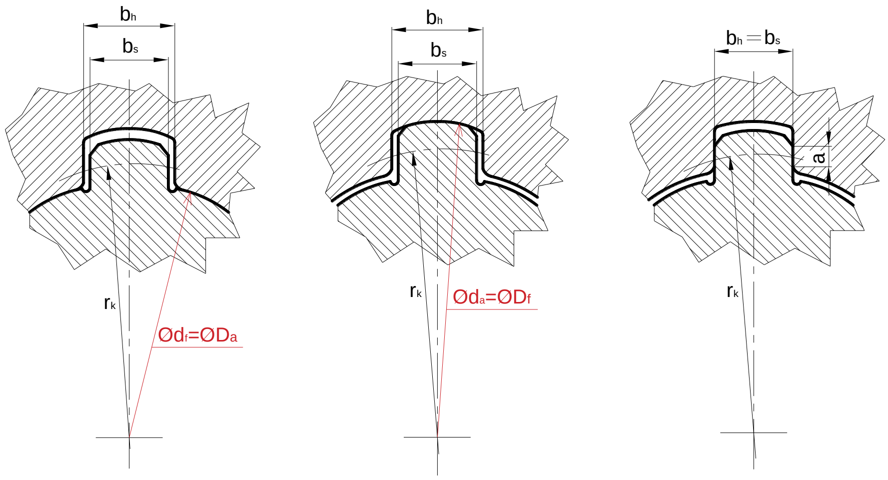


Figure 1. Connection of the elements of the spline fitting

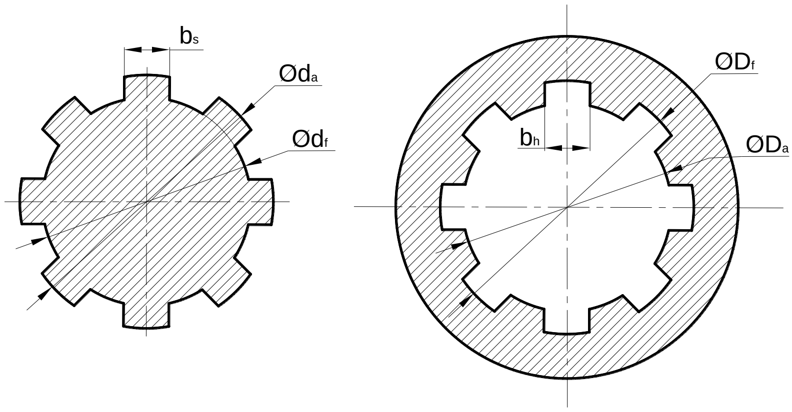


a) minor diameter fit b) major diameter fit c) side bearing fit

Figure 2. The different centralized spline fittings

2. The connection on the major diameter fit: the connection is on the tip circle diameter of the spline shaft (d_a) and the root circle diameter of the spline hole (D_f) (Figure 2.b).
   Advantages: the manufacturing of the tip circle diameter of the spline shaft (d_a) is easier than in case of minor diameter fit since simple traverse grinding technology is usable around the

external perimeter and the teeth can not obstruct the continuous chip separation process around the whole perimeter of the shaft.
Disadvantages: the hole can not be hardened, calibration heat treatment is indispensible after the normal heat treatment.



a) spline shaft b) spline hole
Figure 3. The geometric parameters on the shaft and the hole

3. The connection of the side bearing fit: the connection is on the side surfaces of the elements (Figure 2.c).
Advantages: it has the best accurate centralization, the shaft and the hole can be hardened
Disadvantageous: manufacturing of the side surface of the hole and the shaft needs a lot of manufacturing works, very difficult to execute the grinding technology on the side surfaces because of the little tooth depth and the manufacturing access.

The operations having IT11 tolerance quality can be done finishing turning and finishing milling. Grinding is necessary in case of lower tolerances [3, 4].

The allowance for finishing of the splines is 0.6 – 0.8 mm on the spline width and diameter. The allowance for grinding in case of finishing milling is 0.1 – 0.15 mm per side if the shaft length is shorter than 200 mm. In case of longer shafts the allowance is 0.15 – 0.20 mm [2].

The spline shaft can be manufactured with warm rolling process. The axial feed force is decreased 36.6% by warm rolling process compared to the cold rolling process. After the analysis of the microstructure and hardness tests we get the results that the warm rolling technology are significantly better than manufacturing by cold rolling [5].

The effects of the axial-pushed incremental rolling process parameters and the material flow behavior during the process are investigated by finite element analysis (FEA) [6].

The AC (alternating current) servo axial-infeed incremental warm rolling equipment is analyzed on the basis of the integration of process and equipment. The formed spline shafts has an excellent performance based on the analysis of the microstructure observation and the hardness measurement [7].

The paper [8] presents a non-contact optical measurement method based on a laser displacement sensor (LDS) and spectral confocal sensor the coaxially error measurement of the inner spline-bevel gear composite gears shaft.

The paper [9] presents surface hardness and the case depth are similar to the specification. The critical failure in spline shaft can be overcome due to advancement in designs of spline shaft. For this, different materials, alloyed material, as well as composite material are used. A complex review was created which shows the noteworthy contribution of various researchers in improving the manufacturing technology of spline shaft.

