MANUFACTURING METHOD OF SPIRAL BEVEL GEARS BASED ON CAD/CAM AND 3-AXIS MACHINING CENTER

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Spiral bevel gears have been traditionally machined on special machines commonly known as Gleason, Oerlikon, or Klingelnerg. One of disadvantages of the traditional method is high cost. This paper presents a practical method based on CAD/CAM and 3-axis CNC machining to manufacture spiral bevel gears of the Gleason design. This method can be considered as an alternative method to the traditional methods. For the proposed method, first, the 3D model of the spiral bevel gear was created. Next, the tool path planning for 3-axis cutting of the tooth profiles of the gear was performed. Then, the gear teeth were cut on a 3-axis CNC machining centre using flat-end mills for roughing and semi-finishing, and ball-end mills for finishing. The machined gear was measured and analysed by a non-contact measuring method which allows to compare the actual part to the nominal CAD model. The pitch deviations and the surface roughness of the manufactured gear were also measured. As a result, the validity and effectiveness of the proposed method were confirmed.

KEYWORDS

CAD/CAM, spiral bevel gear, gear manufacturing, 3-axis machining centre, end mill, optical scanner

1 INTRODUCTION

Spiral bevel gears are widely used in various mechanical products in areas of aerospace, automobile, machine tool, mining machinery, … [Jadeja 2013], [Wang 2014]. Because of the complexity of the surface geometry, machining spiral bevel gears requires special machine tools and cutting techniques. Traditionally, these kinds of gears have been machined on Gleason, Oerlikon, or Klingelnerg machines with special tools. The traditional cutting methods are complicated and expensive.

Recent advances in CNC (Computer Numerical Control) technology and CAD/CAM (Computer-Aided Design and Manufacturing) now make it possible to manufacture spiral bevel gears on multi-axis CNC machines with low cost milling cutters that are commonly used in machining. This approach needs CAD models of spiral bevel gears for CAM programming. For CAD modelling and CAM programming of spiral bevel gears, researchers often used commercial CAD and CAD/CAM software [Alvarez 2015], [Badiuzaman 2016], [Lei 2011], [Safavi 2007], [Vosniakos 2017]. From the open literature, it can be seen that 5-axis milling machines are commonly used to manufacture spiral bevel gears [Alvarez 2015], [Alves 2013], [Badiuzaman 2016]. Besides, 4-axis machining centres and multi-tasking machines can also utilized as depicted in [Badiuzaman 2016], [Kawasaki 2011], [Lei 2011], [Suh 2001].

In multi-axis CNC machining, flat-end mills and ball-end mills can be used to cut the tooth surfaces of spiral bevel gears. In these cases, users can choose the optimal directions of the cutting tools in order to get better surface finish and to reduce machining time. Compared to 3-axis CNC machining, multi-axis CNC machining has a much better capability and accuracy. However, multi-axis CNC machine tools are more expensive than 3-axis CNC machine tools. Many small machine shops only invest 3-axis machine tools for their business. Although 3-axis CNC machines have limits that makes the machined spiral bevel gears less precise and lower quality but to some extent, machining spiral bevel gears on a 3-axis CNC machine can be a suitable choice. This paper describes a practical method based on CAD/CAM and 3-axis CNC machining to manufacture spiral bevel gears of the Gleason design. Creo Parametric software (PTC, USA) is used for three dimensional (3D) modelling and tool path planning to machine spiral bevel gears on a 3-axis machining centre.

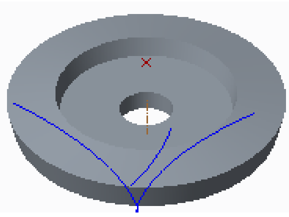
2 GEOMETRIC MODELING OF THE SPIRAL BEVEL GEARS

A number of spiral bevel gears have been modelled and manufactured in our research. In this paper, a spiral bevel gear with some basic parameters as in Table 1 is presented for the purpose of demonstration.

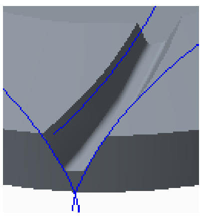
Parameter	Value
Helix angle	35^0
Contact angle	20^0
Number of teeth	31
Module	5 mm
Thickness	28 mm
Pitch circle diameter	155 mm
Pitch angle	$75{,}529^0$
Hand of spiral	right

Table 1. Some basic parameters of the sample gear designed.

