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Novel Technique for Reducing Geometrical Inaccuracies of Clamped Workpiece During Machining: A Hybrid Method

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Abstract. The aim of this paper is to provide a novel technique in production technology, which ensures the adequate tightening torque of workpiece by a vise connector to minimize the effect of elastic deformation, therefore geometrical inaccuracies roughness, during machining process. This effect emerges if the clamping force is excessively high, resulting in a deformed workpiece with a slightly convex surface. Once this surface is machined and the clamping force is released, the material returns to its initial shape and the newly machined flat surface will be concaved, resulting geometrical inaccuracy. The method is based on a simple workpiece, where the elastic deformation is numerically modelled and experimentally measured as a function of different clamping heights and tightening forces. During the experiments, the workpiece is tightened by bolts, step by step, and in each step, the deformation of the surface is measured with a coordinate measuring machine equipped with a Touch Probe Measurement system. This measurement process is followed by finite element modelling, where the same system, with identical boundary conditions (load, constraints, material properties), are computationally created to compare the numerically and experimentally obtained results. As a result of evaluating various cases, a user-friendly database was established that provides recommendations for specific geometry, position, and capture height. Our model can also propose a minimum clamping height if geometry, position, and maximum force(s) are specified during machining.

Keywords. Workpiece clamping, elastic deformation, touch probe, finite element analysis

1. Introduction

Nowadays the number of small and medium sized manufacturing companies is continuously growing. Those enterprises mostly have 1-25 pieces of different manufacturing equipment. These companies are facing with many different customer needs, not just related to the workpieces either in the serial numbers too.

This study is a preliminary study for the optimization of a special clamping system, and during the experiments it was focused to the universal usability of the values. The results of the analyses can be uploaded to a MES or a simple company standard database.

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A fixture is a holding device, which is used in supporting and positioning the workpiece in an exact location and orientation during manufacturing process relative to a cutting tool or measuring instrument or relative to another workpiece [1]. As fixturing plays an important role in manufacturing processes, it also creates new challenges in achieving high quality and efficiency in manufacturing.

The holding of raw materials by the vise causes elastic deformation on the workpiece if the stiffness in the direction of the clamping force is low, which convex the surface. The problem appears after machining, once the clamping forces are released, the material will return to its original shape and the newly machined flat surface will be concaved, resulting geometrical inaccuracy [2]. The workpiece deformation can be avoided or set to minimum by using appropriate clamping methods and parameters, like adjusting the number and location of locators and clamps and use ideal machining and clamping forces [3]. During the machining process, the workpiece undergoes deformation due to cutting and clamping forces, resulting in machining inaccuracies. If these inaccuracies exceed predetermined tolerance levels, the workpiece becomes unusable [4].

2. Methods

2.1. Calculate of parameters for analytical solution

The machining and clamping forces can be calculating analytically to determine the ideal forces which can eliminate the deformation. The machining force is affected by the cutting speed, feed rate, and the depth of cut, tool diameter hardness of the metal and it or its surface, geometry of the tool and the workpiece, machining strategy etc. [5]. Asante in his research work studied the influence of fixture compliance and cutting parameters on workpiece stability. The evaluation involved assessing the minimum eigenvalue of the fixture stiffness matrix, representing minimal displacements at contact points, and analyzing the largest workpiece displacement induced by cutting forces to gauge stability. [6]

The vise provides the clamping force by the trapezoidal thread which in this case uses TR24x5 Thread. The total loading torque calculations for the trapezoidal thread is shown in equations (1) to (6) where; α, lead angle [°], p', friction angle [°], β, thread angle [°], p, pitch [mm], d¬a, nominal diameter [mm], d2, pitch diameter [mm], μ', effective friction coefficient [-], F0, applying force [N], T, total torque [Nmm], Tm, torque generated by applying force [Nmm], Ta, torque due to frictional forces [Nmm].

$$\alpha = arctg\left(\frac{p}{d_2 \cdot \pi}\right) = arctg\left(\frac{5}{21.4 \cdot \pi}\right) = 4.2533° \tag{1}$$

$$\mu' = \frac{\mu}{\cos\left(\frac{\beta}{2}\right)} = \frac{0.13}{\cos\left(\frac{30°}{2}\right)} = 0.1035\ [1] \tag{2}$$

$$p' = arctg(\mu') = arctg(0.1035) = 5.9106° \tag{3}$$

$$T_m = F_o \cdot \frac{d_2}{2} \cdot tg(\alpha + p') \tag{4}$$

$$T_a = F_o \cdot \mu \cdot \frac{d_a}{2} \tag{5}$$

$$T = T_a + T_m \tag{6}$$

2.2. Computer aided engineering solution

In the FEM analyses there was a big question related to components of the workpiece deformation. Outlined a processing methodology, which was developed on the concept of minimizing total residual energy. Finite element method simulations were employed to analyse the interaction between contact forces and workpiece deformation. The study revealed that factors such as clamping force magnitude, point of application, and tightening sequence have significant impact on workpiece deformation [7]. Branko Tadic and his team presented an investigation, where they considered an enormous number of previous knowledges related to the effects of clamping forces [8]. They measured cones and find out, that the differences of real measurements and FEM model were distorted by the effect of friction forces, but in their case the workpiece had higher load of torque than in our study. Based on their values in our case we used $\mu=0.14$.

