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Static and Dynamic Analyses of Spindle Collet Made of Different Steels Using Finite Element Modeling

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Kata kunci:

Spindle collet; mesin perkakas; Penemu Autodesk; tegangan Von Mises; frekuensi alami.

ABSTRAK

Spindle collet, komponen penting dalam berbagai mesin perkakas, memainkan peran penting dalam menentukan keberhasilan operasi pemesinan. Kajian ini bertujuan untuk mempelajari parameter statik dan dinamik struktur collet yang terbuat dari tiga baja berbeda dengan menggunakan metode elemen hingga. Model tiga dimensi dan simulasi komputer dilakukan pada perangkat lunak Autodesk Inventor 2022. Simulasi dilakukan dengan menggunakan kondisi batas dan ukuran mesh yang identik. Analisis statis dilakukan dengan gaya yang diterapkan bervariasi dimana deformasi total dan tegangan Von Mises diukur. Untuk analisis dinamik, frekuensi natural dan bentuk mode diukur hingga lima mode pertama. Variasi tegangan menjadi minimal ketika material diubah. Besarnya deformasi sangat bervariasi seiring dengan perubahan material. Nilai deformasi relatif menunjukkan bahwa baja karbon mengalami deformasi lebih besar daripada baja paduan sebesar hampir 3%, sedangkan baja tahan karat mengalami deformasi lebih besar daripada baja paduan sebesar 6%. Bahan dengan modulus Young lebih tinggi dan kepadatan lebih rendah terbukti meningkatkan frekuensi alami, mengurangi deformasi total dan tegangan Von Mises. Penggunaan baja paduan dalam industri menawarkan keunggulan dibandingkan dua material lainnya. Hasilnya memberikan peningkatan wawasan tentang bahan yang tepat untuk collet.

Keywords:

Spindle collet; machine tool; Autodesk Inventor; Von Mises stress; Natural frequencies.

ABSTRACT

The spindle collet, a critical component in various machine tools, plays a pivotal role in determining the success of machining operations. This paper aims to study the static and dynamic parameters of collet structures made from three different steels using the finite element method. A three-dimensional model and computer simulation were conducted in Autodesk Inventor 2022 software. Simulations are performed using identical boundary conditions and mesh size. Static analysis is performed with varied applied forces where total deformation and Von Mises stress are measured. For the dynamic analysis, the natural frequencies and mode shapes are measured up to the first five modes. The variations in stress are minimal when the material is altered. The magnitude of deformation varies significantly with changes in material. The relative deformation values demonstrate that carbon steel deforms more than alloy steel by almost 3%, while stainless steel deforms more than alloy steel by 6%. Steels with higher Young's modulus and lower density have been found to increase the natural frequencies, reducing total deformation and Von Mises stress. The use of alloy steel in the industry offers an advantage over the other two steels. The results provide improved insight into the appropriate steels for the collet.

1. INTRODUCTION

A spindle collet is essential to various machines, such as lathes, milling machines, drill presses, and other precision machining equipment [1–3] The primary purpose of a collet is to provide a tight and accurate grip on the cutting tools, ensuring precise and consistent machining results. The collet is designed to accommodate various tool sizes within a specific range. This feature makes it versatile, allowing different operations to be performed without changing the entire tool holder. The static and dynamic characteristics of collet play an essential part in machining performance within the high-speed machining process. According to Soriano-Heras et al. [4], the variation in the clamping force is primarily influenced by the stiffness of the collet chuck holder. However, the stiffness of clamping collets is relatively low due to their thin walls and the presence of slots and grooves [5].

A comprehensive understanding of static and dynamic parameters in machine tool structures is essential for achieving optimal surface quality and preventing chatter during machining processes [6]. Thorenz et al. [7] have shown that the collet has affected the surface qualities in milling operations. Like any mechanical system, collets are susceptible to static deformation and vibration during operations, adversely affecting machining performance [8]. In designing a new clamping system, Hajdu [9] has calculated the Von Misses stresses and deformations through numerical analysis. Soriano et al. [10] introduced an analytical model for calculating the static stiffness of collet sleeves, which provides a reliable theory for optimizing the design and application of collet sleeves.

Modal analysis is a technique used to determine the fundamental dynamic characteristics of a system, such as its natural frequencies and mode shapes. Identification of these dynamic characteristics helps prevent structural failures due to excessive vibrations. Song et al. [11] extracted modal parameters through experimental modal analysis to investigate the instability of internal damping due to the collet chuck holder. With advancements in computational systems, modal analysis using the finite element method (FEM) has become a popular approach for predicting the modal parameters of structures. In selecting operating parameters that prevent chatter during the cutting process, Senkus and Jotautiene [12] used the finite elements method to calculate the natural frequencies of the lathe collet chuck. A FEM that incorporates the compliance of the machine tool during clamping to determine modal parameters has been introduced by Saraf et al. [13].