In Creo Parametric, the designed gear can be created by following basic steps: (1) Creating the “blank” model of the gear, Figure 1a; (2) Creating 2 involute curves by using the mathematical equations for involute curves and a helix curve, Figure 1a. These curves will be used to generate the tooth surfaces; (3) Creating the first tooth by sweeping a section along a helix curve, Figure 1b; (4) Creating the last teeth by patterning the first tooth around the axis of the gear, Figure 1c.



(a)



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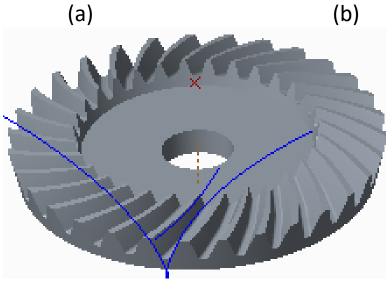

(c)

Figure 1. Some basic steps for modelling the designed gear.

3 TOOL PATH PLANNING AND MACHINING OF THE TOOTH SURFACES

In this study, the material of the workpiece was C45 and the HSS tools were used to machine the gear. Before cutting the tooth surfaces, the workpiece was machined on a lathe to achieve its shape. The tooth surfaces were milled on a 3-axis vertical machining centre. In order to guarantee the geometric accuracy and the surface quality of the tooth surfaces, removal of material was done in 3 sequences: (1) rough cut using a 4 mm flat-end mill, (2) semi-finish cut using a 2 mm flat-end mill, and (3) finish cut using a 2 mm ball-end mill.

The teeth surfaces of spiral bevel gears are slanted and complicated surfaces. They can be considered as sculptured surfaces. Creo Parametric offers some milling sequences which can be used for cutting this kind of surfaces. Volume Milling and Profile Milling sequences can be used for roughing and semi-finishing, respectively. For finishing, the teeth surfaces can be milled using Surface Milling sequence. It can generate a lot of tool path strategies and the surface finish can be controlled with Step Over adjustment or Scallop Height parameter [PTC 2014].

For roughing, the spindle speed was 2000 rpm, the feed rate was 100 mm/min, the depth of cut was 1 mm and the step over was 2 mm. Creo Parametric offers 9 types of tool path to cut the machining area in Volume Milling. Of these, the lace type tool path (TYPE_1, TYPE_2, and TYPE_3) took 7.96 minutes to cut one tooth, while the other took from 10.24 minutes to 47.75 minutes. Hence, TYPE_1 was chosen as the tool path type for roughing.

In the semi-finishing step, the spindle speed was 2200 rpm, the feed rate was 120 mm/min, the depth of cut was 0.5 mm, and the amount of material left after profile cutting was 0.2 mm. In this sequence, ZIG_ZAG was used as the type of cut for machining because it took 13.83 minutes while UPCUT and CLIMB took 24.24 and 23.94 minutes, respectively.

For finishing, the spindle speed was 2500 rpm, the feed rate was 150 mm/min and the scallop height was 0.01 mm. In Creo Parametric, parameter SCALLOP_HGT is used to control tool step by specifying the maximum allowable scallop for surface milling [PTC 2014]. To create a smooth tool path, the Cutline option was used. The cut lines were 2 top edges of the machining surface as shown in Fig 2. There are 5 types of tool path for surface milling such as TYPE_1, TYPE_3, TYPE_SPIRAL or TYPE_HELICAL and TYPE_ONE_DIR. With TYPE_1 or TYPE_3 option, the tool moved back and forth along the cut lines in 20.32 minutes. The tool moved along a helix in 23.28 minutes if TYPE_SPIRAL or TYPE_HELICAL was used. When the tool was moved in only one direction, it took up to 60.54 minutes when TYPE_ONE_DIR was used. Herein, TYPE_HELICAL was used to maintain a high cutting efficiency as well as a constant scallop height.