Material model for Ansys simulation: A linear material is created in Ansys as the deformation due to clamping will act only in the elastic region, and the following properties were set density 2770[kg/m^3], Young's Modulus 70[GPa], and Poisson's ratio 0,33, according to the average values of the aluminium alloy "AlMgSi1". Aluminium is widely used in industry and CNC machining due to its machinability and this alloy was selected for the experiment because it is commonly used in engineering applications.

Simulation used a simplified version of the vise and the magnetic sheet metal, which is attached to it to provide the support to the workpiece. The force provided by the trapezoidal thread in the vise is applied to provide the clamping. The magnitude of the force can be calculated based on the used torque, using eq. (7) which is the result of combining eq. (4) to (6). In this equation the clamping force is known after providing the torque 'T' and the Thread diameters 'da' and 'd2' and the result of eq. (1) and eq. (3).

$$F_o = \frac{2 \cdot T}{d_2 \cdot \tan(\alpha + p') + \mu \cdot d_a} = [N] \tag{7}$$

2.3. MM measurements

Coordinate Measurement machines are widely spread across the industrial quality assurance and measurement processes. The main geometrical and material properties of workpieces are shown in Table 1. During the tests a lates generation Coord3 Universal 10/7/7 machine was used, which operates with RENISHAW system. This setup enables the machine to scan the surfaces with the stylus (Fig. 1). The scanning and touch trigger module was a SP25M, which is allowed to use on straight lines, sweep movements and free-form surfaces too [9]. At the first test the used stylus ball was a typical industry standard material, the ruby, but in this case the ball bounced on the specimen's surface, causing vibrations to the results, and based on the suggestions of producer, we changed to SIN material ball [10].

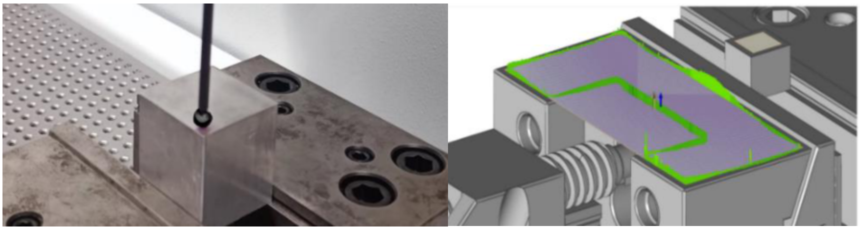

Figure 1. CMM measurement setup and scanning in CMM's built in Touch DMIS system

Table 1. Materials and geometrical properties of the workpieces

Wp. no.	Bar Dimensions (mm)	Wp. Length (mm)	Measured Dimension (mm)	Model Dimensions (mm)
1.	ALU6082 20x20	21 ±0.3	20.75 – 20.85	21x20x20
2.	ALU6082 20x20	40 ±0.3	39.85 – 39.95	40x20x20
3.	ALU6082 20x20	60.5 ±0.3	60.55 – 60.70	60.5x20x20
4.	ALU6082 40x40	41 ±0.3	40.9 – 41.15	41x40x40
5.	Steel 41x14.5	59.5 ±0.3	59.25 – 59.35	59.5x41x14.5
6.	Steel 59.5x14.5	41±0.3	41.00 – 41.10	59.5x41x14.5

Based on the industry standard ISO 10360 [11] the measurements were performed on a constant 21 +/- 1°C temperature. The used vise and workpieces were more than 8 hours between these circumstances in order to avoid the temperature difference caused issues. The used workpieces were sawn from a 3 m extruded long rod, so the end surfaces were sawn, but the surface, where the measurements were performed had the original cold rolled surface.

In case of the select of the vise the main viewpoint was to find a universally and widely used equipment. The selection was a Gerardi StandardFLEX vise with 24mm screw diameter and pitch 5mm. To ensure the different torque level steps an industrially used ½ inch torque wrench with push-through square drive and fine-toothed ratchet head. This ensured the range from 40-250Nm.

