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APPLICATION OF ADAPTIVE MASHINING FORCE TO WORKPIECE-FIXTURE DYNAMIC BEHAVIOR ACCORDING TO MATERIAL REMOVAL EFFECTS

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ABSTRACT

Surface quality is a major factor affecting the performance of a component. The machined surface quality is strongly influenced by degree of stability during the fixturing and machining processes. In machining process development, it is highly desirable to optimum the quality of a machined surface and its dynamic response. The primary goal of this paper is to investigate the dynamic behaviors and surface quality of the verified workpiece-fixture design against the clamping and periodic cutting forces (helical end milling) with the application of frictional contact and chip removal effects using a finite-element technique and the secondary goal is to adapt and change the cutting force cycle and spindle speed along the cutting tool path according to the dynamic responses of workpiece-fixture systems and the maximum elastic deformation of workpiece during machining.

The harmonic and modal analysis is carried out for numerical simulated cutting forces cycle to recognize the dynamic effects of chip removal, machining force and its dominant excitation frequency on stability, dynamic responses of workpiec-fixture and elastic deformation of workpiece under finite-element based model. Cutting forces cycle are numerically simulated according to the geometry and other properties of cutter .the chip removal effects and frictional contact between the workpiece and the fixture elements are taken into account using a material removal approach based on element death technique and nonlinear finite-element analysis.

KEYWORDS: FEA, fixture, chip removal, designs of experiment

1. INTRODUCTION

A machining fixture is a critical link in a machining system as it directly affects the operational safety and part quality. The design of a machining fixture not only must enable the workpiece to remain stable throughout the machining process but also the smart design should adapt the fixture and machining parameters with all dynamic situation of system along the machining operation on part. This kind of design is necessary to protect the part quality from damages that could be happen by uncontrolled clamping pressures , spindle speed and other machining parameters.

Despite the significant developments, this paper is an approach to model a FEA based model that capable to predict the dynamic behavior of workpiece-fixture, elastic deformation, stress and reaction force on fixture component by consideration of chip removal effects under the numerical simulated cutting force profile. A finite element model is an elastic contact model considering friction effect, where the materials are assumed linearly elastic. The contacts between fixture and workpiece are simulated as quadratic surface-to-surface contact. Static frictional coefficient is applied on contact area to simulate the frictional condition. Cutting profile numerically simulated and applied on the machining area. Chip removal is simulated based on element death technique in ANSYS commercial software. All of analysis accomplished in modal and harmonic mode. The flowchart of the proposed workpiece–fixture FEA methodology is shown in Fig.1.

The most common modeling and analysis approaches ignore the dynamic behavior of the workpiece-fixture system treats the workpiece-fixture system as quasi-static [13] to [16]. For example, Melkote et al [1] investigate the effects of various FEM parameters, such as friction and mesh density, on workpiece deformation.

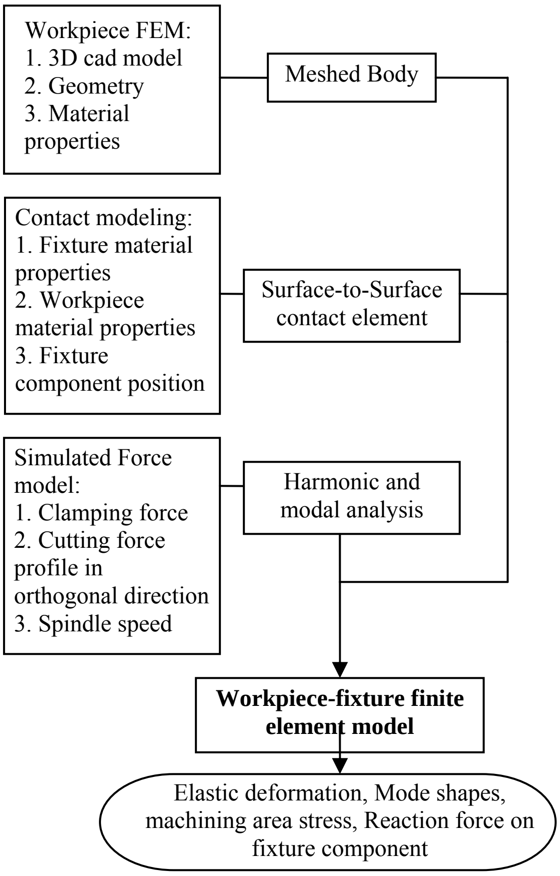


Fig. 1: Flowchart of the Proposed Workpiece–Fixture

Unfortunately previous researches that considered dynamic behavior of workpiece-fixture ignored the periodic nature of the time-varying cutting force. In such works, just the peak of cutting force was applied on the finite element model and profile of the periodic cutting force is not considered. Kaya and Öztürk [4] applied the peak of the cutting force in orthogonal direction on workpiece in FEA of modular fixture that included frictional contact.

