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Design of Gear Tooth Rounding and Chamfering Machine

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Abstract

All movable gears which mesh with another gear require either rounding or chamfering. The operation is generally applied to the teeth of spur gears for use in sliding gear transmission of automotive vehicles and machine tool gear boxes where the gears are moved on their longitudinal axes meshing with another spur gear. In current scenario, the mechanically operated machines require lot of settings, which is time consuming and requires one or two trial runs before production takes place. CNC machines are also available to carry out chamfering/rounding process but are expensive than traditional approach. The objective is to remove all these hassles and make a machine affordable and adjusted easily to manufacturers. The design of gear tooth rounding/chamfering machine has been presented in the paper. Necessary design calculations are performed and the layout of the machine is proposed.

Keywords: *Gear tooth rounding/chamfering, headstock, spindle, machine layout*

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INTRODUCTION

Gear tooth rounding/chamfering is an important operation in gears. It is observed that in present market, manufacturers are using mechanically operated machines. The headstock assembly of these machines is cam driven. If gears of different module are to be chamfered, the cam of the same module has to be installed and requires one or two trial runs before the actual production starts. However, from the market study it is also found that there exist CNC machines to carry out chamfering/rounding process but are costlier which may not be affordable to manufacturers [1]. The objective is to remove all these hassles and make a machine which can be easily adjusted in a short span of time. This can be achieved by using a semi-automated system. In-depth study is carried out to develop the most economical system for gear tooth rounding/chamfering.

The process is performed in special machines (Figure 1), in which the work is mounted with its axis horizontal and the ends of the teeth to be rounded lie in a vertical plane. The rounding tool consists of a circular shank with a pyramidal cutting end. The cutting tool is mounted in a head with its axis horizontal and in the same plane as that containing the work axis [2].

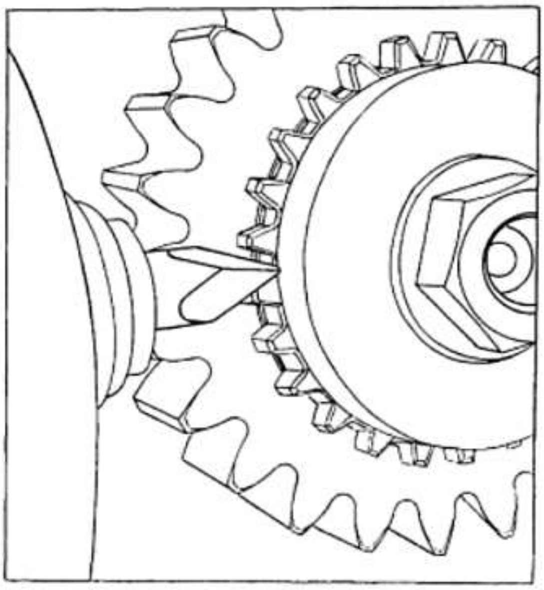

Fig. 1: *Gear Tooth Rounding/Chamfering Machine.*

The work spindle of a chamfering machine can have a continuous rotation indexing or an index plate-controlled intermittent indexing. Indexing may also be performed by a pulse motor, where change-over for different number of teeth becomes very easy. Work clamping device, e.g. collet or fixture, is mounted on the work spindle with a facility for providing correct relation of the teeth with respect to the cutter spindle to ensure uniform material removal. Generally, either fixed or retractable (swivelling or sliding type) work locators are used. On a CNC version, work-gear rotation and the cutter head axes are electronically controlled. Servomotor via a backlash-free worm wheel drive rotates the work-gear axis. An incremental encoder on the work axis eliminates the index plate as used in mechanical versions. The stroke of the cutter spindle is controlled through a ball screw or rack and pinion arrangement [3]. The ends of the teeth may be finished with an end radius or end chamfer. If they slide axially into engagement, tooth-rounding or tooth chamfering is applied. The Figure 2 depicts the basic difference between the end chamfer or end radius with the tooth chamfer or tooth rounding [4].