In the FEM simulation, A simplified geometry of the vice and the workpiece was created, and the vice body were assumed to be a rigid body and the workpiece is flexible body and the material model of the aluminum alloy "AlMgSi1". Then a mesh sizing of 3 mm and a mesh type were set to Tetrahedrons. The model which was used in the simulation is shown in Fig. 2. The first jaw was fixed on one side using a remote displacement and the other jaw was free to move only on the Z axis using another remote displacement then a remote force was applied on the second jaw allowing it to move and apply the clamping force on the workpiece.

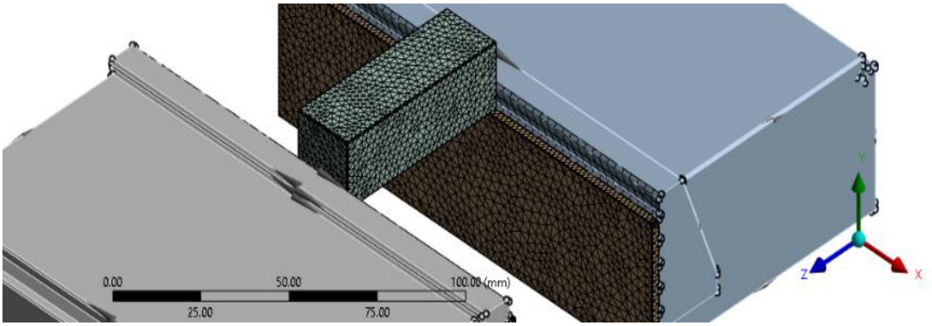

Figure 2. FEM Meshing

3. Results

The measured points for the surface of the workpiece and the sliding jaw side of the vise with the different clamping torque were combined as shown in Fig. 3.

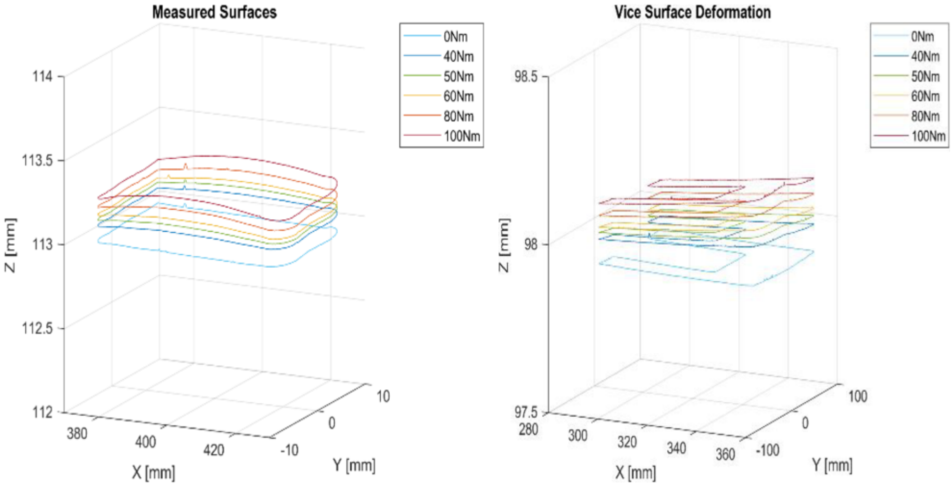

Figure 3. CMM scan results of the measured surfaces, workpiece and moving jaw.

Compare the two graphs it first appears, that, next to the workpiece deformation the jaw of the vise has got a huge deformation too. This is very interesting, because the strength properties of the workpiece and jaw are very different.

The results show the increase of the convex phenomena appearing on the surface of the workpiece by increasing the tightening torque.

It also shows a translation upwards in the positive direction of the z axis. It can be seen more clearly in the view in Fig. 3 as it is going almost a constant amount for every 10 Nm of torque.

Few points also appear with peaks on the measured path which is a wrong measured values from the CMM which the algorithm eliminate these values in the report. This is very important step, because these random points have got a huge effect on the scanning line.

The results show (Fig. 4) that the deformation of the workpiece is linear on the whole surface, and only at 100Nm seems a difference between the side of the jaw and the workpiece. This is normal, because the moving and stabile jaw has got different effect on the workpiece clamping. The random peak values are constant, these were resulted by a surface error which occurs during the whole report. In case of use the values as a basic for advanced statistical model, should be removed these peak points from the data. These values are usable to compare the FEM simulation with the real deformations. Fig. 3 shows the comparison of the workpiece deformation and lifting the surface in direction of Z. Here it can be seemed, that in case of longer workpiece the deformation is significantly higher than the lifting of upper surface in direction Z. The graphs are good comparison between the simulated values, starting from 0, because the flatness is perfect, and the measured values where are geometrical inaccuracies from the beginning.