Previous research has highlighted various factors affecting machining efficiency. Material properties are one of the significant factors impacting machining performance. Therefore, selecting a suitable material for machine tool structures is essential for optimal performance and durability. The selection process for appropriate steels and their applications in high-performance machine tools have been discussed by Mohring et al. [14]. By designing a collet from metallic damping alloy for a conventional tool holder in the end milling process, Kim et al. [15] have reduced machining vibration and improved surface finish quality. Subbarao and Dey [16] show that each material will result in different deformation values, Von Mises stress and natural frequency by comparing four different steels for lathe spindle material. Kumar et al. [17] compared deformation, Von Mises stress and natural frequency of milling machine beds made from composite materials through FEM.

Thus, it is essential to observe changes in static and dynamic parameters to identify potential material improvements for the collet structure that could avoid structure failure due to stress and isolate natural frequency from the operational range. The previous study should have extensively examined the impact of various steels on the static and dynamic parameters of collet, particularly in relation to modal analysis. This paper aims to study the static and dynamic parameters of collet structure made from three different steels using Autodesk Inventor 2022 software. Under the same boundary conditions, the total deformation, equivalent stresses and natural frequencies of carbon steel, alloy steel, and stainless steel are compared. Apart from this introduction, the subsequent sections of this study are structured as follows. The section on modelling and meshing of the collet primarily focuses on developing a 3D model of the collet and the mesh setup using Autodesk Inventor 2022 software. The properties of the steels involved are also provided in the section. The results of both static and dynamic analyses are presented in the Results and Discussion section, where the impacts of the steels are discussed. The article concludes with viewpoints presented in the Conclusion section.

2. MODELING AND MESHING OF COLLET

In this study, the standard ER16 collets for holding endmills and cutters used in milling machine is investigated. The dimension of the collet is shown in Figure 1. For the considered ER16 collet, the length, L is 27.5 mm, the outside diameter, D is 17 mm and the clamping range is within 1 mm to 10 mm.

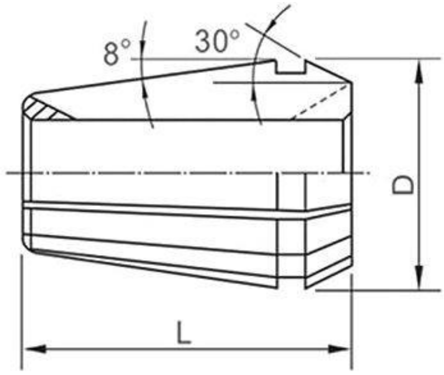
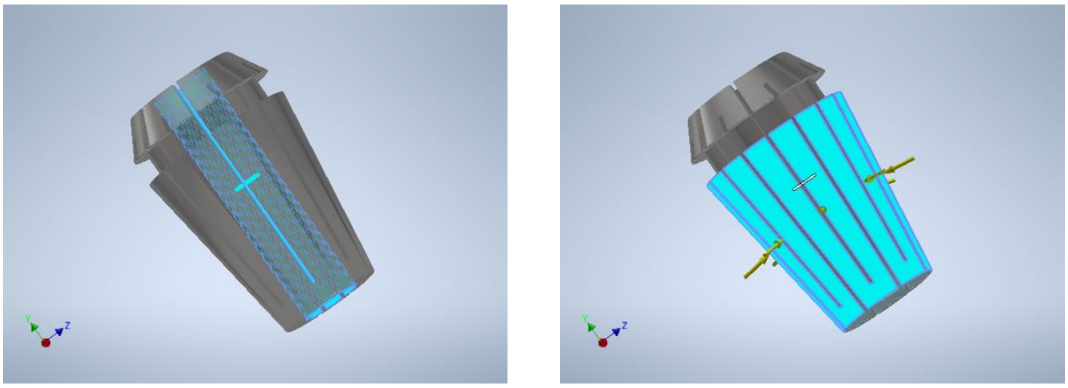