In spite of excellent previous research, the common limitation of them is the fact that the modelling and analysis approaches used for fixture–workpiece systems include the rigid body approach. So in such case models incapable of predicting workpiece deformations and is therefore unsuitable for analysis of the impact of fixturing on part quality [4] and [6].Application of node-to-node contact in finite element modelling of some researches is a major cause of neglecting the frictional contact effects between fixture locators and workpiece. Other researchers have utilized linear springs to approximate the stiffness of the fixture components. However, such an approach requires the stiffness to be measured or approximated, adding time and introducing potential error into the analysis [1]. One of these rigid body-modelling approaches is [7]. In this approach, workpiece deformation measured accounting for chip removal effect, but they model contact as linear spring based on Hertz contact theory.

Other important object that effect the workpiece-fixture system is chip removal effect. Specifically, the mass, moments of inertia, the center of gravity, and the orientation of the principal inertia axes of the workpiece vary with time [3] during machining operation. So ignoring the CRE can have unsuitable impact on analyses. P. Radhakrishnan [8] studied the dynamic behavior of aerospace structure under high speed machining using finite element method but the chip removal effects ignored.

2. WORKPEICE-FIXTURE FINNITE ELEMENT MODEL

A computer-aided numerical methods are preferred for workpiece location analysis. The finite-element model recognizes possible contact pairs by the presence of specific contact elements. To investigate the validity of this assumption, analyses were performed in ANSYS 11.0 a commercial FEA software package. The element type used to mesh is SOLID45, which has eight nodes with three translational DOFs at each node and capable of supporting element death technique for simulating chip removal. A coarse mesh might yield inaccurate results. However, too fine a mesh might be unnecessary as well as computationally expensive [1].because of this reality SMRT smart meshing function of ANSYS was implemented to build solid mesh. All components in the system were modelled as isotropic elastic bodies. Fixture component (locators and clamps) modelled as spherical end cylinders. The contact between fixture and workpiece were modelled as surface-to-surface element. The element type that used in contact area is Target170 and static friction coefficient was applied to simulate the frictional condition in contact area. This type of modelling can simulate the micro slip and lift of in connection. To simulate the locators being rigidly fixed in place, the surface of each locator tip opposite to the contact was restrained in all three translational DOFs. A uniformly distributed pressure was applied over the surface of both clamps in opposite contact to simulate the desired clamping force.

In this paper, cutting forces are calculated according to the method presented by Sutherland and Devor [9]. The paper [10] used this method to optimize number of fixture locators around workpiece. In the tool axial direction, the end mill is divided into several segments, and the length of each segment is equal to that of each element in this direction. In order to calculate the cutting forces, each segment is divided into many equal axial slices. The cutting forces applied on each segment are obtained by summing up the instantaneous cutting forces acting on the slices at this segment. In the finite element model of the workpiece, the cutting forces are equally distributed on the four nodes of the corresponding element. The dominant excitation frequency in a milling process, which is of particular interest to this study, is equal to the tooth passing frequency and is given by:

$$FR = (Num.\quad of\quad flutes \times SpindleSpeed)/60 \qquad (1)$$

3. APPLICATION EXAMPLE

An example is provided to illustrate the application proposed system. The FEM and solution detail of example is presented as follow.

3.1. Workpiece geometry and properties

The geometry, feature under machining of the problem is shown in Fig. 2. The block is aluminium 390 with a Poisson ration of 0.3 and Young's modulus of 71GPa. The inner wall of the thick-walled box is undergoing an end milling process.