The paper [10] presents a finite element method using the birth and death technique in ANSYS Workbench is used to determine the optimal harfacing parameters, taking into account temperature distributions, deformations and stresses. At Kazakhstani repair enterprises, semi-automatic hard surfacing in shielding gases is widely used. This welding method is the most saving. It can provide good adhesion between the base and weld metal. It has high labour productivity.

The paper [11] presents a concept that permits in-situ detection of mechanical overloads on splined shafts by eddy current techniques. Splined shaft connections are among the most heavily stressed machine elements in the drive train. They are usually located centrally in the powertrain. To monitor mechanical overloads, a material-integrated sensor are developed.

The goal of this study is the deep manufacturing analysis of the spline shaft cutting with disc-type milling cutter to provide more detailed manufacturing design in the industry or to further manufacturing researches. The determination of the cutting forces and the machining time are also predictable to estimate the overall machining time for all of the parts and to make finite method analysis for the process. The changing of the spline height and the diameter of the milling cutter are analysed to determine the correlation between the received manufacturing parameters.

2. Manufacturing of the spline slots of the spline shaft with plain milling technology

2.1. Analysis of the manufacturing technology

Based on the type of the milling machine there are two machine types to manufacture the teeth of the spline shaft: conventional horizontal knee-type milling machine or CNC controlled milling machine.

The tool is doing rotation motion and linear motion along the tooth length. After the material removal of one spline slot the workpiece has to be distributed accordingly the tooth pitch and the process can restart (Figure 4). Consequently, the motion of the tool is continuous but the motion of the workpiece is discontinuous.

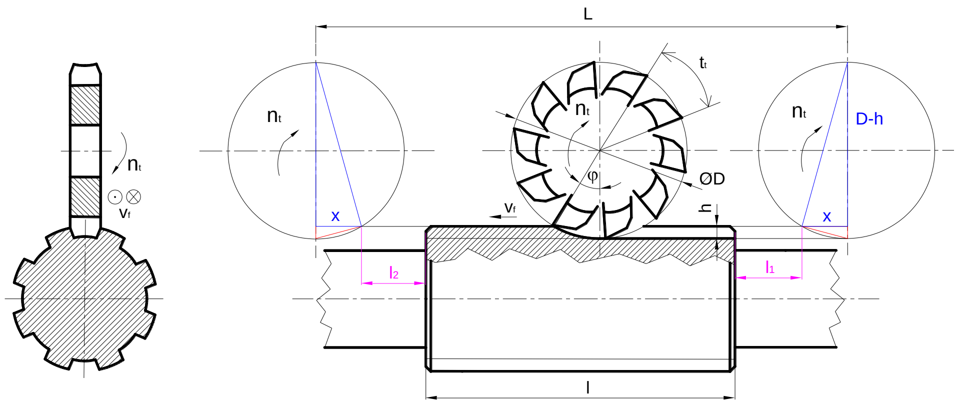


Figure 4. The manufacturing process of the teeth on the spline shaft with plain milling technology

Using of the dividing head the necessary pitch can be adjusted on the hole circle. It can provide the accurate division from tooth to tooth on the spline shaft. The workpiece is intercepted between two centers. The tailstock can provide the support on the opposite side. This is the solution for the conventional way (Figure 5).

