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Structural Optimization of ER Spring Collet for Maximized Gripping Action

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Abstract:
Collet chuck is the most versatile general purpose clamping device. ER spring collets are generally used as tool holder for drills and reamers and may also be used as work holding device in precision machining. The present work aims at obtaining the optimum design parameters of ER spring collet for maximized gripping action. This paper presents the finite element model to analyze the gripping action of ER spring collet. Further the design parameters like number of slots and slot geometry is optimized to obtain maximum gripping action. The design and analysis is carried out using ANSYS workbench. Variation of design parameters is run in Design of Experiments. Sensitivity of gripping action with respect to the variation of design parameters is studied using response surfaces and set of optimum design parameters is obtained.

Keywords: Flexible collet, ANSYS Workbench, Design of Experiments, Design optimization, Collet chuck.

I. INTRODUCTION

Flexible collet chucking systems are extensively used to hold the workpieces or tools with circular features. Majority of collet chucks use solid thin slotted clamping sleeves made of a hardened steel and ground to a high degree of accuracy on both internal and external contacting surfaces, one of which is tapered and the other is cylindrical [1]-[4]. External collets have cylindrical inner surface, to hold the shank and tapered external surface. When squeezed against a matching taper the inner surface contracts and clamps the object to be held. Internal collets or expanding mandrels have cylindrical outer surface, to hold the object with bores and conical inner surface. When a matching cone is driven internally by an actuating mechanism it expands radially and clamps the object with bores. The alternatively cut slots in the sleeve makes the sleeve radially flexible.

The "ER" collet system, developed and patented by Rego-Fix in 1973, is the most widely used clamping system in the world and today available from many companies worldwide. The standard sizes are: ER-11, ER-16, ER-20, ER-25, ER-32, and ER-40. "ER" came from an existing "E" collet (Emergency collet) which Rego-Fix modified and appended "R" for "Rego-Fix". The number is the cavity opening diameter in millimeters. ER collets contract over a range of 1mm and are available in 1mm or 0.5mm steps, so a range of ER collets can hold any cylindrical shank, metric or imperial. ER collets may also be used on a lathe to hold work pieces.

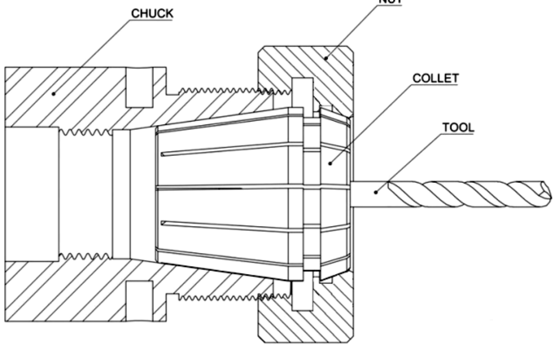

FIGURE 1
ER COLLET CHUCKING SYSTEM

As shown in Figure 1, ER spring collet is a sleeve with cylindrical inner surface and a double conical outer surface, made of spring steel with two or more kerf cuts along its length to generate flexible jaws designed to grip smooth cylindrical elements. The chuck system comprises tapered receiving socket that is made integral with collet chuck, the ER spring collet which is inserted into the receiving socket and a lock nut that screws over the collet chuck, pushing the collet via another taper. When ER spring collet is squeezed against the matching taper in receiving socket the flexible jaws deflect and grip the component which is inserted into the collet.

II. LITERATURE REVIEW

Soriano, et al [1]-[2] presented an analytical model to determinate the static stiffness of collet sleeves. The Finite Element Method analyses that were conducted to check the proposed analytical model was also presented. The proposed analytical model was verified by means of Finite Element Analyses (FEA) and experimental investigation. The amount of driving force used for deforming the collet obtained from analytical model, FEM model and experimental test and corresponding radial deflection produced are plotted. From the value of the slope of the resulting line in the plot it is possible to determine the collet radial stiffness. The results confirmed the linear behavior of the models with excellent levels of correlation. The work results provide reliable theoretical and technical supports for the optimization of the design and application of collet sleeves. It was established that the transmitted clamping force strongly depends on the clearances determinate by the tolerances of the collet and the work piece and also on the collet radial stiffness. Lower clearances and collet radial stiffness contribute to provide more effective clamping force. It was also found that machining accuracy and productivity while using collets as work holding device can be increased by means of reducing the preset static clamping force.