Figure 1. Dimension of ER16 collet

The three-dimensional model of the collet is developed in AI software. In the field of finite element methods, an important concern is the optimization of meshing and the selection of an appropriate mesh size [18]. The size of large elements may compromise the accuracy of results, while smaller elements tend to yield more accurate results. The AI static and modal analysis tool allows for control of mesh settings by adjusting the average element size value. The average element size denotes the mean separation between nodes of a mesh element. The value represents a fraction of the maximum dimension of the model in the x, y, or z directions. The accuracy of these results is influenced by the level of detail inputted into the software. The recommended range for this value, as suggested by AI, is 0.05 to 0.1. An average element size of 0.05 is selected for the entire study as smaller elements are presumed to produce more precise outcomes [19]. The three different steels that are considered for the static and modal analysis are alloy steel, carbon steel and stainless steel, as studied by Subbarao and Dey [16]. The properties of the steels, as listed in Table 1, are taken from a standardized database by Autodesk Inventor. For static analysis, a fixed boundary condition is applied on the internal diameter surface of the collet, as shown in Figure 2a. A constant load is applied to the external surfaces of the collet, as shown in Figure 2b. The simulation is performed under free-free conditions for the modal analysis, and the corresponding modal parameters are determined by neglecting the rigid body modes.

Table 1. Mechanical properties of materials

Material	Young's modulus (Gpa)	Shear modulus (GPa)	Poisson's ratio	Mass density (kg/ m^3)
Alloy steel	205	80	0.3	7720
Carbon steel	200	80	0.29	7860
Stainless steel	193	86	0.30	8000



(a) (b)

Figure 2. Model setup: (a) boundary condition and (b) loading area on the collet

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3. RESULTS AND DISCUSSION

3.1 Von Misses stress and deformation

The application of static structural analysis proves valuable in identifying and quantifying stress and deformation experienced by the collet as a result of applied conditions. The total deformation is the cumulative displacement in all three spatial dimensions, namely the x, y, and z directions. The elastic properties of the collet determine the overall deformation caused by the applied load. The total deformations of the collet for different steels under various cutting forces are investigated by varying the applied loads. The total deformation for all three steels at different loads is presented in

Table 2. Results show that the maximum total deformation is increasing with a load increment. The increment in deformation is linearly proportional to the load. For example, doubling the load results in doubled deformation for all considered steels. For the load of 200N, maximum deformation of 10.88×10^{-6} mm is observed in stainless steel, and a minimum deformation of 10.24×10^{-6} mm is in alloy steel. Alloy steel has the lowest deformation for all considered load. A relative value is calculated to demonstrate the effect of different steels on deformation. Deformation recorded in alloy steel for each load is taken as a reference. The relative deformation values depicted in Figure 3 indicate shows that stainless steel causes 6% more deformation than alloy steel, and carbon steel causes nearly 3% more deformation than alloy steel.

Table 2. Maximum total deformation for the different steels

Cutting force (N)	**Total deformation (10^{-6} mm)**		
	Alloy steel	Carbon steel	Stainless steel
50	2.56	2.63	2.72
100	5.12	5.26	5.44
150	7.68	7.90	8.16
200	10.24	10.53	10.88

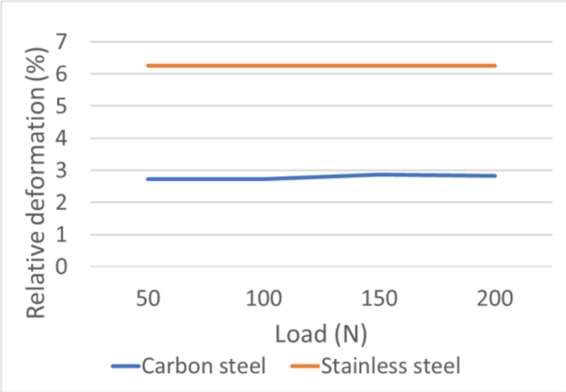

Figure 3. Relative deformation

The equivalent stress, or Von Mises stress, is employed to predict whether a specific material will undergo yielding or fracturing when subjected to an externally imposed load or force. This technique is mainly employed to analyze ductile steels, particularly metals. The purpose is to depict the structural condition as a consequence of the prior applied load. Table 3 displays the results of Von Mises stress corresponding to various load values. Alloy and stainless steel exhibited the lowest stress levels for all considered loads, while carbon steel experienced the highest stress. Then, this study examines the impact of increased load on different steels using a relative value approach. Since the Von Mises stress is equal for alloy steel and stainless steel, only the relative value of carbon steel is calculated. Figure 4 illustrates a 0.2% increase in carbon steel stress compared to alloy steel and stainless steel.