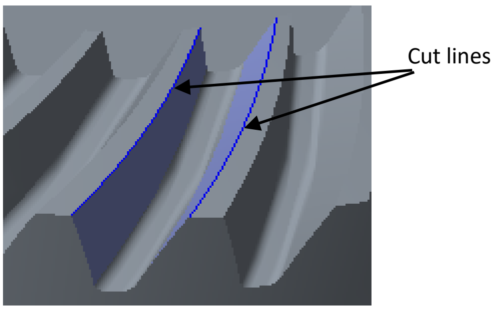

Figure 2. Cut lines.

Figure 3 shows the tool paths generated for rough cut, semi-finish cut, and finish cut. Each sequence was setup for one tooth then the tool paths were patterned to all teeth. The machining simulation results of the whole gear without gouges was shown in Figure 4.

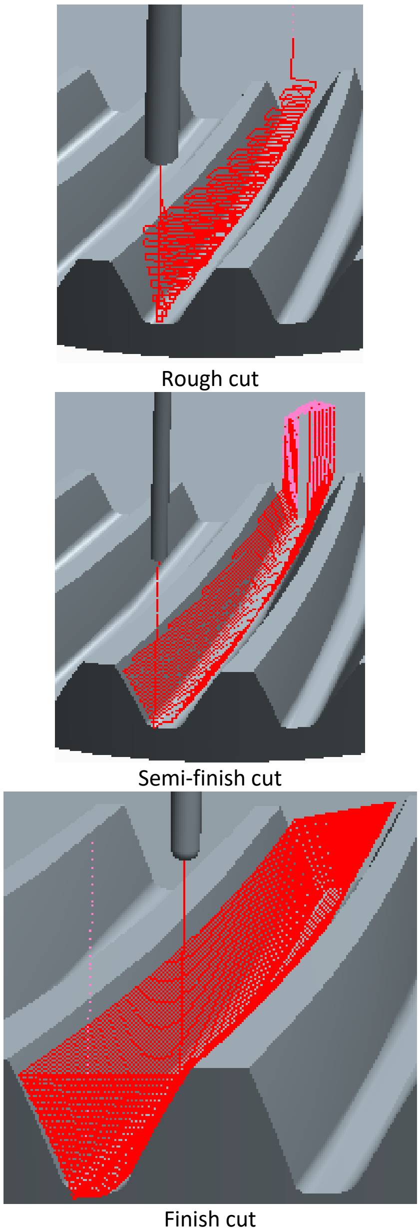

Figure 3. Tool paths for gear cutting.

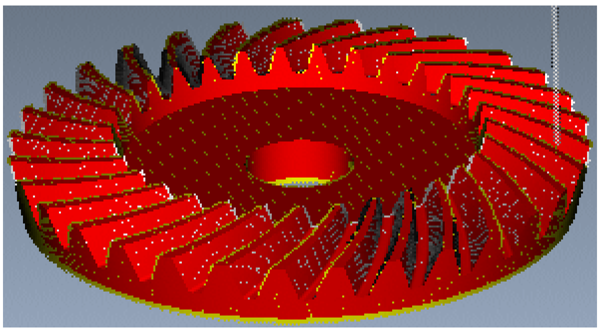

Figure 4. Machining simulation results.

From the machining simulation results, it can be concluded that the proposed method has been successfully implemented in theory. In order to validate the implementation in practice, an experiment is required. The milling operation for gear cutting was carried out on a 3-axis machining centre (Brigdeport VMC 2216, USA), as shown in Figure 5. It took nearly 4 hours and a half for roughing. The machining time for semi-finish and finishing sequences were about 8 and 13 hours, respectively. The machining was completed without trouble.

Figure 5. Cutting the designed gear on a 3-axis machining center.

4 MEASUREMENT OF THE MACHINED GEAR AND DISCUSSION

The geometry of spiral bevel gears is very complicated and special hardware and measurement methods are needed for testing its geometric parameters. The international standards for evaluating the grade of spiral bevel gears are limited to only few items related to pitch errors [Suh 2002]. Besides, the tooth faces of a spiral bevel gear are sculptured surfaces that are formed from spherical involute curves in 3D space. Hence, it is very difficult to measure their geometric parameters directly. Instead of using a coordinate measuring machine together with special software, a 3D optical scanner can be used for measuring of spiral bevel gears. Compared to other conventional methods, the optical contactless measurement method offers several significant advantages. Due to the high data density, it allows obtaining a high precision 3D model of objects with complex shapes [Keller 2015]. Optical, non-contact scanners could be used to verify the accuracy of bevel gears fast and generally [Marciniec 2014], [Pisula 2016]. ATOS 3D scanners (GOM, Germany) could perform measurements of spiral bevel gears and software such as ATOS Professional or GOM Inspect could be used to analyse the accuracy of spiral bevel gears [Marciniec 2011], [Marciniec 2014], [Marciniec 2015], [Pisula 2016].