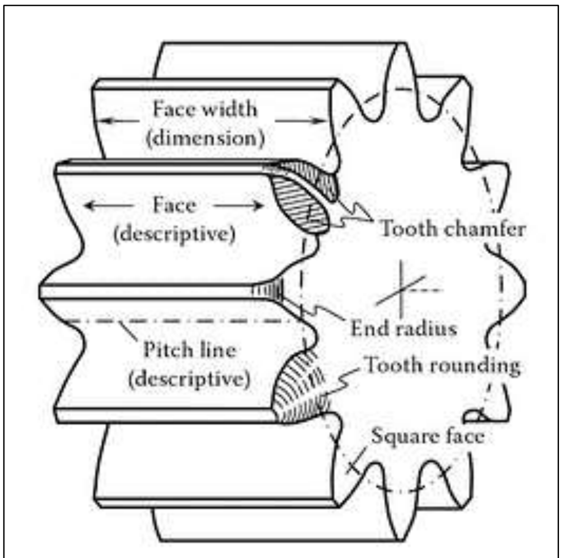

Fig. 2: *Tooth Elements of a Spur Gear.*

DESIGN OF TOOL-HOLDER ASSEMBLY

Tool holder assembly provides the necessary cutting action needed for the operation. The cutter spindle is directly coupled to the induction motor. The motor should be chosen such that it should overcome the cutting forces generated during tooth chamfering/rounding. Axis orientation of the cutter with that of workpiece can be achieved by manually raising or lowering it. Workpieces having variable diameters can also be performed on this machine by moving the tool-holder towards or away from the workpiece with the help of screw and nut arrangement (Figure 3).

Power and Force Requirements in Machining

Cutting forces generate at the interface between the tool and workpiece. The tool spindle should be able to overcome these cutting forces for machining operation. The tangential cutting force constitutes about 70–80% of the total cutting force and is used to calculate the power required at the machining. In gear tooth chamfering, the primary motion is given to the cutting tool. The tool will be rotating continuously causing relative motion needed for a machining operation. The cutting tool for chamfering has four cutting teeth which is similar to that of end milling cutter. Aforementioned are the reasons for applying end-milling principle to gear teeth chamfering/rounding in calculating machining power.

Following are some of the assumptions made while calculating the power:
Diameter of the cutter, D=15 mm,
RPM of the cutter, n=1440 rpm,
Feed per minute, S_m=60 mm,
Cutting speed, $v = \pi Dn/1000$ m/min (1)

$= (\pi \times 15 \times 1440)/1000$

=67.85 m/min,

Taking Feed per tooth S_z=0.06 mm [5],
Number of Teeth, Z =4,
Feed per minute $S_m = S_z Zn$ mm/min, (2)

$= 0.06 \times 4 \times 1440$

$S_m = 345.6$ mm/min,

Taking depth of cut as, t=0.3 mm,
Taking width of cut as height of the gear tooth, b=2.25×m,
Where m= module of the gear to be chamfered which is considered as 4,
∴ Width of cut= 2.25×4=9 mm.
Metal removal rate, $Q = btS_m/1000$ cm^3/min (3)

$= (9 \times 0.3 \times 345.6)/1000$

$= 0.933$ cm^3/min.

Average Chip thickness $a_s = 114.6 S_z t / D\psi_s^0$ (4)

Assuming ψ_s^0 =2°

$a_s = (114.6 \times 0.06 \times 0.3)/(15 \times 2)$

=0.068≈ 0.075 mm.

∴ For a_s =0.075 mm and Alloy steel as a work material,

Unit Power, U=59×10^{-3} kW/cm^3/min [5],
Power at the spindle,
$N = UQ = 59 \times 10^{-3} \times 0.933 = 0.055$ kW,
Efficiency is taken as, E=0.8,
Power of the motor,
N_{el}=N/E=0.055/0.8=0.06875 kW.

Tangential cutting force $P_z = \frac{6120 \times N}{v}$ (5)

$$= \frac{6120 \times 0.055}{67.85}$$
=5 N.

Torque at the spindle $T_s = \frac{975 \times N}{n}$ (6)

$$= \frac{975 \times 0.055}{1440}$$
=0.037 N-m.

∴ Power required for gear tooth chamfering and rounding is 0.06875 kW.

So, the motor power selected for cutting operation should be greater than the above value. In the design process, we selected 1 HP (0.75 kW) motor to overcome the cutting power. The selected motor is ballooned as part number 1 in the tool holder assembly as shown in Figure 3.