Table 3. Von Mises stress for the different steels

Cutting force (N)	Alloy steel	Carbon steel	Stainless steel
50	0.2289	0.2294	0.2289
100	0.4578	0.4588	0.4578
150	0.6866	0.6882	0.6866
200	0.9155	0.9176	0.9155

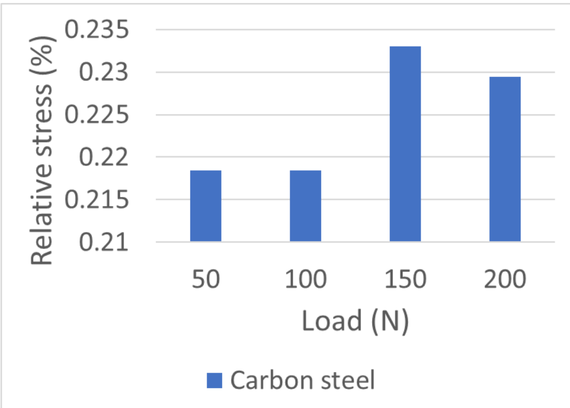

Figure 4. Relative Von Mises stress

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3.2 Modal parameters

Modal analysis is a technique that reveals the natural frequencies and mode shapes of a structure or component. Natural frequencies are essential for understanding and predicting the dynamic behaviour of structures. Each natural frequency corresponds to a specific mode of vibration that the structure can undergo. When a structure is subjected to dynamic loads that match its natural frequencies, resonance can occur. At resonance, the amplitude of the vibrations can increase significantly, potentially leading to excessive stresses. Structures designed without consideration of their natural frequencies may experience destructive resonance when exposed to periodic forces.

The use of finite element method (FEM) in modal analysis has become a common practice for predicting the modal parameters of structures due to the progress in computational systems. The tool is highly regarded in structural engineering for its ability to handle intricate structural geometry effectively and conduct diverse analyses. The modal analysis for different types of material under free-free boundary conditions was studied in this section. Table 4 presents a comparison of the natural frequencies for each material. Among the three steels, alloy steel has the highest natural frequencies, whereas stainless steel has the lowest. This is because alloy steel has a greater Young's modulus and lower density.

Table 4. Natural frequencies for the different steels

Mod	Alloy steel	Carbon steel	Stainless steel
1	535.9	525.2	511.1
2	627.9	615.5	598.9
3	879.8	862.6	839.2
4	1027.7	1008.0	980.2
5	1115.4	1092.7	1063.8

Mode shapes are critical in understanding the dynamic behaviour of structures, particularly how they respond to various types of excitations, such as vibrations and dynamic loads. Mode shapes describe the specific pattern of displacement that a structure undergoes at particular natural frequencies. Each mode shape corresponds to a distinct natural frequency, indicating how different parts of the structure move relative to each other during vibration. They provide insights into how structures behave under dynamic conditions, guiding design improvements and safety measures to ensure structural integrity. The first three mode shapes for the collet are shown in Figure 5 to Figure 7. In the first mode, as shown in Figure 5, the top part of the collet is significantly affected, where higher displacement occurs. A torsional mode in the y-axis is observed in the second mode, as shown in Figure 6, where higher displacement is in the top part of the collet. For the third mode, as shown in Figure 7, the bottom part expanded around the y-axis.