An optical contactless measurement method was chosen to measure the gear in this study. The gear was scanned using a ATOS Compact Scan 2M device (measuring volume: 250x190x190 mm, 1624 x 1236 pixels), as shown in Figure 6. Before scanning, the object was cleaned up, fitted with reference points, and coated by a thin layer of anti-reflection coating to prevent light reflections during scanning. In the scanning process, individual scans were performed at various scanning positions and angles in order to scan the whole surface of the object. Between the two scans, the object was rotated manually. The software used in the scanning system, ATOS Professional V 7.5, allows to combine scanned images to receive the complete measuring area of the object. As a result, the measured surfaces of the gear were presented by millions of measurement points and described in optimized mesh triangles [Marciniec 2011]. The obtained data were a 3D digital model in .STL format. This model were utilized to compare to the 3D CAD model of the gear using ATOS Professional software.

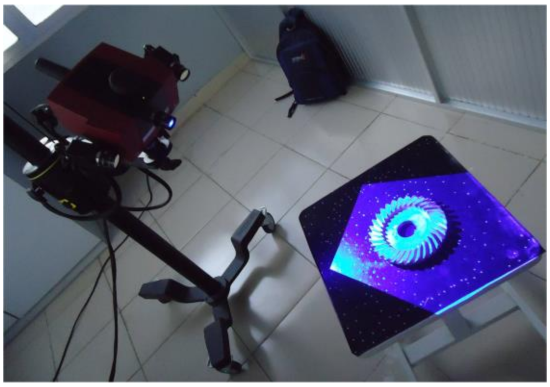

Figure 6. Scanning the machined gear.

ATOS Professional software enables to analyse the accuracy of manufactured components based on the comparison of model measurement results with the 3D CAD model which is considered as the reference standard. The results of analysis can be presented quantitatively as well as in the form of a colour map of deviations [Marciniec 2014].

Figure 7 shows the colour map of deviations and their extremum of some selected flanks. It can be seen that the deviations were identified on all flanks. On some tooth surfaces (mainly at fillets and bottom lands), there are extremely positive deviations. This can be because of excessive tool wear. The chips on edges at the bigger end of some teeth caused extremely negative deviations (not presented on the colour map). These extreme deviations were detected up to ±0.4 mm, but they may not be relevant and these errors could be overcome. Despite of the fact that there are some extreme deviations on some areas of some teeth, the deviations on most flanks are low. Without taking into account the areas with extreme deviations, the deviations range from -0.006 mm to 0.165 mm for the concave side, and the deviations are from 0.015 mm to 0.195 mm for the convex side. On each flank of the concave side, the differences between the two extreme values are from -0.006 mm to 0.062 mm, while these values for the convex side vary from 0.002 mm to 0.087 mm. It should be noted that the distribution of deviations is irregular and the displacements measured on the convex side are bigger than those of on the concave side. An example of the detailed deviations of the tooth profiles of a tooth gap which have low deviations is displayed in Figure 8. In this example, the obtained measurement results showed that the tooth profile displacements on the concave side are smaller than 0.012 mm, while the maximum values on the convex side come to 0.089 mm. The flanks which have higher deviations may have been machined by tools with higher tool wear in the finishing sequence. In order to reduce the deviations of the tooth surfaces, more tools could be used for finishing. The deviations on the flanks can cause various errors such as tooth form error, tooth pitch error, ...

