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Research Article

Clamping Force Optimization for Four-Jaw Lathe Chuck Operators

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Abstract:
The manufacturing industry faces critical challenges related to shortages of skilled technicians and declining skill levels, compounded by a lack of instructors and limited training time. Effective skill transfer and the development of new skilled operators are essential. In lathe operations, proper clamping of workpieces is crucial for safety and machining accuracy. However, in the absence of clear standards for clamping force, reliance on instructors' experience is common. This study addressed this issue by developing a clamping force monitoring device for a four-jaw lathe chuck, incorporating theoretical calculations and experimental verification of the required clamping force. Additionally, it investigated the clamping force applied by instructors and quantified the operator's clamping force using a safety factor. For rough cutting, the safety factor was 1.7 times the reference instructor's force, and for finish cutting, it was 2.1 times. The optimal clamping force was determined by adjusting the required force with a safety factor and half the observed variation width, resulting in 15.1 kN for rough cutting and 4.7 kN for finish cutting. The study concluded that the clamping force monitoring device optimizes clamping for safe and accurate machining, establishing a clear standard for beginners.

Keywords: *Clamping force, lathe chuck, skills training, education, tacit knowledge*

1. Introduction

The manufacturing industry faces a critical shortage of highly skilled technicians, leading to a notable decline in proficiency. As highlighted in the white paper on manufacturing [1], challenges in skill development and human resource training are particularly acute. These challenges include a scarcity of instructors and inadequate time allocated for training. To sustain high-level proficiency at production sites, it is essential to transfer skills effectively and train new technicians. Extensive practical training is required to cultivate these skills, which are expected to be acquired not only at production sites but also through formal education at technical high schools and engineering colleges [2]. Consequently, it is crucial to facilitate the acquisition of these skills by providing practical, comprehensible education in machining for beginners and students. Typically, the initial practical training in machining at technical high schools and engineering colleges involves general-purpose lathe operations, which are fundamental to metal cutting. Proficiency in general-purpose lathe operations requires mastering various skills, including tool selection, setting cutting conditions, workpiece clamping, depth of cut adjustments, dimensional measurements, and understanding the overall machining process. The clamping operation, used to secure the workpiece to the lathe chuck, is critical for ensuring both safety and machining accuracy. Insufficient clamping force can lead to workpiece ejection or displacement during the turning process, potentially causing accidents. Conversely,

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excessive clamping force might deform the workpiece, compromising machining accuracy. Thus, mastering the optimal clamping force is indispensable for effective lathe operation.

In the field of lathe machining, the study of clamping force encompasses numerous themes, notably the impact of gripping force on the shape accuracy of three-jaw chucks [3-5]. Research has led to the development of analytical methods and measuring tools specifically for thin, ring-shaped workpieces. Additionally, variations in jaw configurations have been shown to affect the distribution of gripping force, with significant implications for machining vibrations known as chattering [6-8]. There have also been investigations into how changes in centrifugal force and processing heat alter the gripping force exerted on workpieces [9, 10]. However, research on the clamping force applied by operators during practical training and what constitutes a safe clamping force remains limited. One notable study involved the creation of a safety simulator for lathe operations, which assesses the likelihood of workpiece dropout or displacement due to the extended attachment length of the lathe chuck [11]. Furthermore, research comparing the clamping motions of skilled technicians and beginners has been conducted using electromyographic sensors and motion capture technology. These studies quantitatively evaluated the differences in clamping stance [12] and the energy expended during these motions [13]. Other research has employed augmented reality and virtual reality to develop simulators for lathe setup tasks [14]. One such simulator, designed for lathe centering operations, quantifies eccentricity based on striking and clamping forces, thereby enhancing training outcomes. Additionally, investigations into visual and gazing behaviors during machining tasks have quantified changes in gaze duration, focus points, and eye movements, correlating these metrics with operators' experience levels, and the use or absence of digital position displays [15].