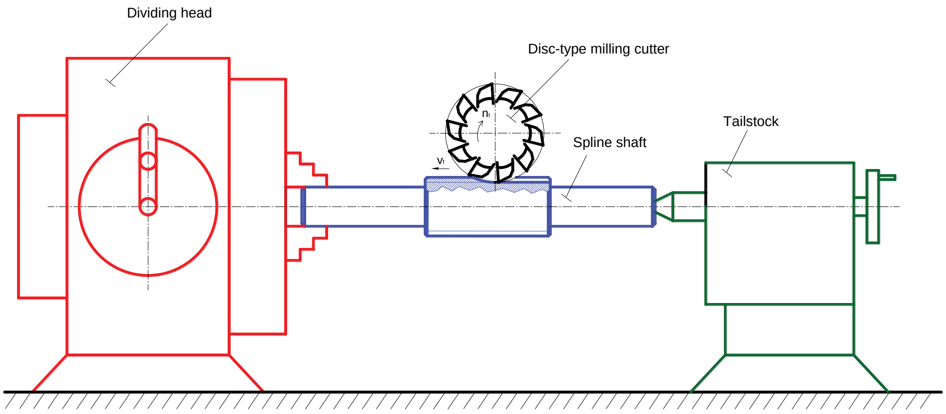


Figure 5. Manufacturing of the teeth on the spline shaft by conventional way

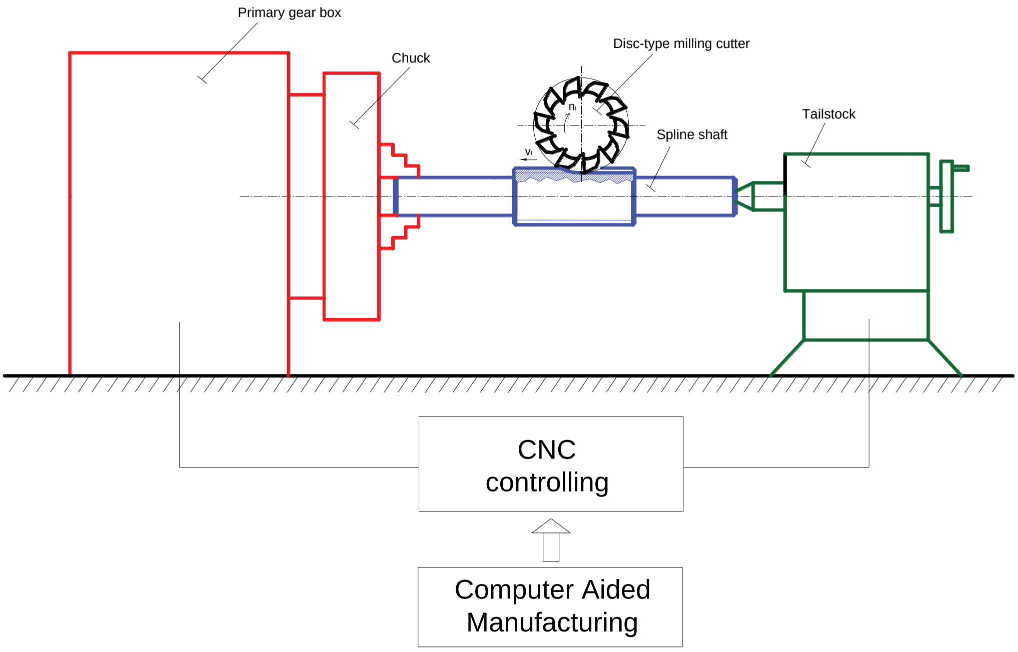


Figure 6. Manufacturing of the teeth on the spline shaft by modern way

The necessary division happens based on the CNC program in case of CNC controlled manufacturing. After the CAM design a CNC program can be generated. This program can be imported into the CNC milling machine where the directions can be implemented. This is the most modern solution (Figure 6).

The type of the tool is a formed disc-type milling cutter that has an individual profile which is equal with the spline slot of the spline shaft (Figure 7). This tool can have also changeable inserts.

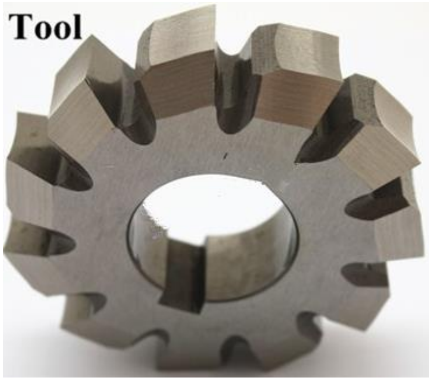


Figure 7. The geometric establishment of the tool

2.2 Calculation of the parameters for the manufacturing technology

The initial parameters are the followings: $h, z, l, l_1, l_2, b_s, n_t, d_a, d_f, z_t, D, f_z, k_c$. Regarding the spline shaft firstly the $\widehat{w_1}$ and the $\widehat{w_2}$ arc lengths have to be determined based on Figure 8.

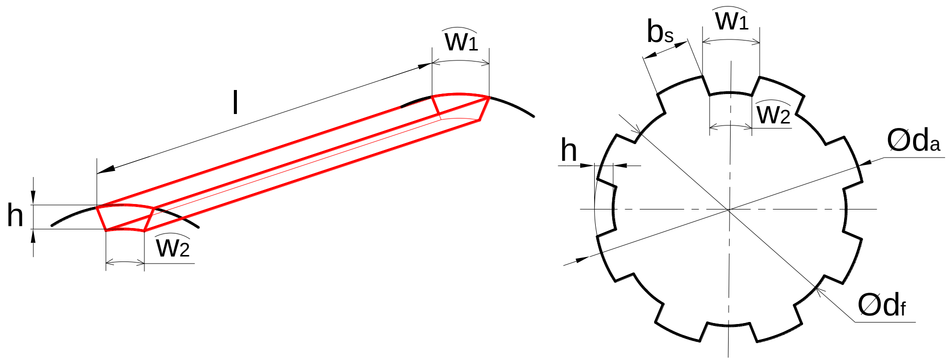


Figure 8. Determination of the geometric parameters of the tooth space

In case of the d_a diameter, the $\widehat{w_1}$ is (Figure 8)

$$\frac{d_a \cdot \pi - b_s \cdot z}{z} = \widehat{w_1} \tag{1}$$

In case of the d_f diameter, the $\widehat{w_2}$ is (Figure 8)

$$\frac{d_f \cdot \pi - b_s \cdot z}{z} = \widehat{w_2} \tag{2}$$

The cutting speed of the formed disc-type milling cutter is (Figure 4)

$$v_c = D \cdot \pi \cdot n_t \tag{3}$$

The feed speed of the formed disc-type milling cutter is (Figure 4)

$$v_f = z_t \cdot f_z \cdot n_t \tag{4}$$

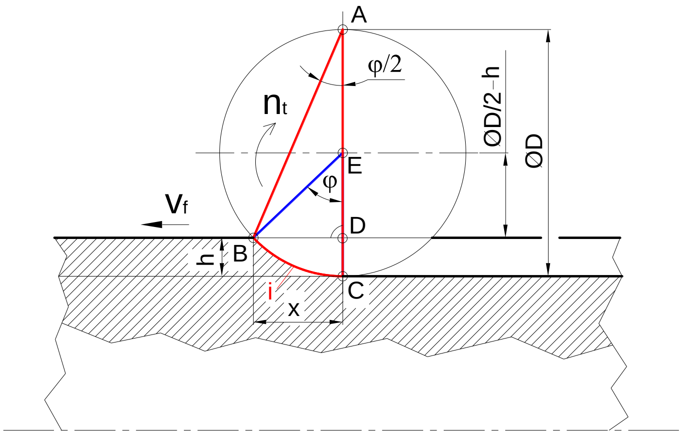


Figure 9. Determination of the x distance, the center angle and the arc of contact