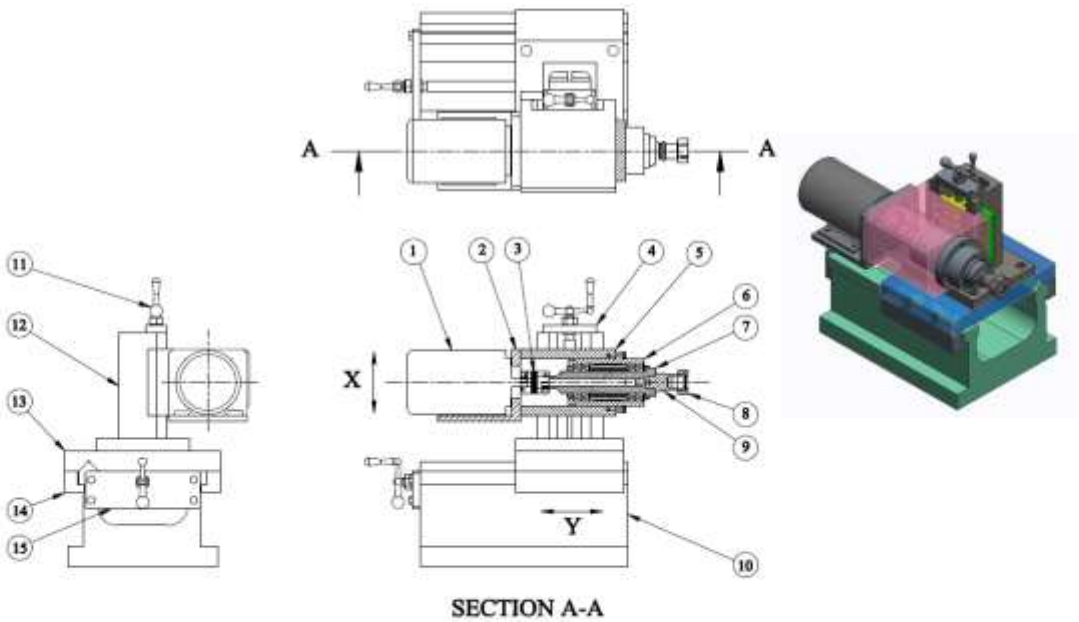

Fig. 3: *Detailed View of Tool Holder Assembly.*

Following Table 1 gives description of each of the parts made in accordance with the Figure 3.

Table 1: *Part Description of Headstock Assembly.*

Part No.	Parts	Description/Make
1	Induction Motor	Power of 1 HP
2	L Bracket	Supports the motor
3	Bellows coupling	RW couplings, BK2/30/69
4	Plate1	Used to fix the screw
5	Housing support	Supports the housing
6	Housing	Houses spindle, bearings and spacers
7	Spindle	7/24, BT 30, milling machine spindle nose
8	Nut	RD-32 Collet chuck holder nut
9	Adopter	BT30 shank
10	Guideway (Flat and prismatic)	Guides the cutting tool along Y axis
11	Handle	Handle connected to the LH screw helps in X movement of cutting tool
12	Guideway (Flat)	Guides the cutting tool for X movement
13	Plate	Slides on the guideways
14	Keeper plates	keeps the plate to slide onto the guideways
15	Plate	Slides onto the guideways carrying flat guide way block and housing.

DESIGN OF HEADSTOCK ASSEMBLY

As previously mentioned, the machine constitutes of headstock, tailstock, base and coolant tank assembly. Referring to the Figure 4, the workpiece can be clamped to the headstock spindle by means of collet fixture. The rack and pinion mechanism through servomotor provides the necessary feed motion for the gear tooth operation. Ball screws can be an alternative to the rack and pinion, but considering low maintenance cost of the later makes it a better choice. The whole headstock can be swiveled through $\pm 30°$ to achieve required geometry while tooth chamfering/rounding. The worm and worm wheel coupled to another servomotor supply the indexing motion to the headstock spindle so that every teeth can be chamfered.