As previously mentioned, efforts to enhance practical training in vocational education often focus on quantifying tacit knowledge. Despite this, studies quantifying operational and clamping forces during the initial training on general-purpose lathe machines for beginners are scarce. Specifically, research is lacking in the quantification and optimization of clamping forces for each machining process and condition, particularly using a four-jaw chuck—an apparatus commonly employed in the training of novice lathe operators. Furthermore, the instructions provided by trainers to novices are often ambiguous, with directives such as “tighten hard” or “clamp at 80% of your full strength” relying on personal experience and intuition. The consistency of these instructions varies significantly between instructors, and clamping operations are typically guided by instinct rather than standardized procedures. A review of existing vocational training materials and commercial publications on lathes reveals no specific references to quantifiable tightening forces. Even basic training documents for beginners tend to describe the tightening force only in general terms during workpiece installation [16, 17]. According to the procedural manual for the intermediate-level lathe grade 2 certification, each jaw of the four-jaw chuck should be tightened with equal force [18], implying that any deviation might prevent the workpiece from withstanding the cutting force, potentially causing it to detach. Other educational resources merely discuss the deformation caused by excessive tightening without offering optimized values for sufficient clamping force.

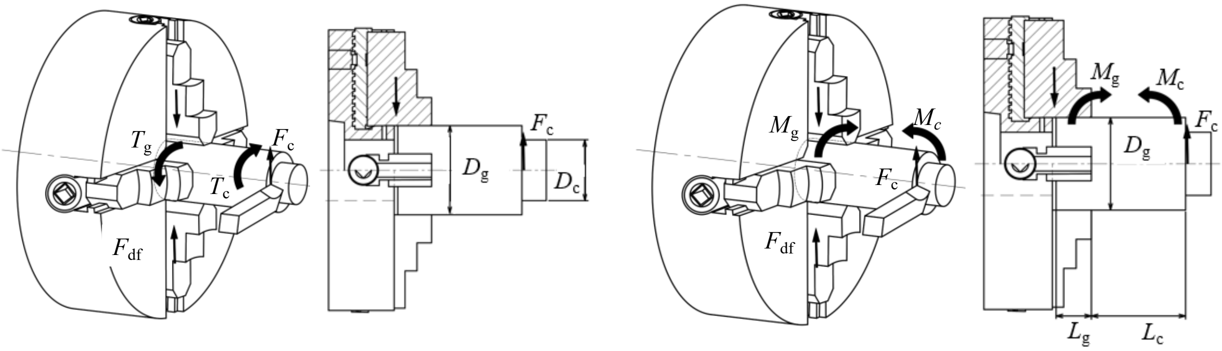
This study aims to optimize the clamping force applied by operators using a four-jaw lathe chuck, enhancing both safety and machining accuracy. The primary focus is on the safety of operators. Initially, a device to monitor clamping force was developed to evaluate operator performance. The minimum clamping force necessary to prevent workpiece dropout or displacement during the turning process was then calculated using theoretical equations. Subsequent optimizations were made by quantifying the clamping forces used by a vocational training instructor and assessing the safety margins through experimental trials in turning. Thus, the study addresses the lack of research on the quantification and optimization of clamping forces in four-jaw chucks and is expected to contribute to safe lathe-machining operations.

2. Calculation of Minimum Clamping Force Based on Theoretical Equation

Fig. 1 illustrates the general-purpose lathe used in this experiment, along with the clamping operation. In this operation, two distinct forces act: the clamping force exerted by the operator and the gripping force exerted on the workpiece. The clamping force, applied via the chuck handle by the operator, is transmitted through the chuck's structure depending on the workpiece's shape and gripping position, becoming the gripping force that secures the workpiece. The required clamping force is calculated using a theoretical formula provided by the chuck manufacturer [19], which considers the attachment state of the workpiece to ensure it neither dislodges nor shifts.

(a) General-purpose lathe used in the experiment (b) Clamping the workpiece

Fig. 1. General-purpose lathe.



(a) Balance of slip in the direction of rotation (b) Balance of deflection in the direction of falling

Fig. 2. Balance of forces acting on workpiece dropout and displacement.

Fig. 2 depicts the equilibrium of forces acting on the workpiece during displacement. A balance must be maintained between slip in the direction of rotation and deflection in the direction of falling. The rotational forces include the gripping torque T_g from the chuck, which tries to rotate the workpiece, and the cutting torque T_c from the cutting tool, which opposes this motion. Safe machining is achieved when the gripping torque exceeds the cutting torque. These moments are calculated using the dynamic gripping force F_{df}, which combines the static gripping force F_{sf} and the centrifugal force F_{cf}, gripping diameter D_g, coefficient of friction μ, cutting diameter D_c, and principal cutting force F_c. Each torque is expressed as follows:

$$T_g = \frac{\mu F_{df} D_g}{2} \geq T_c = \frac{F_c D_c}{2}. \quad (1)$$

The forces acting in the direction of overturning involve the overturning moment M_c, created by the bite that tries to deflect the workpiece, and the resistance moment M_g, generated by the chuck to hold the workpiece in place. These moments are calculated using the dynamic gripping force F_{df}, along with the gripping length L_g, gripping diameter D_g, coefficient of friction μ, number of jaws n, jaw factor k, principal cutting force F_c, and overhang length L_c. In this case, the jaw factor k is a coefficient that changes depending on the number of jaws n of the chuck. In this experiment, $k = 2$ was used because two sets of chucks were used for gripping. Each moment is expressed as follows:

$$M_g = \frac{F_{df}}{n}\left(\frac{2}{3}L_g + k\mu D_g\right) \geq M_c = F_c\left(L_c + \frac{L_g}{2}\right). \quad (2)$$

The dynamic gripping force is derived from Eqs. (1) and (2), with the larger value being used for calculations. The static gripping force is computed from the centrifugal force during rotation and this dynamic gripping force. Finally, the minimum clamping force F_{wmin} necessary to prevent the workpiece from falling off or shifting during the turning process is determined by considering the transmission rate from the gripping state of the workpiece and using the static gripping force F_{sf}.

3. Development of Clamping Force Monitoring Device

3.1 Configuration and principle of clamping force monitoring device

The development of the clamping force monitoring device aims to measure several forces: the clamping force exerted by an operator, the centrifugal force generated during chuck rotation, and forces causing workpiece displacement during cutting. Fig. 3 illustrates the internal structure of a four-jaw chuck alongside the developed monitoring device. The investigation of the four-jaw chuck's internal structure was driven by the goal of monitoring the clamping force applied by the operator. The chuck consists of three primary components: jaws, a screw rod, and a U-shaped stopper embedded and fixed within the chuck body. The screw rod, facilitated by the stopper and chuck body holes, allows for rotational movement. Connected to the trapezoidal screw of the screw rod, the jaws advance along the guide within the chuck body upon the operator's rotation of the screw rod, applying a gripping force to the workpiece. Concurrently, the reaction force from the workpiece to the jaws is transmitted to the stopper via the screw rod, inducing bending strain in the stopper. This strain is used to calculate the clamping force indirectly by measuring the strength of the reaction force. To facilitate this measurement, a U-shaped stopper was machined to accommodate a strain gauge. Four strain gauges were affixed to one U-shaped stopper, utilizing the four-gauge method to measure the force exerted by all four jaws. To evaluate the effect of centrifugal force on the gripping state during turning, the strain gauge signals were wirelessly transmitted, and a transmitter was installed within the four-jaw chuck. A receiver and dynamic strain gauge connected to a personal computer allowed for continuous monitoring of the clamping force. The clamping force monitoring device was designed with a maximum measurement load of 26 kN and a resolution of 0.1 kN based on the operator's clamping force and the structural design of the device.