Considering Figure 4 the Figure 9 can be created where the geometric and the manufacturing parameters are eyeable detailedly during the chip separation process. Based on the BDE right angle triangle the x distance is (Figure 9)

$$x = \sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{D}{2} - h\right)^2} \tag{5}$$

$$x = \sqrt{D \cdot h - h^2} \tag{6}$$

The φ center angle is (Figure 9)

$$\varphi = tan^{-1}\left(\frac{x}{\frac{D}{2} - h}\right) \tag{7}$$

The i arc of contact is (Figure 9)

$$i = \varphi^{\circ} \cdot \frac{D \cdot \pi}{360^{\circ}} \tag{8}$$

Since $\widehat{w_1}$ and $\widehat{w_2}$ are not same and considering Figure 4 where the formed disc-type milling cutter is doing rotation and linear motion simultaneously we can gain the separated chip volume for one spline slot of the spline shaft (Figure 10).

The dark contour shows the real geometric shape of the chip volume. Determining an average arc length ($\frac{\widehat{w_1}+\widehat{w_2}}{2}$) a consistent theoretical chip volume can be created (purple contour). The h chip thickness is gradually changing between the two arcs on the side surfaces that is why an $\bar{h}$ medium chip thickness can be determined. The blue area shows the middle theoretical chip section for which the cutting force can be calculated (Figure 10).

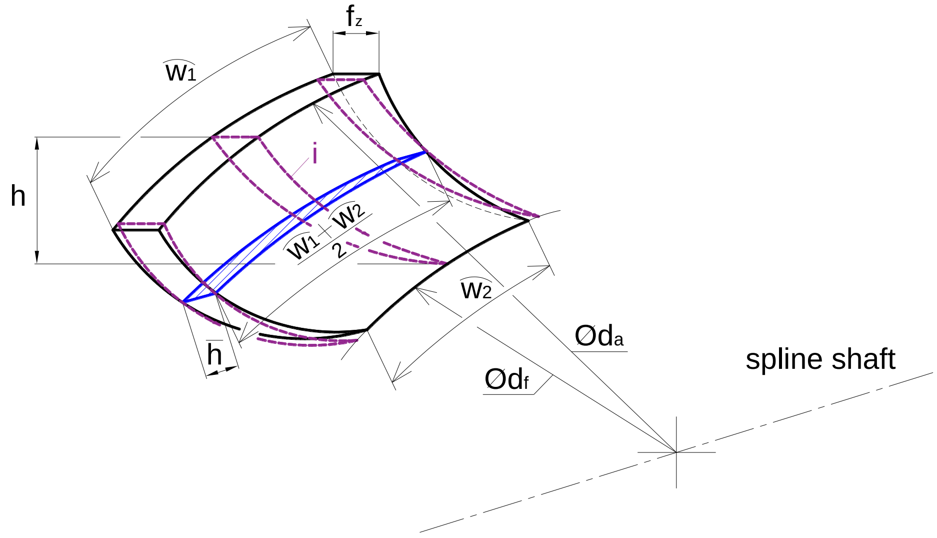


Figure 10. The geometric establishment of the separated chip volume for one spline slot of the spline shaft

The V_1, V_2 and V_3 volumes are approximately the same. Based on this approximation the following equation can be received (Figure 11)

$$V_1 \approx V_2 \approx V_3 \tag{9}$$

$$f_z \cdot h \cdot \frac{\widehat{w_1} + \widehat{w_2}}{2} = \bar{h} \cdot i \cdot \frac{\widehat{w_1} + \widehat{w_2}}{2} \tag{10}$$

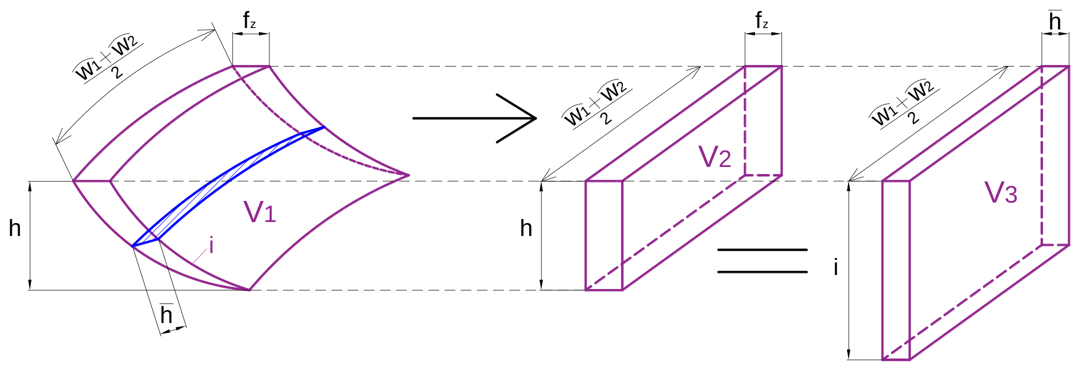


Figure 11. Approximation of the arched volume with prisms

Based on (10) the middle chip thickness is

$$\bar{h} = \frac{f_z \cdot h}{i} \tag{11}$$

By substituting (8) to (11) we obtain

$$\bar{h} = h \cdot f_z \cdot \frac{360°}{\varphi^{\circ} \cdot D \cdot \pi} \tag{12}$$