McIlraith, A.H [3] developed a theory of action of collets using the normal laws of friction to explore dependence of grip, ease of release and interface stresses on cone angle, interface coefficients of friction and the axial forces employed.

The central part played by hysteresis is revealed. It is shown that for a collet to withstand axial forces up to the design maxima and yet be able to release its grip when these forces are withdrawn, its cone angle should be close to the jamming angle. In addition, the coefficient of friction at its inner surface should be much greater than that at its outer surface. Experiments carried out using a test model give good support to the theoretical conclusions.

Qingqing Lv, et al [4] developed a finite element model and set reasonable boundary conditions to perform a nonlinear contact analysis and obtained corresponding nephogram for deformation, equivalent stress and equivalent strain. From the results it is interpreted that stress concentration occurs at the middle slotting of collet in the working process of flexible collet device. It was suggested that the repeated working process will produce alternating stress and fatigue, so which should be taken seriously in the course of product design.

III. Development Of Parameterized Solid Model

A collet based on the standard ISO 15488 (A collet of form B, nominal size 40 and nominal bore diameter 20 mm) [5] is used for the analysis. ISO 15488 prescribes collet, nuts and fitting dimensions for collets with 8˚ setting angle for tool shanks to ensure replaceability and performance regularity. The dimensions that are left to the manufacturer's discretion are the one to work with and optimization is done by varying these dimensions. Geometry and dimensions of the analyzed collet is detailed in the Figure 2.

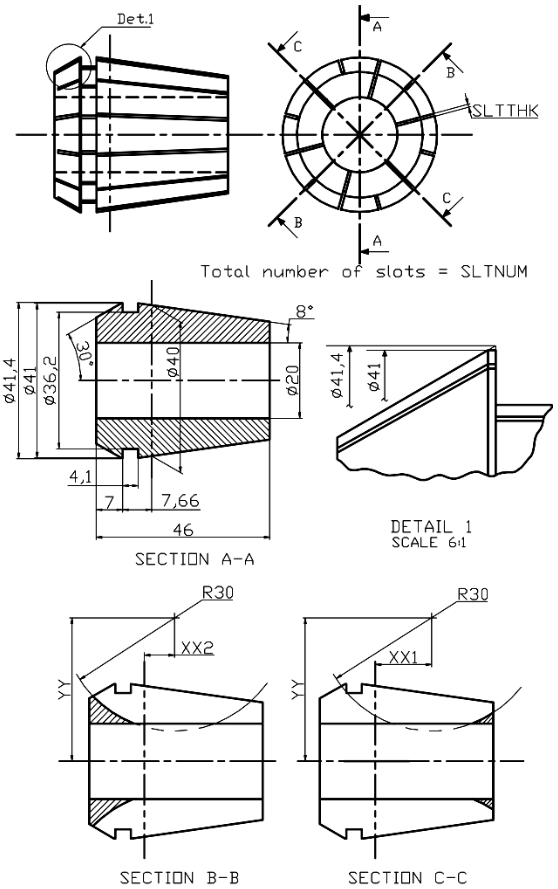

FIGURE 2
DETAILS OF ER40 COLLET
(ALL DIMENSIONS ARE IN MM)

In Figure 2 the geometric parameters that are to be optimized are shown as used in ANSYS. Parameter 'SLTTHK' is meant for slot thickness or width. Parameter 'SLTNUM' is meant for total number of slots. Parameters 'XX1', 'XX2' & 'YY' are the variables defining the slot profile that corresponds to the slit cutter position. A feature based parametric solid model of collet chucking system is developed using ANSYS Design Modeler.

For the ease of analysis and quick convergence of result the assembly is simplified as shown in the Figure 3. Intricate details like thread and Tommy bar holes in chucks are ignored as it may take longer time while meshing and solving.