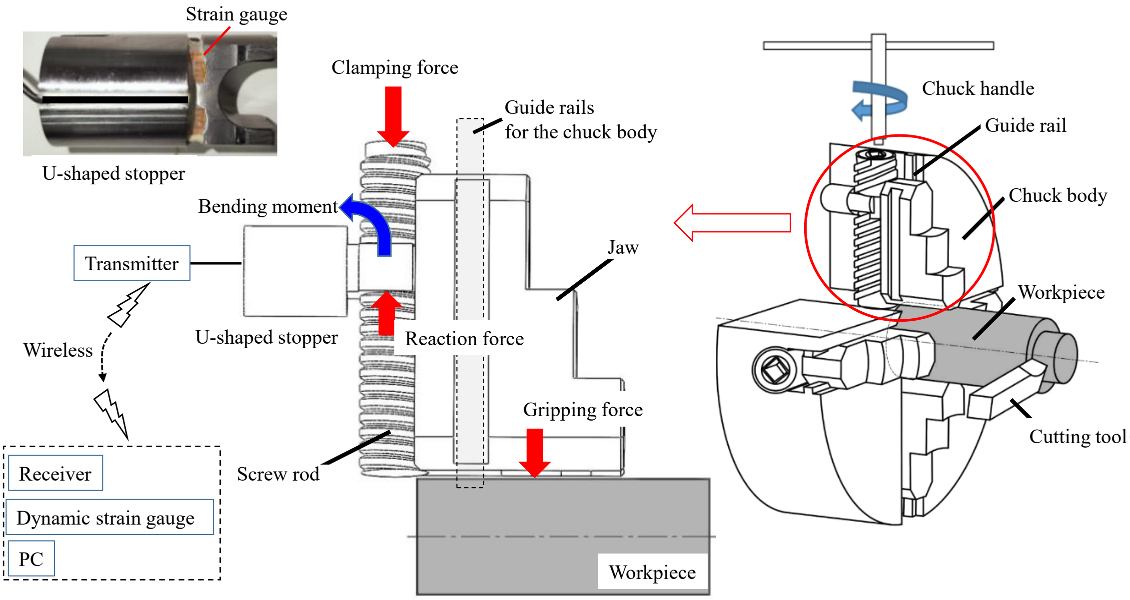


Fig. 3. Internal structure of four-jaw chuck and developed clamping force monitoring device.

3.2 Performance evaluation of clamping force monitoring device

The performance of the clamping force monitoring device was evaluated by incorporating a U-shaped stopper into the device's chuck. A commercially available load cell (Hokuyo Co., Ltd., HLC-50N, size φ30×30), with a total accuracy of 0.19 % of rated output (RO), was installed at the deepest position within a jaw to evaluate the relationship between the applied clamping force and the load cell's measurement of gripping force.

Table 1 summarizes the results from the performance tests [20] conducted on each of the jaws (1 to 4) of the device. The test was conducted five times, and the average values are presented in the table. The total accuracy reflects the overall accuracy that incorporates both nonlinearity and repeatability. The standard deviation of nonlinearity was 0.15 for Jaw No. 1, 0.15 for Jaw No. 2, 0.26 for Jaw No. 3 and 0.36 for Jaw No. 4. The accuracy for jaws 1 to 3 was found to be within 1.86% RO, while stopper 4, which was not used in this experiment, showed a higher variation with an accuracy of 4.45% RO. This discrepancy posed no issues owing to its non-utilization in the tests. Notably, even at clamping forces exceeding 20 kN, the measurement error for the maximum rated clamping force of 26 kN was approximately 1 kN. Such a level of measurement error is typically imperceptible through tactile feedback by the operator and is considered acceptable within the operational context.

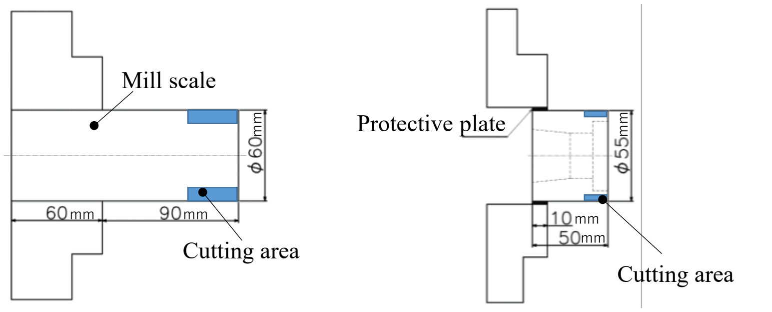
Table 1: Characteristic performance of clamping force monitoring devices.

Measuring parts	Non-linearity (%RO)	Repeatability (%RO)	Total accuracy (%RO)
No.1 Jaw	1.48	0.26	1.50
No.2 Jaw	1.07	1.10	1.53
No.3 Jaw	1.34	1.29	1.86
No.4 Jaw	4.42	0.50	4.45

4. Demonstration Experiment of Falling Off and Shifting with Minimum Clamping Force

4.1 Workpiece shape and experimental method

Given that the requisite clamping force varies depending on the shape of the workpiece, the grade 2 machining (lathe) skills test task [21], sponsored by the Japan Vocational Ability Development Association, was chosen as a representative example of general turning processing. The material used for the subject is carbon steel for machine construction (S45C). Fig. 4 illustrates the specific shape employed in the experiment, derived from the machining process steps. Fig. 4(a) illustrates the rough outer diameter machining of part ①, representing the initial stage of the machining process, while Fig. 4(b) depicts the finish outer diameter machining of part ②. The required clamping force was determined using Eqs. (1) and (2), with parameters such as centrifugal force, coefficient of friction, and cutting force derived from preliminary experiments. The coefficient of friction between the jaws and the workpiece was determined from the load at which the workpiece shifted; the measurements used the developed clamping force monitoring device shown in Fig. 3 and a load meter installed between the workpiece and the tailstock. To enhance safety, the required clamping force was set higher when there was a variation in the parameter values. These parameters are detailed in Table 2. The clamping forces measured in the experiments were within the range of approximately ±2 kN for rough machining and approximately ±0.5 kN for finish machining, based on the established clamping force requirements. A demonstration experiment was conducted to test the efficacy of the theoretical formulas. The processing conditions are outlined in Table 3, and misalignment was specifically checked when processing the colored part shown in Fig. 4. The method for assessing misalignment involved monitoring changes over time in the measured values from the tightening force monitoring device and verifying these measurements with a dial gauge after processing. To confirm the reliability of the theoretical formula, each demonstration experiment was conducted three times.