Motor Selection for Feed Motion

Several conditions decide the selection of servomotor. Out of which, following are the two factors which play an important role [6]:

- Steady-State Load Torque: The steady-state load torque including mechanical friction and gravity must fall within approximately 70% of the stall torque of a motor.
- Load Inertia Ratio: The ratio of motor inertia and load inertia (load inertia ratio) greatly affects the controllability of the motor as well as the acceleration/deceleration time in rapid traverse. When the load inertia does not exceed three times the motor inertia, an ordinary metal cutting machine can be used without problems.

Steady-State Load Torque Calculations

Steady-state load torque for rack and pinion mechanism is given by, $T_L = \dfrac{FD}{2\eta i}$ (7)

Where, $F = \mu m_1$

(Ref: Oriental motor general catalogue)

μ = Friction coefficient of the sliding surface,

For a contact of steel on cast iron with oil lubrication, μ =0.06 [5],

m_1 = mass of the object moving along a straight line =300 kg,

D = Diameter of pinion =0.05 m,

η = Efficiency of the driving system =0.9,

i = Gear ratio =1/1.

$$T_L = \frac{FD}{2\eta i} = \frac{0.06 \times 300 \times 9.81 \times 0.05}{2 \times 0.9 \times 1} = 5 \therefore$$

$$T_L = \frac{FD}{2\eta i} = \frac{0.06 \times 300 \times 9.81 \times 0.05}{2 \times 0.9 \times 1} = 5 \text{ N-m}$$

Considering the load torque of 5 N-m, the nearest standard motor of 8 N-m can be used. But load torque alone cannot decide the selection of motor and the load inertia also has to be taken into consideration.

Load Inertia Calculations

Inertia of cylindrical objects (Shaft, couplings, etc.)

$$J_1 = \frac{\pi\gamma}{32} D^4 L \quad \text{kg-m}^2 \tag{8}$$

Where, γ = Weight of the object per unit volume (kg/m^3),

L = Length of the object (m),

D = Diameter of the object (m).

$$\therefore J_1 = \frac{\pi \times 7.8 \times 10^3}{32} \times 0.025^4 \times 0.195$$

$$= 5.833 \times 10^{-5} \text{ kg-m}^2$$

Inertia of a heavy object moving along a straight line (table, work piece, etc.),

$$J_2 = m_1 \left(\frac{l}{2\pi}\right)^2 \text{kg-m}^2 \tag{9}$$

l = Travelling distance along a straight line per revolution of the motor (m),

=

$$r\theta = \frac{0.05}{2} \times 360 \times \frac{\pi}{180} = \pi \times 0.05 = 0.157 \text{ m}$$

$$\therefore \text{Inertia } J_2 = 300 \times \left(\frac{0.157}{2\pi}\right)^2 = 0.187 \text{ kg-m}^2$$

Total Load inertia, $J_L = J_1 + J_2$

$$= 5.833 \times 10^{-5} + 0.187$$

$$J_L = 0.18706 \text{ kg-m}^2$$

$\therefore$ The motor has to be selected in such a way that the load inertia should not exceed three times the motor inertia.

i.e. (Load inertia)/(Motor inertia)< 3

If we choose the motor αiS 30/4000 (Part No. 5 Referring to Figure 4), which has the motor inertia J_M =0.0836 [6],