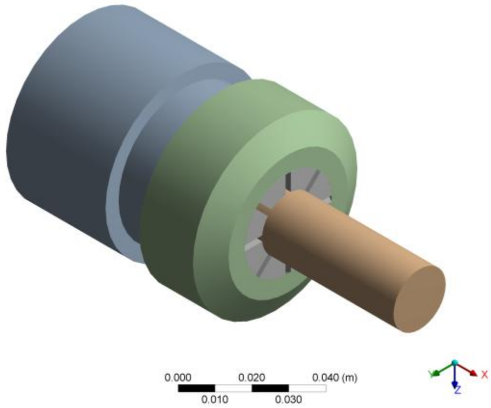

FIGURE 3
FINITE ELEMENT MODEL WITH COORDINATE SYSTEM

IV. Defining The Contacts

There are totally four locations where actual surface contacts occur between the parts. They are

- Collet and the receiving 8˚ conical taper in the holder.
- Collet front end 30˚ bearing conical taper and the matching taper in the nut.
- Collet inner bore and the shank of the tool (test bar).
- Contact between external thread at holder and mating thread at nut.

For convenience all the surface contacts excluding the threaded contact are considered to be frictional contacts with the coefficients of static friction of 0.15 [1]. The threaded contact is not defined in FE model since it may increase the number of iterations and delay the convergence of solution. Instead it is included in theoretical model to account for the axial thrust exerted on collet by nut due to thread action while applying tightening torque at nut. In FE model this contact is defined as frictionless contact and the axial thrust is directly applied at the inner bore of the nut in negative 'X' direction which will simulate the thread action.

V. Defining Materials And Meshing

All the parts of collet chucks are made up of steel. The mechanical behaviors of materials are considered to be linear elastic exhibiting isotropic elasticity. Various material used for analysis and their corresponding physical properties are summarized in Table I below.

TABLE I
MATERIAL SPECIFICATION AND PROPERTIES [2]

Component	Material	Elastic Modulus (GPa)	Poisson ratio	Yield Strength (MPa)
Collet	18CrMo4	210	0.28	685
Nut & Holder	50CrV4	210	0.28	950
Test bar	C45E	210	0.2	430

Meshing is done with fine relevance center under sizing control option default element size is chosen. All the other options are left program controlled and default options are chosen. In order to obtain a regular mesh symmetric with axis mapped face meshing option is inserted under mesh; all the contact surfaces and lateral cylindrical surfaces are selected as faces for mapped face meshing. The meshed assembly is shown in Figure 4.

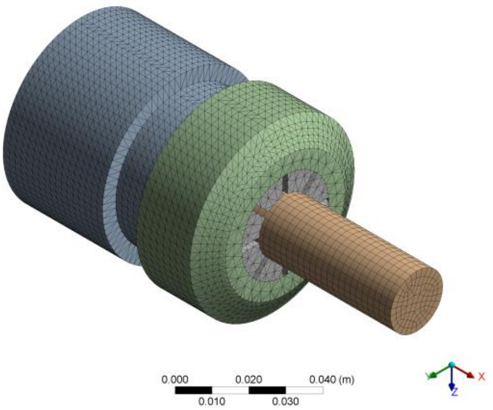

FIGURE 4

FINITE ELEMENT MODEL WITH MESHES

VI. APPLYING LOADS AND CONSTRAINTS

For analysis collet chucks having threaded bore at rear end to mount on spindle is used. As the threads are not detailed in the finite element model for the sake of simplicity, the corresponding bore in the chuck is made to be fixed in the model. When the tightening torque is applied at nut the nut will rotate and advances in a direction so as to squeeze the collet as indicated by negative X direction in the Global Coordinate system. As the nut advances the collet will get squeezed by the axial thrust which is proportional to the applied tightening torque. For an applied tightening torque of 40 Nm the axial thrust on the collet is theoretically found to be 4200 N. The theoretical calculations are made accounting the friction at threads and the thrust bearing friction at the front end of the collet. The force constraint is applied directly on the inner cylindrical face of the nut that corresponds to the threads. This distributes the force vector across curved faces, resulting in uniform traction across the face so as to simulate the thread action. Figure 4 shows the various constraints applied.