Journal of Physics: Conference Series **2848** (2024) 012013 doi:10.1088/1742-6596/2848/1/012013

Based on Figure (4) the tooth pitch t_p on the formed disc-type milling cutter is

$$t_t = \frac{D \cdot \pi}{z_t} \tag{13}$$

Switch number means the number of the working teeth of the formed disc-type milling cutter along the *i* arc of contact:

$$\Psi = \frac{i}{t_t} = \frac{\varphi^{\circ} \cdot \frac{D \cdot \pi}{360°}}{\frac{D \cdot \pi}{z}} = \frac{\varphi^{\circ}}{360} \cdot z_t \tag{14}$$

The cutting force for one tooth of the milling cutter is (Figure 10)

$$F_{c1} = k_c \cdot A_{c1} = k_c \cdot \bar{h} \cdot \frac{\widehat{w_1} + \widehat{w_2}}{2} \tag{15}$$

By substituting (12), (14) and (15), the total cutting force is obtained

$$F_c = \Psi \cdot F_{c1} = \frac{\varphi^{\circ}}{360} \cdot z \cdot k_c \cdot h \cdot f_z \cdot \frac{360°}{\varphi^{\circ} \cdot D \cdot \pi} \cdot \frac{w_1 + w_2}{2} \tag{16}$$

$$F_c = \Psi \cdot F_{c1} = z \cdot k_c \cdot h \cdot f_z \cdot \frac{1}{D \cdot \pi} \cdot \frac{w_1 + w_2}{2} \tag{17}$$

The total cutting power is

$$P_c = F_c \cdot v_c \tag{18}$$

The power of the working machine is considering the efficiency η

$$P_m = \frac{P_c}{\eta} \tag{19}$$

The machining time T_g can be determinable based on Figure 4. We have to consider the x distance twice due to the geometric establishment of the tool plus the l_1 and l_2 overrunings. We need to repeat the chip separation process in the function of the number of teeth z of the spline shaft:

$$T_g = \frac{L}{v_f} \cdot z = \frac{x + l_1 + l + l_2 + x}{v_f} \cdot z \tag{20}$$

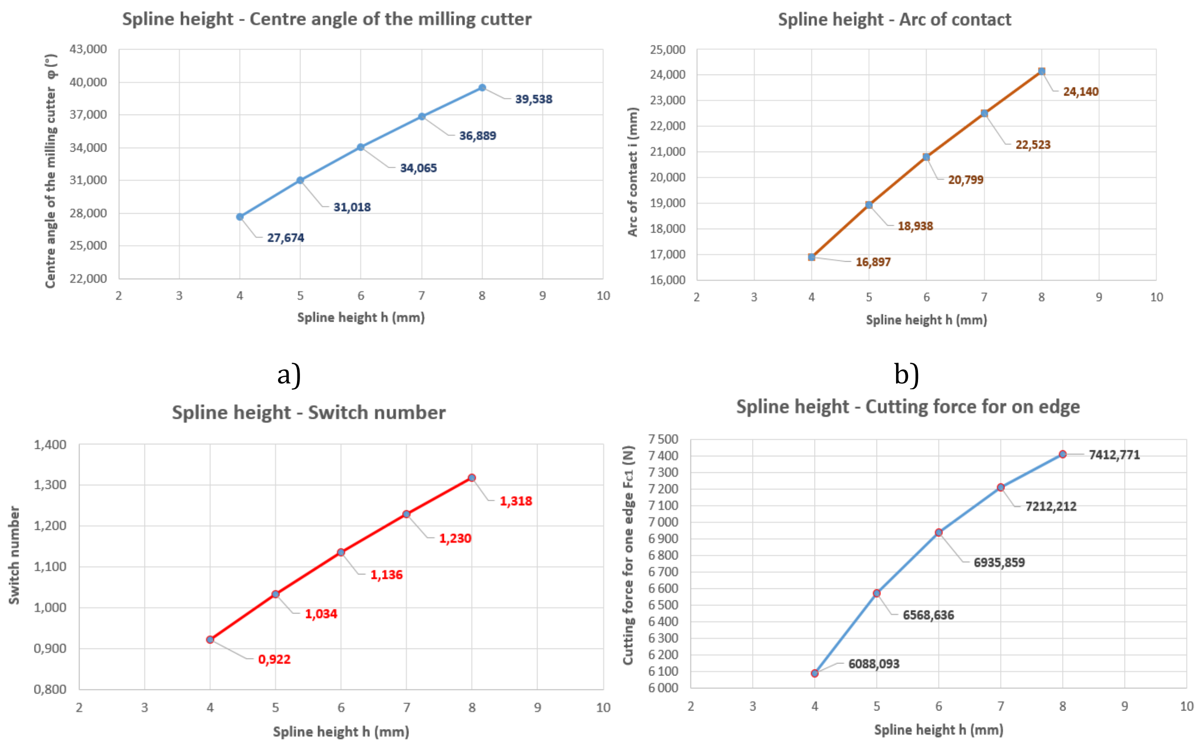
2.3 Analysis of the effect of the manufacturing parameters in the function of the varying of the spline height

The initial parameters for the experiment are in Table 1 based on general spline shaft establishment and manufacturing adjustment. The spline height (h) was changed from 4 mm to 8 mm with 1 mm steps.