(a) Part ① (rough cutting) (b) Part ② (finish cutting)

Fig. 4. Workpiece shape for selected grade 2 machining (lathe) skills test.

Table 2: Parameters used in the theoretical formula.

Workpiece shape	(a) ①	(b) ②
Centrifugal force F_{cf} (kN)	0.41	0.45
Coefficient of friction μ	0.20	0.15
Principal cutting force F_c (kN)	1.65	0.02

Table 3: Experimental cutting conditions.

Workpiece shape	**(a)** ①	**(b)** ②
Rotational speed N (min^{-1})	570	1140
Depth of cut a_p (mm)	2.5	0.1
Feed rate f (mm/rev)	0.25	0.05
Gripping state	Mill scale	Protective plate

4.2 Experimental results and discussion

Table 4 presents the minimum required clamping force for part ① in Fig. 4(a), along with the results of the demonstration experiment for each clamping force. An "×" indicates that the workpiece shifted during the experiment, while a "○" denotes that the workpiece remained stationary. The experimental results demonstrate that at 6.0 kN—less than the theoretically required clamping force—there was no dislodgment or shifting of the workpiece. This is attributed to a coefficient of friction higher than the value used in the preliminary experiment calculations. Table 5 lists the minimum required clamping force for part ② in Fig. 4(b) and the results of each demonstration experiment. The results indicate that even at 1.0 kN, below the required clamping force, there was no dislodgment or shifting of workpieces, aligning with theoretical expectations. During the finishing of part ②, which features a hole and a wall thickness of 15 mm or more, it was confirmed that the clamping force applied did not cause any deformation, maintaining machining accuracy. Additionally, the analysis concluded that for the accuracy requirements specified in the grade 2 machining (lathe) skills test, the influence of clamping force on machining accuracy is negligible.

The findings confirm that the minimum required clamping force calculated based on the theoretical formula is adequate for safe cutting. In this experiment, the minimum required clamping force F_{wmin} for the rough cutting part ① was 7.3 kN, and for the finish cutting part ②, it was 1.3 kN. Therefore, it can be concluded that this calculated minimum clamping force is effective for both rough cutting and finishing without any issues.

Table 4: Required clamping force for part ① and demonstration experiment results.

Minimum required clamping force F_{wmin} (kN)	7.3			
Experimental clamping force F_{w} (kN)	4.0	6.0	8.0	10.0
Condition after experiment	×Shift	○Stationary	○Stationary	○Stationary

Table 5: Required clamping force for part ② and demonstration experiment results.

Minimum required clamping force F_{wmin} (kN)	1.3			
Experimental clamping force F_{w} (kN)	0.5	1.0	1.5	2.0~6.0
Condition after experiment	×Shift	○Stationary	○Stationary	○Stationary

5. Clamping Force Optimization for Four-Jaw Lathe Chuck Operators

5.1 Measurement experiment of clamping force by vocational training instructor

Instructors typically operate based on their past experiences, considering their applied clamping force is appropriate. However, few have considered what the actual optimal clamping force should be. The minimum required clamping force, calculated using the theoretical formula from the previous section, proved sufficient for turning. When actually clamping, it is advisable to use an optimized value that includes a safety factor rather than just the minimum required clamping force. In this study, the clamping force for each workpiece shape—based on the instructor's past experience—is measured. The safety factor for the clamping force is determined by comparing the instructor's measured clamping force with the minimum required clamping force calculated in the demonstration experiment. This comparison is used to optimize the clamping force for workers based on the necessary safety factor.