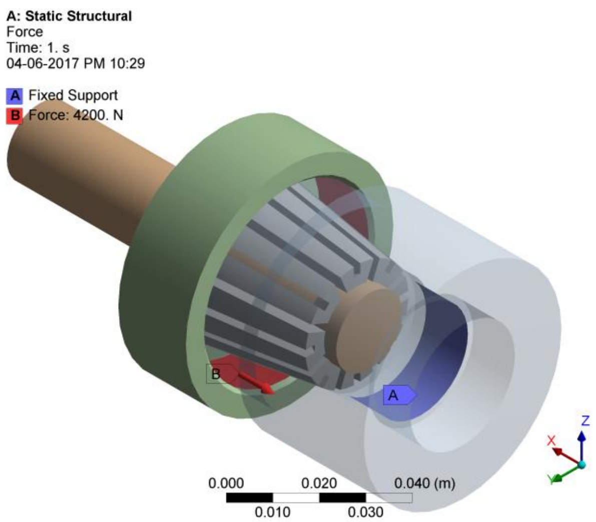

FIGURE 5
APPLIED CONSTRAINTS

VII. DEFINING ANALYSIS SETTING AND INSERTING RESULT ITEM

As a result of applied axial thrust a radial force is transmitted between each jaw and the bar. This radial force provides the necessary clamping force to resist slippage of the bar under the influence of the torque induced by the main cutting forces which acts tangentially on bar and also the axial cutting forces developed due to feed force. The net radial force transmitted through contacts (F_{radial}) gives the direct measurement of the gripping performance. Further this radial force transmitted between the inner cylindrical surface of the jaws of flexible collet and the test bar has associated frictional forces (μF_{radial}) in the tangential direction. This constitute a frictional torque (T_{CF}), as long as the torque induced by main cutting forces is less than this frictional torque there will be no slippage in rotation. The total frictional torque due to the Coulomb frictional forces is given by the equation.

$$T_{CF} = \mu F_{radial} R_b \qquad (1)$$

Where, μ = Coefficient of friction for collet and test bar interface; R_b = Radius of the test bar.

The net radial force transmitted through contacts (F_{radial}) is found in analysis by inserting a Force reaction probe scoped to Contact region. The components of the reaction force are defined by Local Cylindrical coordinate system, since the reaction force to be found is acting radially in 'X' direction as shown in the Figure 6. This reaction force is set as an output parameter so that the input parameters are optimized to get maximum value of this radial force. It is required that Nodal forces and Contact miscellaneous is set to yes in the output controls under analysis setting. Stress tool is inserted to find the minimum safety factor under maximum equivalent stress theory. This result is also parameterized to check whether the optimized design is safe. Contact tool is also inserted to review and study about the contact behavior. Further Total Deformation, Equivalent Stress, etc. are also inserted in the result items.

VIII. FINITE ELEMENT ANALYSIS AND POST PROCESSING

Through the finite element analysis, we get the deformation of nut and flexible collet model in simulation working condition and the deformation nephogram is obtained. Various contact behavior such as contact status, pressure at contact surfaces, frictional stress at contact surfaces, sliding distance and penetration at contacts are reviewed to study the clamping action of collets. From the analysis it is found that according to Von Misses criterion the applied constraints do not generate stresses beyond the yield limit of the collet material. This is ensured by Safety factor nephogram, which gives the minimum safety factor. The force reaction probe scoped to the contact region returns the directional values of the force reaction along various axes of the local cylindrical coordinate system as shown in Figure 6.

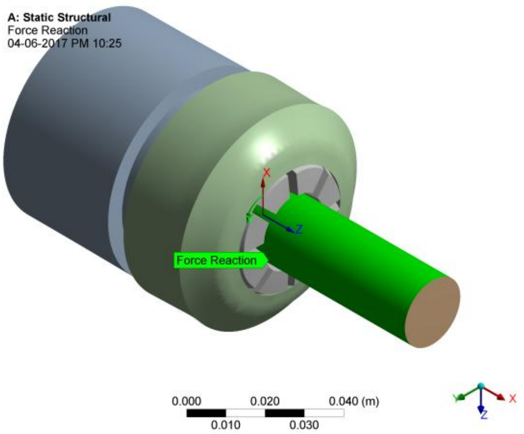

FIGURE 6

REACTION FORCE WITH CYLINDRICAL COORDINATE SYSTEM

The results show that that the majority of force transmitted through the contacts acts radially. In all other directions the probe returns a negligible value. It is to be noted that the radial force and safety factor are the parameterized output variables that are used for optimization.Once the finite element model is solved the model is ready for Goal driven optimization (Response surface optimization).

IX. Setting Up The Design Of Experiments

Design of Experiments (DOE) is a technique used to scientifically determine the location of sampling points and is included as part of the Response Surface Optimization system. Central Composite Design with Auto defined Design type is opted for the present analysis. The first step in DOE is to set up the input parameters by specifying a meaningful range for each of them. In our analysis the parameters 'SLTTHK', 'YY', 'XX1' and 'XX2' are continuous variables and they are confined to have a set of manufacturable values. While the parameter 'SLTNUM' is a discrete one and it may be 12 or 14 or 16 as prescribed by ISO15488 [5] for the collets having Form–B. The range of values for the various continuous parameters and their manufacturable values are summarized in Table II.