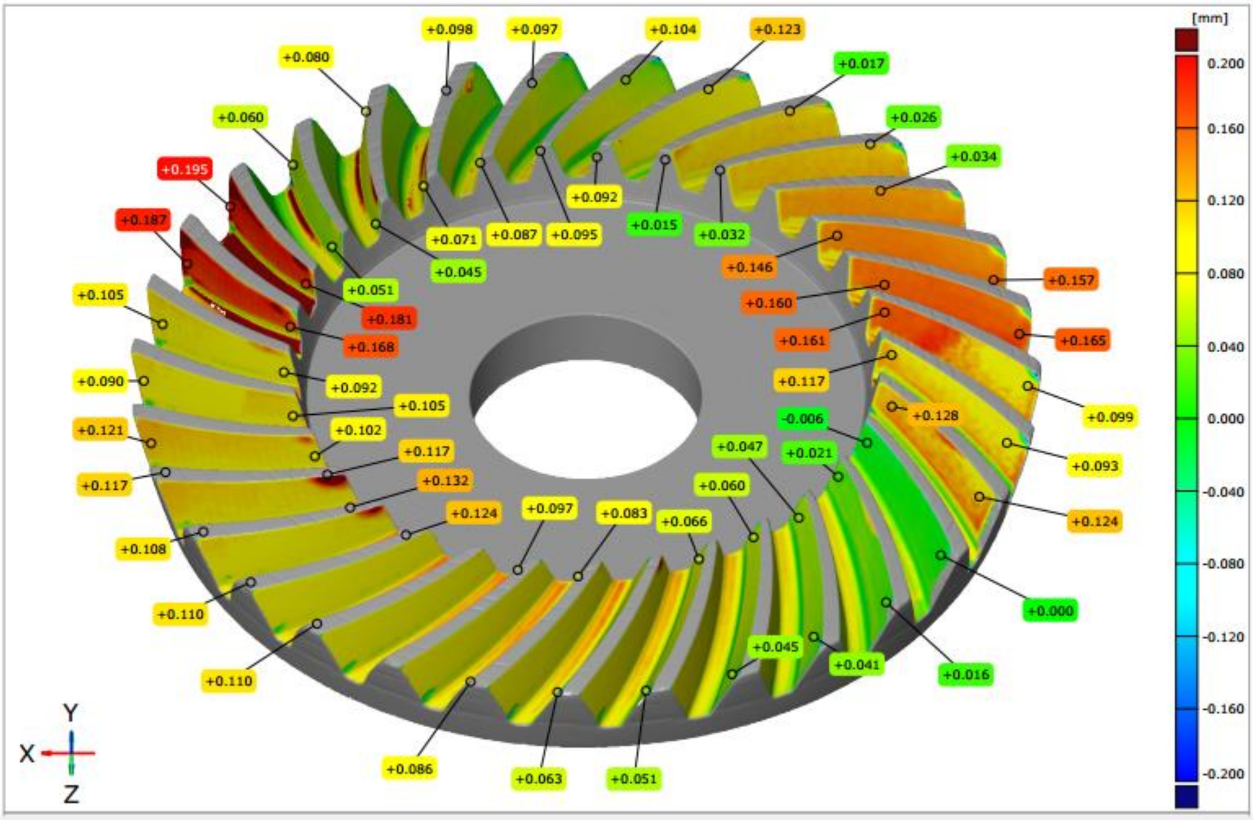

Figure 7. Colour map of deviations and their extremum of some flanks.

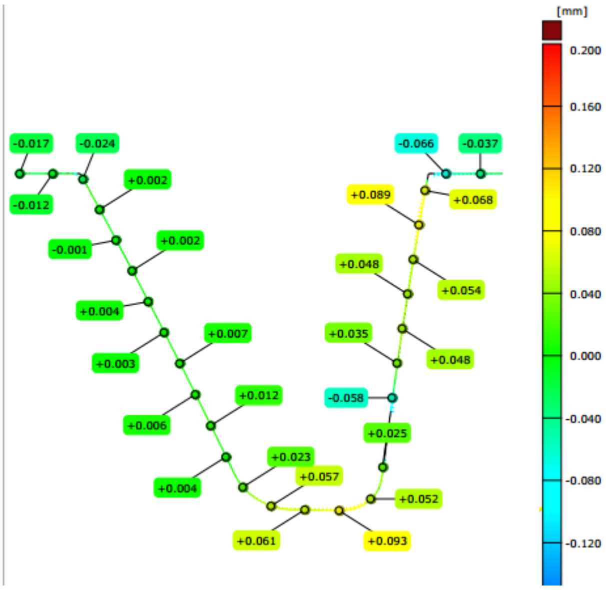

Figure 7. Detailed deviations of some tooth profiles.