The instructors measured the clamping force three times under actual conditions, simulating the operations for the external diameter rough cutting of part① and the external diameter finish machining of part②, as shown in Figs. 4(a) and 4(b), respectively. Rough cutting utilized a surface gauge, while finish cutting employed a dial gauge for centering. A clamping force monitoring device was used to record the clamping forces. In this experiment, measurements were taken at three jaws, numbered 1 to 3, with one instructor collecting clamping force data nine times.

5.2 Measurement results of tightening force by the vocational training instructor

Fig. 5 illustrates the clamping force used during rough cutting and finishing by nine instructors, presenting both the average value and the range from maximum to minimum for each instructor. During rough cutting, the average clamping force across the nine instructors was 19.1 kN, with a variance of 13.5 kN in average clamping force among instructors. A detailed comparison of the range and variation for each instructor indicates notable individual differences. The maximum variation exceeded ±3.1 kN (instructor F), and the minimum was ±1.3 kN (instructor D), with an average variation of approximately ±2.7 kN across all measurements. This variation, which represents 14% of the average clamping force, can be attributed to differences in individual proficiency and consistency in clamping performance. Instructor A, with significant variability, is unable to achieve consistent clamping. Variation in the clamping force is evident even among instructors qualified to instruct students. Thus, guiding students is challenging, and lathe chuck clamping operations require specific skills. Interviews with instructors regarding their tightening practices revealed that variations in average clamping force are primarily due to differing perceptions of "what percentage of their full strength they should use" and their experiences.

In finish cutting, as shown in Fig. 5, the average clamping force was 6.6 kN, with differences in average clamping force among instructors reaching 7.5 kN. Similar to the rough cutting process, these findings demonstrate that optimized clamping varies significantly by individual instructor. In finish cutting, the maximum variation was ±3.1 kN (instructor E), and the minimum was ±1.3 kN (instructor G), with an average variation of approximately ±2.0 kN. This represents 32% of the average clamping force, indicating substantial individual variation. Given the setting of the dial gauge in finishing operations to an eccentricity of ±0.02 mm, it is inferred that instructors prioritized the accuracy of centering over clamping force to achieve precise adjustments. The measurement results of the clamping force of the instructors in rough and finishing processing also reveal that the optimized clamping differs depending on the individual instructor.

5.3 Determining the safety factor and optimizing the clamping force

From the clamping force data during rough cutting presented in Fig. 5, the average clamping force for instructors D and G is approximately 15 kN, which is the lowest among the instructors. Considering their extensive teaching experience and the fact that cutting operations can be safely performed at this force level, instructors D and G were used as the baseline. The average of their minimum clamping forces is 12.7 kN. The standard instructor's clamping force thus has a safety factor S of 1.7 times the minimum required clamping force F_{wmin} of 7.3 kN for part shape ①, as found in the results from Section 4.2. Consequently, the safety factor for the clamping force in rough machining was set at 1.7. However, to determine the optimized clamping force F_{s}, it is necessary to account for potential decreases in force due to variation, as clamping is predominantly dependent on the worker's skill and can vary significantly. Therefore, the optimized clamping force F_{s} is calculated using the required minimum clamping force F_{wmin}, the safety factor S, and the decrease value in clamping force due to variation α, as shown in the following equation:

$$F_{\mathrm{s}} = SF_{\mathrm{wmin}} + \alpha. \tag{3}$$

The average variation in clamping force during rough machining was ±2.7 kN. Assuming the clamping force reduction α is 2.7 kN, the optimized clamping force for part shape ① was determined to be 15.1 kN. For finish machining, instructor D's force was significantly lower than that of other instructors and was thus excluded. Instructors F and H, who had the next smallest clamping forces and were similar to each other, were used as standards. The average of their minimum clamping forces is 2.7 kN. The standard instructor's clamping force in this context has a safety factor of 2.1 relative to the minimum required clamping force of 1.3 kN for part shape ②, as per the findings in Section 4.2. The safety factor for finish machining was also set at 2.1. Taking into account the average variation of ±2 kN in the finishing process, the optimized clamping force for part shape ② was calculated to be 4.7 kN using Eq. (3).

This study facilitated the optimization of clamping force for four-jaw lathe chuck operators. Table 6 summarizes the minimum required clamping forces, safety factors, average variations, and optimized clamping determined in this study. For the grade 2 machining (lathe) skills test cutting process, a system was established that allows for the determination of the optimal clamping force, adjusting according to various machining conditions and using the formulas, parameters, and conditions outlined in each section, as summarized in Table 6. This system can determine the optimal clamping force not only for grade 2 skill test tasks but also for variations in shape and material by adjusting variables such as cutting force and coefficient of friction.