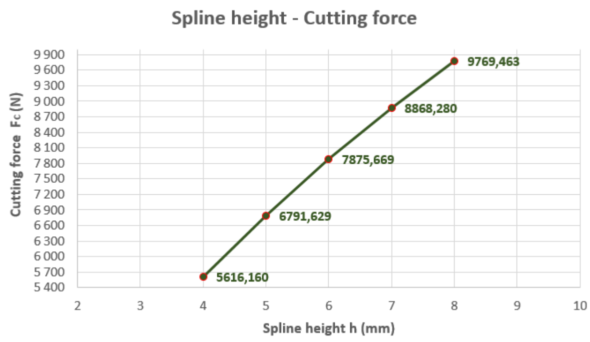
Table 1. The initial parameters for the changing of the spline height

Parameter	Value
z	6
l	200 mm
b	8 mm
n_t	120 1/min
f_z	0.5 mm/rev.
d_a	50 mm
D	70 mm
z_t	12
k_c	3200 N/mm^2
l_1 and l_2	3 mm

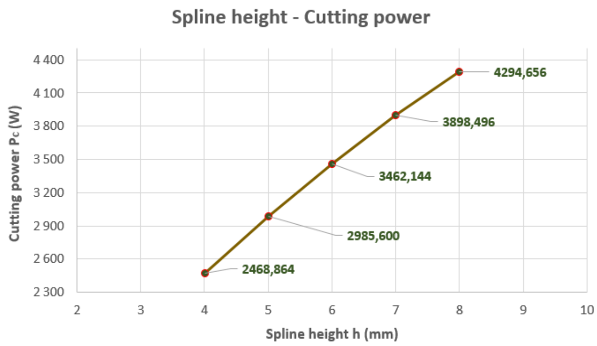
Considering the necessary calculation formulas in subchapter 2.2. we got the correlations between the technological parameters and the changing of the spline height (Figure 12).



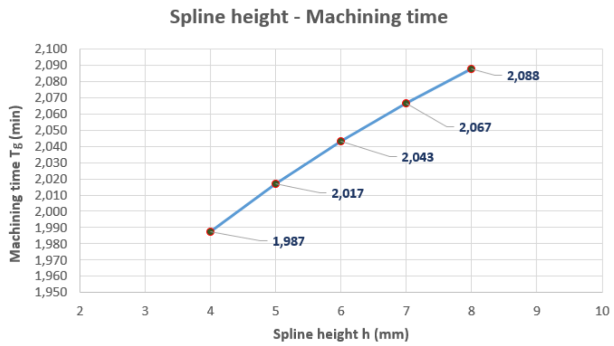
c) d)



e)



f)



g)

Figure 12. The calculated technological parameters in the function of the spline height

2.4. Analysis of the effect of the manufacturing parameters in the function of the varying of the diameter of the milling cutter

The initial parameters for the experiment are in Table 2. This parameter (D) was changed form 70 mm to 90 mm with 5 mm steps based on general spline shaft establishment and manufacturing adjustment.
Knowing of the formulas of the technological design in subchapter 2.2. we got the following charts after the calculations in the function of the changing of the diameter of the milling cutter (Figure 13).

Table 2. The initial parameters for the changing of the diameter of the milling cutter

Parameter	**Value**
z	6
l	200 mm
b	8 mm
n_t	120 1/min
f_z	0.5 mm/rev.
d_a	50 mm
h	5 mm
z_t	12
k_c	3200 N/mm^2
l_1 and l_2	3 mm