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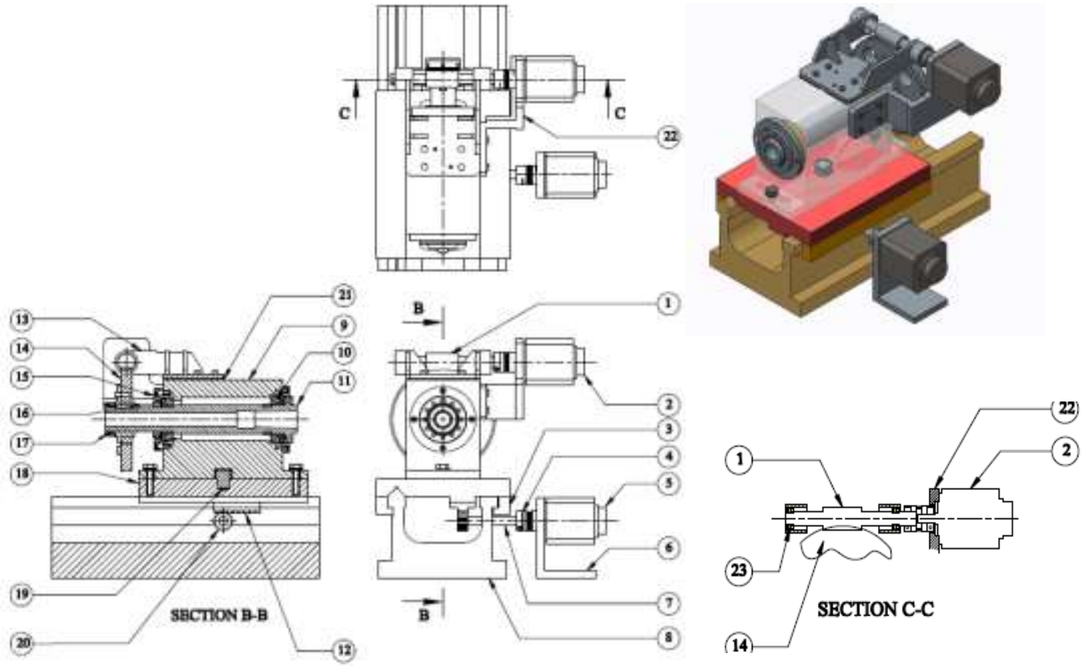

Fig. 4: *Assembled View of Headstock Assembly.*

Table 2: *Part Description of Headstock Assembly.*

Part No.	Parts	Part Description/Make
1	Worm	Driven by an AC Servomotor 01
2	AC Servomotor 01	Fanuc AC Servomotor, $\alpha\ iS$ 8/4000 (For indexing of headstock spindle)
3	Keeper plates	To keep the sliding plate and guideways together
4	Bellow couplings	To connect shaft with servomotor
5	AC Servomotor 02	Fanuc AC Servomotor, $\alpha\ iS$ 30/4000 (Feed motion)
6	Supporting bracket	Supports the servomotor 02
7	Shaft	Drives the rack and pinion through AC servomotor 02
8	Guideway block	To support the housing as well as to necessitates the feed motion
9	Headstock housing	Houses the spindle and taper roller bearings
10	Taper roller bearings	For smooth rotation of spindle
11	Headstock spindle	A2-5 spindle, to locate the workpiece
12	Rack	Converts rotational motion of pinion into linear motion.
13	Bracket	Holds the bearing and worm
14	Worm wheel	Driven by worm and in turn drives the head stock spindle
15	Cover plate	Covers the bearings from dusts and coolant water
16	Key	Parallel key to connect shaft and worm wheel (b×h×l=20×12×60 mm)
17	Locknut	Spieth locknuts, MSR 70×1.5
18	Plate	Slides onto the guideways carrying headstock housing
19	Swivelling pin	The headstock can be swivelled about this pin to facilitate the chamfering action and can be locked to respective position
20	Pinion	Drives the rack
21	Spacer	Spacer can be ground in-assembly to compensate manufacturing errors
22	Bracket	Supports the AC servomotor 01
23	Deep groove ball bearing	Supports the worm shaft

$$\therefore \frac{J_L}{J_M} = \frac{0.18706}{0.0836} = 2.24 < 3$$

Therefore the chosen motor can be used for the current machine.

Power Available at the Headstock Spindle

Rated speed of servomotor = Maximum rpm available at the worm = N_w =4000 rpm.

Rated stall torque of motor =8 N-m.

Maximum rpm available at the headstock spindle = Maximum rpm at the worm gear = N_g.

And, i = worm drive reduction ratio =71:1.

∴ Speed at the headstock spindle =4000/71=56.33 rpm.

Torque available at the headstock spindle = $71 \times 8 = 568$ N-m.

∴ Power at the headstock spindle, $P = \frac{2\pi NT}{60000}$ =3.35 kW.

The detailed part description of headstock assembly is mentioned in Table 2.

MACHINE LAYOUT

As mentioned earlier the machine constitutes of headstock, tailstock, base and coolant tank assembly. Headstock and tool-holder assemblies are bolted onto the base which is either fabricated or casted and have their own advantages. The base has a provision for easy flow of coolant water and is collected in coolant tank. In turn the coolant water is filtered and resupplied to the machine. The complete machine layout is represented as in Figure 5 with the size mentioned in millimetres. Specifications and technical features of the designed gear tooth rounding and chamfering machine can also be observed in Table 3.