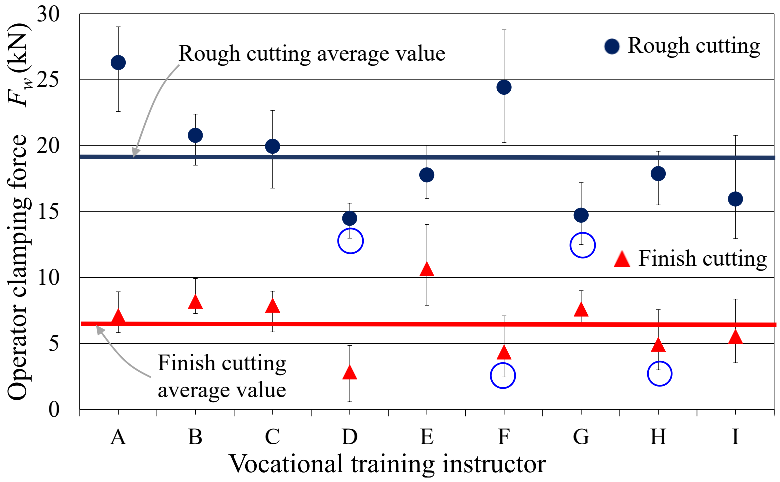


Fig. 5. Instructor clamping force during rough cutting and finishing cutting.

Table 6: Summary of this experiment.

Workpiece shape	**(a)** ①	**(b)** ②
Minimum required clamping force F_{wmin} (kN)	7.3	1.3
Instuctor's clamping force F_{w} (kN)	12.7	2.7
Safety factor S	1.7	2.1
Decrease value in clamping force variation α (kN)	2.7	2.0
Optimized clamping force F_{s} (kN)	15.1	4.7

6. Conclusion

The aim of this study was to examine the clamping operation of a general-purpose lathe with the objective of optimizing the clamping force to ensure safety and processing accuracy. The key findings are summarized as follows:

1. By analyzing the structure of the four-jaw chuck and integrating a strain gauge onto the U-shaped stopper, we developed a device capable of monitoring the clamping force applied by an operator to the workpiece. The performance test results indicate that the device was adequately reliable for use in this experiment.
2. The forces causing workpieces to come off or shift were analyzed, focusing on the balance of slip in the direction of rotation and the balance of deflection in the direction of falling. The minimum required clamping force for each scenario was calculated using theoretical formulas. A demonstration experiment was conducted to explore the phenomena of workpiece displacement and detachment. The larger of the calculated values was established as the required clamping force. The results confirmed that the minimum required clamping force was sufficient to ensure safe processing during both rough and finish cutting. Moreover, the theoretical formula developed in this study offers a method for calculating the minimum required clamping force.
3. The clamping forces applied by several instructors were quantified, revealing considerable variability in force magnitude. The safety factor for rough cutting was established at 1.7 times the force of the benchmark instructor, and for finish cutting, it was set at 2.1 times. Given the observed variability among instructors, ensuring safety was a critical consideration. The optimized clamping force was determined by multiplying the required force by the safety factor and adjusting for half the width of the observed variation. This methodology led to the development of a system capable of identifying the optimal clamping force during the grade 2 machining (lathe) skills test.

Nomenclature

a_p	depth of cut, mm
D_c	cutting diameter, mm
D_g	gripping diameter, mm
F_c	principal cutting force, kN
F_{cf}	centrifugal force, kN
F_{sf}	static gripping force, kN
F_{df}	dynamic gripping force, kN
F_s	optimized clamping force, kN
F_w	operator clamping force, kN
F_{wmin}	minimum required clamping force, kN
f	feed rate, mm/min
k	jaw factor
L_c	overhang length, mm
L_g	gripping length, mm
M_c	overturning moment, Nm
M_g	resistance moment, Nm
N	rotational speed, min^{-1}
n	number of jaws
S	safety factor
T_c	cutting torque, Nm
T_g	grip torque, Nm
α	clamping force variation, kN
μ	coefficient of friction
Subscripts	
c	cutting
cf	centrifugal force
df	dynamic grasp force
g	gripping
s	safety
sf	static gripping force
of	optimized clamping force
w	workpiece

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