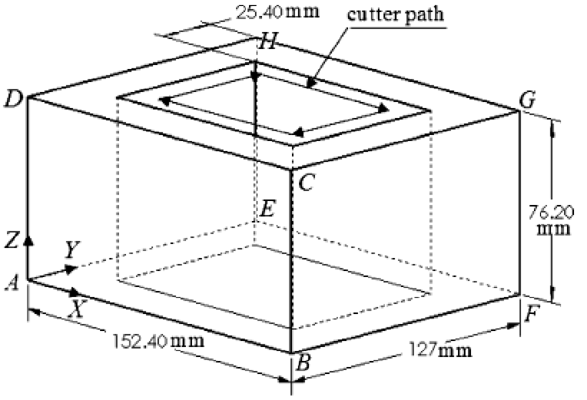


Fig. 2: The Feature under Machining and Position of the Cutter [8]

Table 1: Machining Parameters and Conditions [11]

Parameters	Descriptions
Type of Operation	End milling
Cutter Diameter	25.4mm
Number of Flutes	4
Spindle Speed	500
Feed	mm/tooth0.1016
Radial Depth of Cut	2.54mm
Axial Depth of Cut	25.4mm
Helix Angle	30

3.2. Machining operation simulation

A peripheral end milling operation is carried out on the example workpiece. The machining parameters of the operation are given in Table 1 To validate the approach according to published data in [7] the entire tool path is divided into 26 load steps and cutting force directions are determined by the cutter position. End milling cutting force in original direction of x, y and z are numerically simulated and is shown Fig.3. This force profile is applied on the four nodes near the machining area. Tree fourth degree function are used to approximate the cutting force profiles and coded to ANSYS. The approximated functions are:

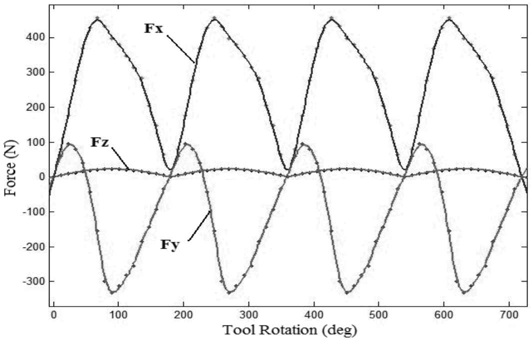
$$F_x = -102.63x^4 + 74.38x^3 + 367.34x^2 - 183.28x - 202.45 \qquad (2)$$

$$F_y = 6.48x^4 + 35.59x^3 - 188.65x^2 - 79.66x - 423.74 \qquad (3)$$

$$F_z = 0.68x^4 + 0.088x^3 - 10.75x^2 - 0.53x - 22.57 \qquad (4)$$

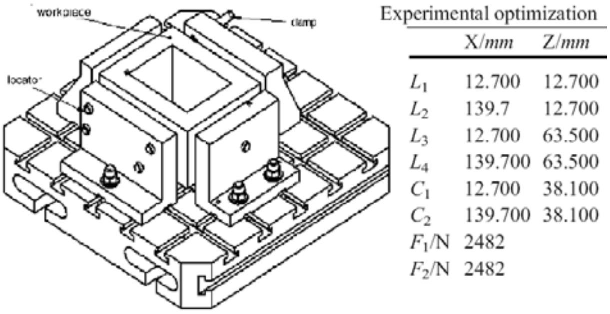
3.3. Fixture design plan

Weifeng Chen [7] experimentally optimized a fixture design plan to hold the block against the machining operations. The fixture plan for holding the workpiece in the machining operation and coordinate bounds for the locating/clamping regions are shown in Fig.4.



Z

Fig. 3: Simulated Cutting Force Profiles



Experimental optimization

	X/*mm*	Z/*mm*
L_1	12.700	12.700
L_2	139.7	12.700
L_3	12.700	63.500
L_4	139.700	63.500
C_1	12.700	38.100
C_2	139.700	38.100
F_1/N	2482	
F_2/N	2482	

Fig. 4: The Fixture Plan [7]

3.4. Dynamic analysis

3.4.1. Harmonic and modal anlysis

Dynamic characteristics of workpiece-fixture system can achieved through dynamic (harmonic and modal) analysis. The effect of dominant excitation of frequency in milling process , which is determined by the spindle speed and number of cutter flutes on the elastic deformation and vibration of workpiece-fixture are measured by implementing modal analysis. The experimental design results related to maximum elastic deformation along tool path in machining area reported in [7] is quoted for comparison and validation. These two set of results are derived through different approaches. As shown in fig.5, 92.4% compatibility presents the accountability of the method used in this study.