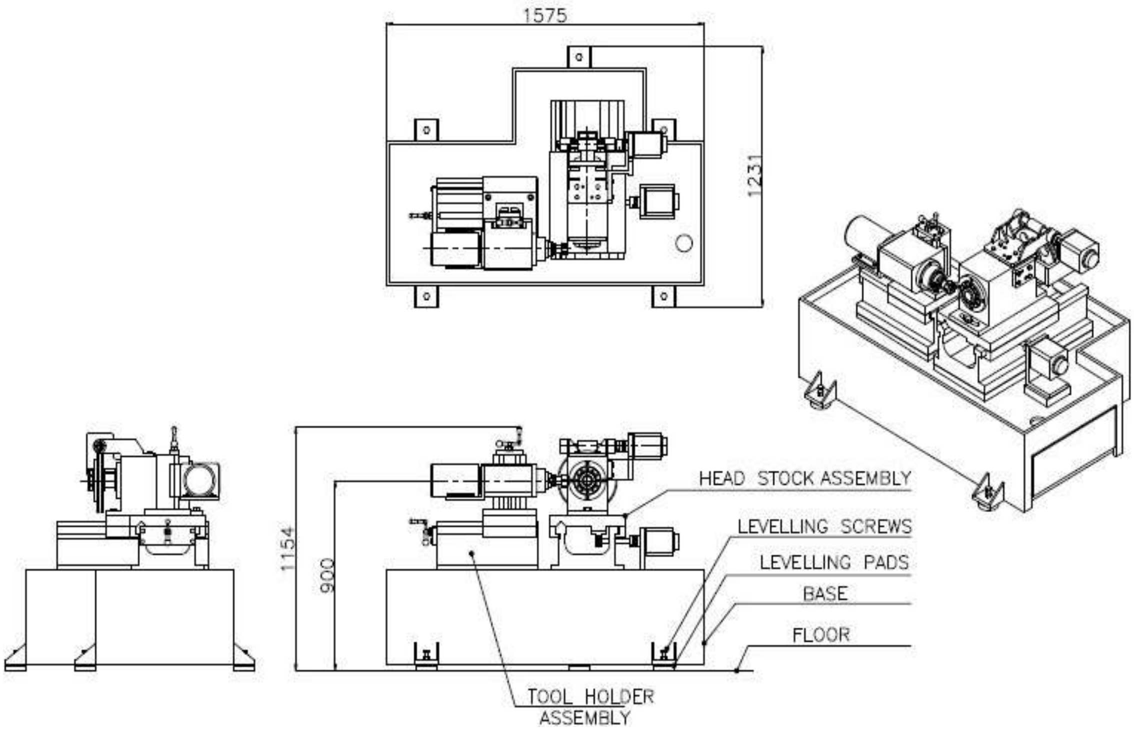

Fig. 5: *Machine Layout of Gear Tooth Rounding/Chamfering Machine.*

Table 3: *Technical Features of the Designed Gear Tooth Rounding and Chamfering Machine.*

Maximum Diameter of Work	250 mm
Module Range	1–6 mm
Cutter Head	single spindle type
Cutter Spindle Speed	1440 rpm
Cutter Spindle Drive	1 HP Induction motor
Adjustment of Cutter Spindle	Manually
Work Head Drive	AC servomotor 8 Nm with worm and worm wheel indexing
Swilling of Work Head	manually
Feeds	AC servomotor 30 Nm with the help of rack and pinion mechanism
Control Panel	PLC controlled
Weight	1600 kg approximately
Dimension (L×W×H)	1575×1230×1200 (mm)

CONCLUSION

Conceptual design of rounding/chamfering machine is prepared in AutoCAD and Creo-parametric modeling softwares. In addition, power requirements for the machining, power available at the head stock spindle are calculated. Final machine layout is prepared and assembly drawings for each of the assemblies are presented in the paper.

SCOPE FOR FUTURE WORK

The rounding/chamfering machine is a conceptual design with no particular component taken into consideration. The machine can be redesigned as per the requirements of an industrial component.

Electrical circuit diagram, sensors interfacing and PLC programming can be planned with the consultation of electrical and electronics engineers.

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