TABLE II
INPUT VARIABLES
(Values are in mm)

Parameter	Value	Lower bound	Upper bound	Manufacturable values
SLTTHK	1	1	2.5	1, 1.5, 2, 2.5
YY	37	35	38	35, 36, 37, 38
XX1	15	10	15	10, 11, 12, 13, 14, 15
XX2	8	2	16	2, 3, 4, ... , 15, 16

X. Optimization Using Response Surfaces

The Response Surfaces are functions of different nature where the output parameters are described in terms of the input parameters. They are built from the Design of Experiments in order to provide quickly the approximated values of the output parameters, everywhere in the analyzed design space, without to perform a complete solution. By examining the sensitivities of various parameters it is found that the parameters 'YY', 'XX1' and 'XX2' have lesser impact on the gripping performance.

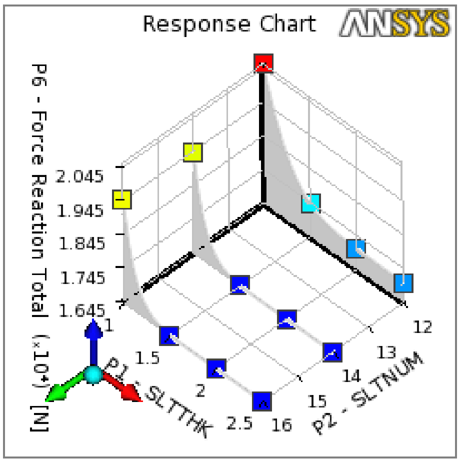

FIGURE 7

RESPONSE CHART

However the sensitivity of these parameters changes with change in slot thickness (SLTTHK) and number of slots (SLTNUM). The parameters 'SLTTHK' and 'SLTNUM' has high impact on total radial reaction force and hence on gripping performance. The impact of slot thickness and number of slots on the gripping performance can be understand from the response chart obtained as shown in Figure 7. Optimization is done by using Screening method by generating 1000 samples out of which 3 candidate points are chosen. The values of the various parameters of the candidate points are summarized in Table III.

TABLE III
OPTIMIZED VARIABLES

Parameter	Candidate 1	Candidate 2	Candidate 3
SLTTHK (mm)	1	1	1
SLTNUM	12	16	16
YY (mm)	36	36	37
XX1 (mm)	10	11	15
XX2 (mm)	13	9	9
FORCE REACTION TOTAL (N)	20583	19533	19533

The tradeoff between the reaction force total and safety factor minimum is analyzed from the trade off chart as shown in the Figure 8. From the chart it is noted that for all the design points the factor of safety is greater than 5.

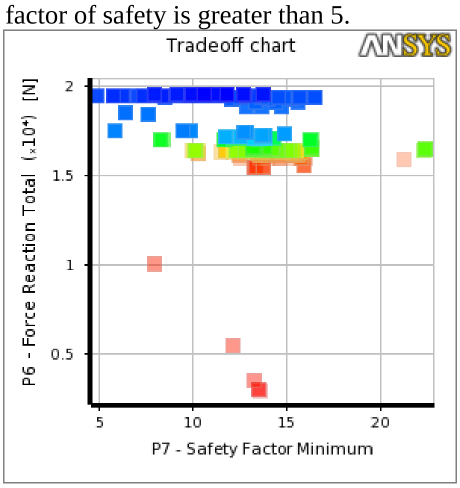

FIGURE 8

TRADEOFF CHART

XI. CONCLUSION

The presented finite element model that simulates the static clamping of the collet chuck is successfully used to analyze the variation of clamping effect with change in parameters in order to optimize the design. The optimized design candidate thus obtained having 12 slots each of width 1 mm; YY = 36 mm; XX1 = 10 mm and XX2 = 13 mm is found to have maximum gripping performance and has net radial reaction force of 20583 N. Further the stresses produced do not exceed the yield limits for all the values within the design space. This justifies the meaningful confinement of various parameters. The proposed FE can also be used to optimize the design parameters to achieve a specific value of frictional torque as per the application.

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