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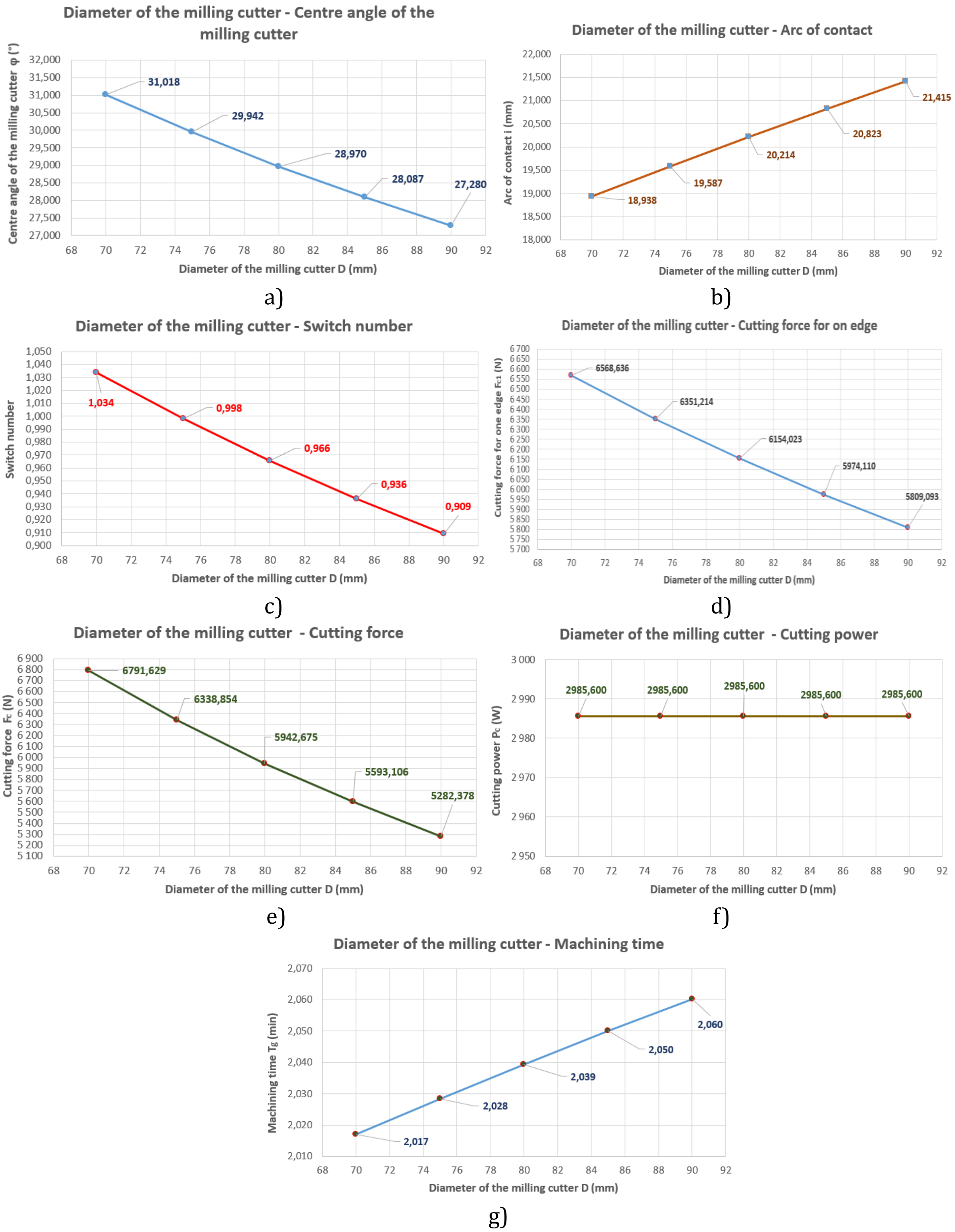

Figure 13. The calculated technological parameters in the function of the diameter of the milling cutter

3. Results and discussion

After the determination of the correlations between the technological parameters in mathematical way we changed the spline height and the diameter of the milling cutter beside of the constancy of the initial geometric and technological parameters. We got the following results:

- changing of the spline height:
  - all of the function that we got has a parabola shape. Consequently, the higher the spline height the higher the center angle of the milling cutter, the arc of contact, the switch number, the cutting force for one edge, the total cutting force, the cutting power and the machining time (Figure 12).
- changing of the diameter of the milling cutter:
  - the function is hyperbola between changing of the diameter of the milling cutter and the center angle of the milling cutter. It means inverse proportion (Figure 13.a).
  - the function is parabola between changing of the diameter of the milling cutter and the arc of contact on the tool and the workpiece. The higher the diameter of the milling cutter the higher the arc of contact. (Figure 13.b).
  - the function is hyperbola between changing of the diameter of the milling cutter and the switch number (Figure 13.c), the cutting force for one edge (Figure 13.d) and the total cutting force (Figure 13.e). It means inverse proportion.
  - the cutting power is constant in the function of the changing of the diameter of the milling cutter (Figure 13.f).
  - the function is parabola between changing of the diameter of the milling cutter and the machining time. The higher the diameter of the milling cutter the higher the machining time. (Figure 13.g).

4. Conclusion

The application of the spline fitting is reasonable in case of high load transmission when the usage of key joint is not possible.

There are more manufacturing technologies (manufacturing with disc-type milling cutter or end mill or slot milling cutter or hob, etc.) for the creation of the teeth of the spline shaft. The main common principle of them is the material removal in the tooth spaces. I focused for the manufacturing with formed disc-type milling cutter whose comprehensive name is plain milling technology in this study. The tool does rotation and linear motion simultaneously during manufacturing of one tooth space. This removal process has to be recuped in the function of the number of teeth around the perimeter on the spline shaft.

I determined all of the manufacturing parameters that are needed for the deep and detailed technological design. Using of the formulas this technology can be analyzed detailedly to provide better accuracy and surface roughness for the shaft that can effect for the connection and load transmission. After the execution of the milling technology grinding technology is also needed on the connecting surfaces between the shaft and the hole.

Considering the determinable technological parameters CAM simulation and creation of CNC program is also possible if we want to have the spline shaft manufactured by a CNC machine having more axes.