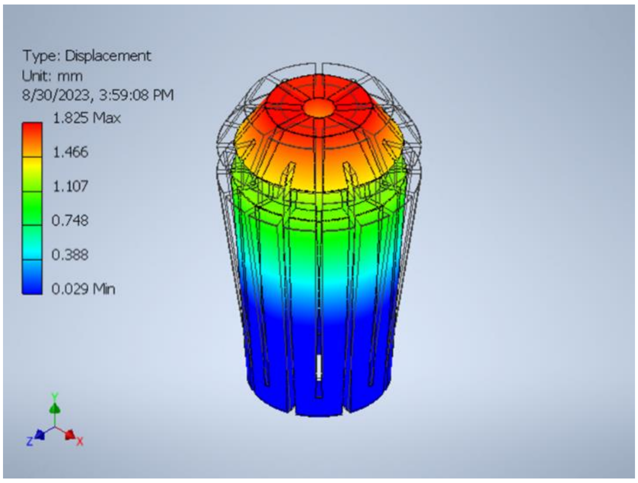

Figure 5. First mode

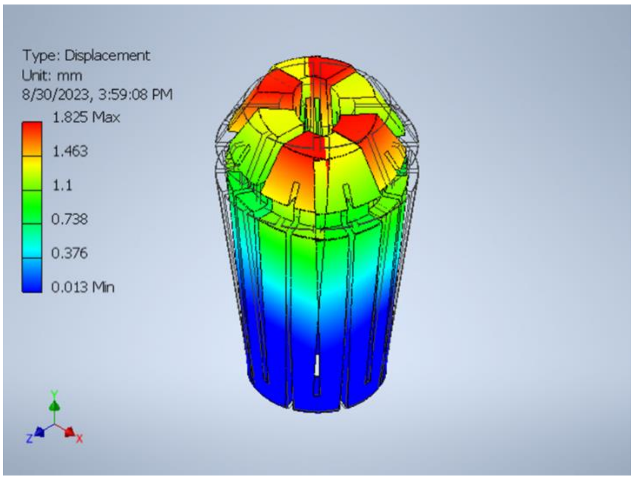

Figure 6. Second Mode

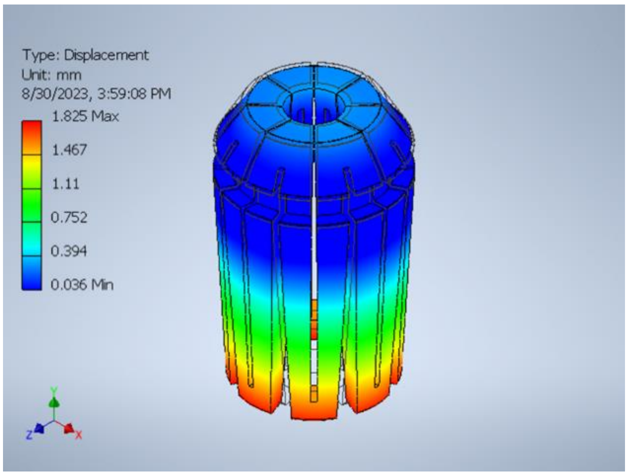

Figure 7. Third mode

Compared with the alloy steel, Figure 8 shows a reduction percentage in natural frequencies for the first five modes. The percentage of reduction in natural frequencies is almost constant for each mode. Carbon steel has an average of about 2% reduction, followed by stainless steel at 4.5% compared to alloy steel. Alloy steel exhibited favourable outcomes regarding reduced stress, deformation, and the highest natural frequencies. Thus, alloy steel is highly effective in mitigating structural failure due to stress and isolating the natural frequency within the operational range.

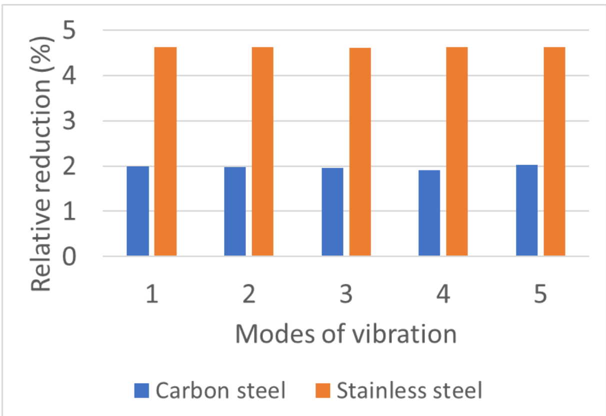

Figure 8. Relative reduction in natural frequency

4. CONCLUSION

In this study, the static and dynamic parameters of collet structures made from three different steels, alloy steel, carbon steel, and stainless steel, were analyzed using the finite element method. A three-dimensional model and computer simulation of the collet has been generated using Autodesk Inventor 2022 software. The simulations were conducted with identical boundary conditions and mesh size. Static analysis was performed with varied applied loads where total deformation and Von Mises stress were measured. The deformation value was represented by displacement, a scalar value showing how much the collet changes in response to applied loading. The magnitude of deformation varies significantly with changes in the material. Alloy steel has the lowest deformation for all considered loads. The relative deformation values demonstrate that stainless steel causes a 6% greater deformation than alloy steel, whereas carbon steel causes a nearly 3% higher deformation than alloy steel. The Von Mises stress, which converts multidirectional stresses to equivalent stresses, describes the stress condition at any location in the structure. Relative stress analysis revealed a 0.2% higher stress level on carbon steel when compared to alloy steel. For the dynamic analysis, the natural frequencies and mode shapes were measured up to the first five modes. Alloy steel, with its higher Young's modulus and lower density, has been found to enhance natural frequencies. The findings offer an enhanced understanding of the suitable steels for the collet, a vital machine tool component. Alloy steel showed the best results with less stress and deformation and the highest natural frequencies. Overall, alloy steel is more effective in preventing structural failure caused by stress and isolating the natural frequency within the operational range.

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