3.4.2. Work holding base on 3-2-1 principle

In the fixture plan proposed by approach [7], conventional methods for fixturing work holding prismatic parts is remarkably simplified. Therefore, to implement the current methodology and investigate its possible limitations a more practical plan is advised. It uses the conventional principle 3-2-1 for prismatic parts.

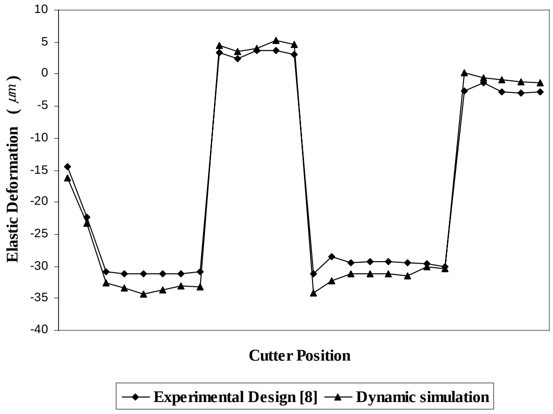
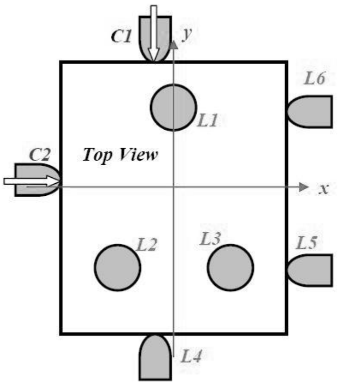


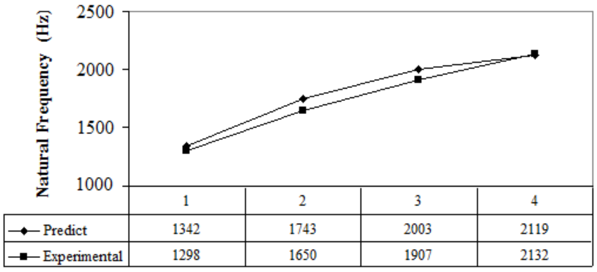
Fig. 5 : Comparison of elastic Deformation along tool path between two methods



Fixture Element	Coordinate (x, y, z) (mm)
L1	(0.97, 54.1, -38.1)
L2	(-44.75, -64.26, -38.
L3	(45.09, -64.26, -38.1
L4	(-16.51, -76.2, -0.51
L5	(63.5, -46.23, -0.38)
L6	(63.5, 55.63, 0)
C1	(-1.52, 76.2, 0.51)
C2	(-63.5, 5.08, 1.02)
C3	(0, 0, 38.1)

Fig. 6: 3-2-1 Fixture Design[3]

The same workpiece and coordinates of these fixture elements based on a fixture design in paper [3] is shown in Fig.6. The harmonic and modal analyze is applied on this fixture design plan. The instantaneous forces for the milling force model derived form [12]. Fig. 9 shows the cutting force in three orthogonal directions for a double tool revolution (720^0). The mode shapes of workpiece-fixture modal analyze are shown Fig. 7 and compared to the experimental data that published in paper [3].



	1	2	3	4
Predict	1342	1743	2003	2119
Experimental	1298	1650	1907	2132

Fig. 7: Comparison of Natural Frequency Simulated vs. Experimental [3]

Error between experimental data and simulated data is about 4.3% that, this is shown the good agreement between the FEA modelling and experimental data. The result of harmonic response at the first and last machining operation is shown in Fig. 8. Correspond to the three groups of natural frequencies of the workpiece-fixture system there is the three resonance regions in plot. At the end of machining operation because of the workpiece losses material, the natural frequencies of workpiece-fixture system are increased and became separated.