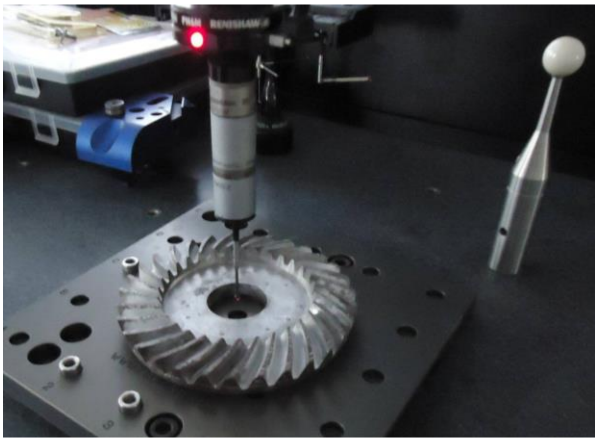

Figure 8. Measuring single pitch error on the Smart CMM.

A Smart CMM (Wenzel America, USA), which has a resolution of 0.0001 mm, was used to measure single pitch error of the machined gear, as shown in Figure 8. The investigated result shows that the single pitch error of the gear was 0.0475 mm. It is less than the value of tolerance of grade 4 in JIS B 1704:1978, [SDP/SI 2012]. It is obviously that the single pitch error was caused by the deviations of the tooth flanks. Compare to 3-axis machining, 5-axis machining offers a higher accuracy and lower machining time. Kawasaki and Tsuji [Kawasaki 2014] machined large-sized spiral bevel gears (teeth: 59, normal module: 8.7282) on a multi-tasking machine tool by swarf milling in about 24 hours. The pitch variation of the gears met grade JIS 0 when using a new end mill and grade JIS 3 when an old one was used.

In this study, the surface roughness of the gear tooth surfaces, measured using a surface roughness tester (SJ-301, Mitutoyo, Japan), were Ra = 2.76 µm. This value is a little bit higher than that of the gears machined on a 5-axis milling machine and a multi-tasking machine but lower that of the gears machined on a special generator in the studies of Alvarez et al. [Alvarez 2015] and Kawasaki and Tsuji [Kawasaki 2014]. In the study of Alvarez et al., the surface roughness (Ra) of the tooth surfaces of the gear, finished by 2 mm ball-end mills, was 2.67 µm when the scallop height parameter was set to 0.015 mm. Meanwhile, the surface roughness of the gear machined on a multi-tasking machine tool and on a special generator in the study of Kawasaki and Tsuji were 0.25 µm and 0.30 µm, respectively. To a certain extent, it can be said that the surface quality of the gear tooth faces in this study can be good enough for some applications. It is possible to reduce the surface roughness on the gear tooth surfaces by choosing a smaller scallop height. However, a reduced surface roughness leads to a higher machining time.

From the measurement results above, it can be said that spiral bevel gears can be manufactured based on CAD/CAM and 3-axis machining centre and it is possible to use the gears manufactured by this method in some applications. It is obvious that machining on 3-axis machining centres makes the machined gears less precise and less qualitative than machining on 5-axis machines. The productivity of this method is also lower than that of the traditional method and 5-axis machining method. However, this method does not require special gear manufacturing equipment and tools or expensive 5-axis machines. Because the proposed method is time consuming, it can be suitable for small batches, prototypes, and repairs.

5 CONCLUSIONS

A manufacturing method of spiral bevel gears based on CAD/CAM and 3-axis machining centre instead of special machine tools and cutting techniques was proposed. By using Creo Parametric, the CAD model of the spiral bevel gread was created and the tool paths for 3-axis machining of tooth surfaces of the gear were developed. A sample gear was machined on a 3-axis CNC machining centre for the purpose of demonstration. The measurement of surface deviations, performed by comparing the actual part to the nominal CAD model, shows that low deviations could be obtained when finishing the teeth by a suitable number of tools. The roughness surface of the tooth surfaces and the single pitch errors are small enough for some applications. Hence, the validity and effectiveness of the proposed method can be confirmed. This method can be suitable for use in small shops for prototyping, repairing or producing spiral bevel gears in low volume production. The effect of tool wear, cutting parameters on the accuracy and surface roughness of the gear and the machining time are some problems for further study.

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