I modified the spline height and the diameter of the formed disc-type milling cutter. Considering the constancy of the initial geometric and technological parameters I determined the effect of those changing parameters for the manufacturing parameters and made the consequences.

References

[1] S. Bodzás, 'Manufacturing of the surfaces of spline fitting connection', International Journal of Advanced Manufacturing Technology 111 pp. 909-920. , 12 p. 2020

[2] I. Dudás, 'Gépgyártástechnológia III. A. Megmunkáló eljárások és szerszámai. B. Fogazott alkatrészek gyártása és szerszámaik', University book, Technical Publisher, 2011., p. 538, ISBN 978-963-16-6531-4

[3] F. Klocke, 'Manufacturing Processes I, Cutting', RWTH Edition, RWTH Aachen University, p. 524, ISBN 978-3-642-11978-1

[4] H. A. Youssef, H. El – Hofy, 'Machining Technology, Machine tools and operations', CRC Press, United States of Amerika, p. 672, ISBN 978-1-4200-4339-6

[5] H. Hou, Y. Zhao, M. Cui et al. 'Experimental study on the axial-infeed incremental warm rolling process for spline shaft production', Int J Adv Manuf Technol 112, 2177–2186 (2021). https://doi.org/10.1007/s00170-020-06422-3

[6] MC. Cui, SD. Zhao, C. Chen, et al. 'Process parameter determination of the axial-pushed incremental rolling process of spline shaft', Int J Adv Manuf Technol 90, 3001–3011 (2017). https://doi.org/10.1007/s00170-016-9604-2

[7] H. Sun, MC. Cui, Y. Zhang et al. 'Performance of AC servo axial-infeed incremental warm rolling equipment and simulated production of spline shafts', Int J Adv Manuf Technol 94, 2089–2097 (2018). https://doi.org/10.1007/s00170-017-1003-9

[8] Lu, Yong-hua; Fang, Yuanyuan; Xu, Jiajun; Liu, Heng; Zhang, Tianyi, 'Research on coaxiality measurement system of inner spline-bevel gear composite gears shaft', Optica Open. Preprint (2023). https://doi.org/10.1364/opticaopen.23732985.v2

[9] R. Kumar, N. Kumar Singh. 'A Comprehensive Report on the Thermal, Static and Dynamic Behaviour of Spline Shaft', IJSRD - International Journal for Scientific Research & Development, Vol. 7, Issue 01, 2019, ISSN (online): 2321-0613 (2019), https://www.researchgate.net/publication/332719243_A_Comprehensive_Report_on_the_Thermal_Static_and_Dynamic_Behavior_of_Spline_Shaft

[10] O. Nurzhanova, O. Zharkevich, A. Bessonov, Y. Naboko, G. Abdugaliyeva, G. Taimanova, T. Nikonova, 'Simulation of the distribution of temperature, stresses and deformations during splined shafts hardfacing', Journal of Applied Engineering Science, Vol. 21, No. 3 (2023), https://aseestant.ceon.rs/index.php/jaes/article/view/42774/23309

[11] R. Gansel, S. Zwoch, C. Heinrich, A. Lohrengel, H. Jürgen Maier, S. Barton, 'Identification of overloads on splined shafts by means of eddy current testing technology', Special Issue of Research and Review Journal of Nondestructive Testing (ReJNDT) ISSN 2941-4989 Vol. 1(1) (2023), https://doi.org/10.58286/28069

Nomenclature

Parameter	Unit	Name
z		Number of splines
b_h	mm	Spline slot width on the hole
b_s	mm	Spline width on the shaft
d_f	mm	Root circle diameter of the spline shaft
D_a	mm	Tip circle diameter of the spline hole
d_a	mm	Tip circle diameter of the spline shaft
D_f	mm	Root circle diameter of the spline hole
a	mm	Length of the contact surfaces
r_k	mm	Resultant distance of the surface pressure form the centre line of the shaft
n_t	1/min	Number of revolution of the disc-type milling cutter
v_f	m/min	Feed speed of the disc-type milling cutter
x	mm	x distance based on the geometry of the tool
φ	°	Center angle of the disc-type milling cutter
l_1 , l_2	mm	Overrunings

l	mm	Spline length
L	mm	Total manufacturing length
D	mm	External diameter of the disc-type milling cutter
t_t	mm	Tooth pitch on the disc-type milling cutter
h	mm	Spline height
CNC		Computer Numerical Control
CAM		Computer Aided Manufacturing
z_t		Number of teeth on the disc-type milling cutter
f_z	mm/rev.	Feed for one edge
$\widehat{w_1}$	mm	Arc length around the tip circle diameter of the spline shaft
$\widehat{w_2}$	mm	Arc length around the root circle diameter of the spline shaft
i	mm	Arc of contact between the tool and the spline shaft
V_1, V_2, V_3	mm^3	Volumes
$\bar{h}$	mm	Medium chip thickness
Ψ		Switch number
k_c	N/mm^2	Specific cutting force
F_{c1}	N	Cutting force for one edge
F_c	N	Total cutting force
A_{c1}	mm^2	Theoretical chip section for one edge
P_c	kW	Cutting power
η		Efficiency
P_m	kW	Power of the working machine
v_c	m/min	Cutting speed
T_g	min	Machining time