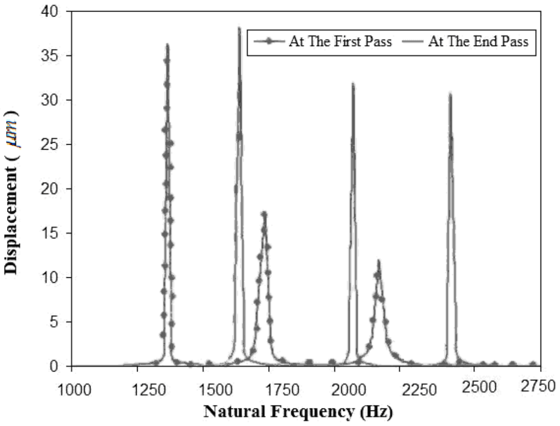


Fig. 8: Displacement vs. Natural frequencies

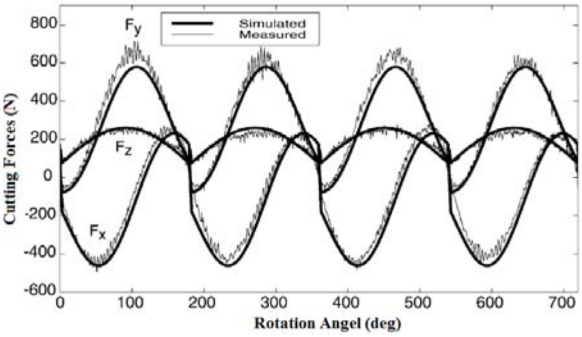


Fig. 9 : Simulated Cutting Force 1 [12]

3.4.3 Fixture stability

The stability of the fixtured workpiece during machining can be analyzed by determining the status of the interaction between the workpiece and fixture elements at each contact. By applying the machining force on the workpiece, it is necessary to ensure that the normal forces at the contact elements are negative all the time. Any zero normal force indicates that the workpiece is free from the fixture elements. The reaction normal force at the locators is given in Fig.11 to 12. It is shown that there is no separation at the supports and locators. All the reaction forces are positive, and contact is maintained during machining.

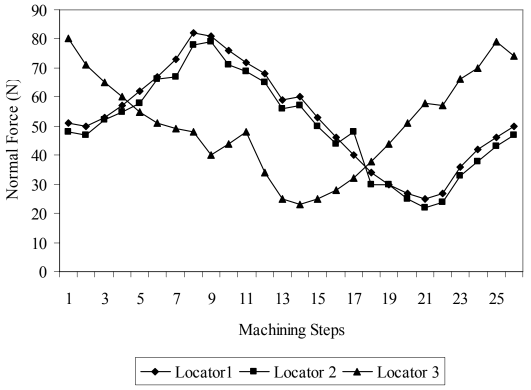


Fig. 10: Reaction Force on Locator 1 to 3

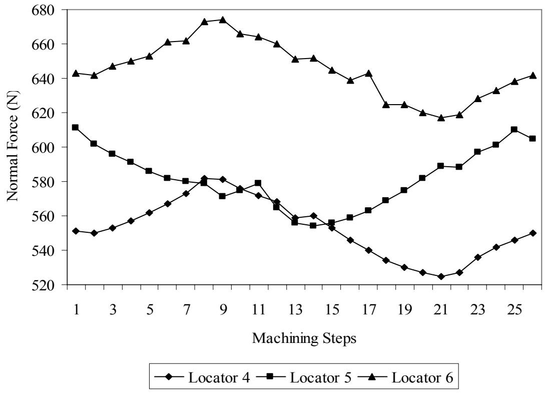


Fig. 11: Reaction Force on Locator 4 and 6

4. APPLYING THE ADAPTIVE MASHINING FORCE

Consideration of MRE is crucial for an accurate analysis of the fixture workpiece system dynamics when a significant portion of volume is removed in the machining operation. The MRE can be broken down into several sub-effects resulting from the change in system inertia, stiffness, geometry, etc. Significant material removal affects the fixture-workpiece system stiffness via the following changes: i) change in the fixture-workpiece contact stiffness due to change in workpiece weight and the (*xyz*) frame; and ii) change in workpiece structural compliance evaluated at the fixture-workpiece contacts. The effect of chip removal consideration on finite element analysis is shown in Fig.13. It is see that there is about a 17% increase in stress values near the cutting area compared to the analysis, which does not consider chip removal effects. After the reducing the material in first steps of operation applying the cutting force that have smaller peak value in orthogonal directions, at the subsequent passes of machining operation could be useful to reducing the effect of chip removal on increasing the stress value on this passes. In this study, the force profile shown in Fig. 9 that derived from [12] is applied on first 13 step of machining and the machining force profile in Fig.10 with the smaller cutting force[12] is applied on the rest steps of machining. As shown in Fig. 13 the stress values in the first 13 steps are the same but it is clear that by controlling cutting forces along tool path the stress values near the cutting area reduced in about 4.3%.

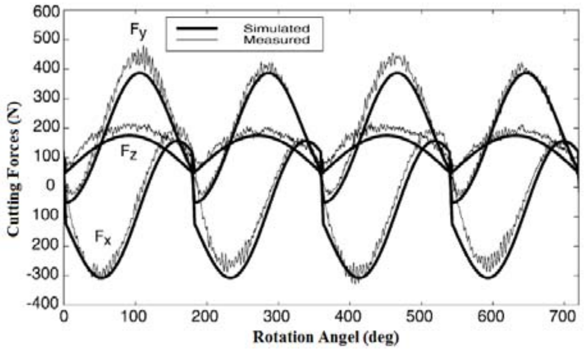


Fig. 12: Simulated Cutting Force 2 [12]

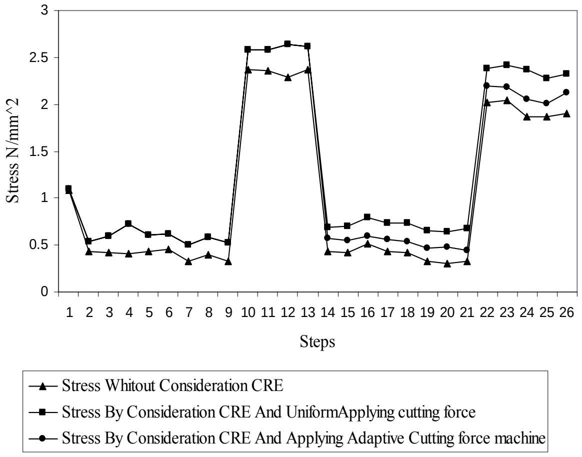


Fig. 13 :Applying Adaptive Cutting Force

The system analyzed in this research, as material is removed, the modal frequencies resulting from the fixture-workpiece contact compliance grow slightly and become separated while those arising from the structural compliance of the workpiece decrease significantly. By decreasing the workpiece compliance applying high clamping force that implemented on the first passes of machining operation is not only unnecessary ,but also could be a source of damages on the contact areas between locators and workpiece. Table 2 compares the predict modal frequencies of system in first pass and last pass of pocketing operation with different clamping force in last pass and their predicted maximum elastic deformation along tool path. As shown when a main portion of material is removed on last pass applying the constant clamping force result in increasing the system stiffness and the natural frequency. The other advantage in reduction of clamping force is that the stress on workpiece on locator areas are reduced. Fig.13 in other hand by changing the natural frequency according to material removal and reduction of clamping force applying a suitable spindle speed that have good distance from natural frequency of the system can reduce the value of peak to valley and high quality finished parts.1332 Hz and 1665 Hz are the four and five times the tool passing frequency. As listed in Table 2 by the clamping pressure used in case 1 is 3000psi on all machining passes while that is 2500psi in case 2. As a result, by reduction of clamping force on last pass in case 2 because, the part lost main portion of material the maximum peak to valley in entire tool paths in case 2 is not mush higher that case 1. It is clear that in case 3 by applying the smaller clamping force and changing the spindle speed according to the natural frequency of system that have suitable distance from natural frequencies and avoiding from resonance areas, the maximum peak to valley can be reduced to 31.23. so applying adaptive machining parameters according to dynamic behaviour of workpiece fixture system is directly affects the operational safety and part quality.

Table 2: Effect of diff. mashing parameter on surface quality

mode	Pass	C.F	S.S.	Stability	Na. Freq	Peak to valley
1	First Pass	3000	5000	✓	1315, 1690, 1922	37.34
	Last Pass	3000	5000	✓	1430, 1834, 2146	
2	First Pass	3000	5000	✓	1315, 1690, 1922	38.42
	Last Pass	2500	5000	✓	1398, 1788, 2050	
3	First Pass	3000	5000	✓	1315, 1690, 1922	31.23
	Last Pass	2500	4500	✓	1398, 1788, 2050	

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