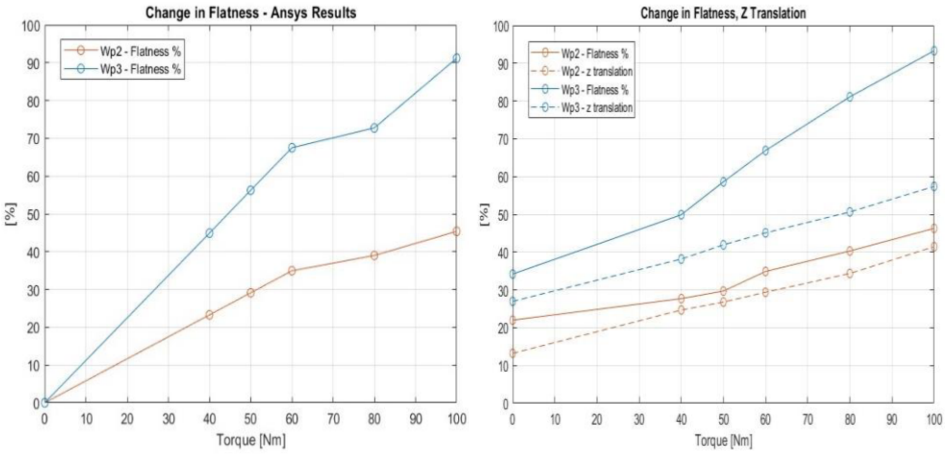

Figure 4. Torque and force values with deformations of Z axis for the workpieces 2 and 3

By comparing these results with the results of Schoppe et al. [12] where they simulated the flatness changes caused by the cutting forces and when they compared their measured results with their FEM results, they had an almost constant difference between both which they concluded the to be linear in our study there was also a linear relation between both the measured and the FEM results which we concluded to be the change of the Z offset as a constant value.

The CMM measured results in Table 2 shows not only the convex of the workpieces which affected the flatness but also existence of translation in the positive direction of z axis, which still needs to be considered separately. As the simulation results shown in Table 2 resulted only the convex of the surface which determined the effect of the clamping torque of the flatness of the workpiece. By comparing the measured and FEM results shown in Table 2, high similarity appeared between the simulation and the measured surface. Wp2 and Wp3 both made out of 20x20 aluminium bar and they are 40 mm and 60 mm long respectively.

Table 2. Comparison of FEM simulation and measured values of the workpiece 2 and 3

M [Nm]	**F** [N]	**Wp 2**			**Wp 3**		
		Sim. def. [mm]	Meas. def. [mm]	Sim. disp. z [mm]	Sim. def. [mm]	Meas. def. [mm]	Sim. disp. z [mm]
40	12800	0.02328	0.0277	0.1147	0.04492	0.0499	0.1120
50	16000	0.02911	0.0297	0.1357	0.05624	0.0586	0.1495
60	19200	0.03494	0.0349	0.1617	0.06750	0.0669	0.1813
80	25600	0.03898	0.0403	0.2114	0.07274	0.0811	0.2366
100	32000	0.04539	0.0463	0.2823	0.09120	0.0933	0.3042

The FEM analysis results show that the deformation of workpiece is fully constant and symmetrical, there is no difference between the moving and stabile jar.

The model is an ideal model, and not considering this acting of the vise. It was a decision, because deviation appeared only at higher torque values, where the workpiece reached a value which can cause an out of tolerance effect. This called a hybrid method as the results of the analytical solution, FEM solution, and Measured solution needs to be combined to make a database where it is usable to determine the ideal clamping torque and position to result an expected known workpiece deformation which can eliminate the unnecessary overload of our manufacturing system. The results of the Ansys simulation can be validated after the comparison with the measured results and the similarity between them.

A conclusion can be made from these values which is the simulation only misses the value of the surface translation which is resulting from the tightening torque. These results are important because it's putting outlines for more realistic simulations in the future to determine the actual deformation of workpieces in industry.

4. Conclusions

In ideal case the clamped workpiece should have a flat surface. The research introduced a method which combined the measurement of CMM with FEM simulation to agile use a typical small or medium sized company's resources to effectively present the effect of torque on workpiece deformation. During the CMM measurements there were performed probe scanning measurements to see the elastic deformation of the workpiece and vise jaw. The research showed the effect of torque on workpieces deformation and how it can significantly affect the accuracy of the machined parts. Ansys simulated a change in the surface flatness of the workpiece as the surface convex, by changing the clamping torque. The amount of deformation also changed based on material, workpiece cross section and length. The measurements validated the simulation results as the flatness changed accordingly but also showed a translation of the surface upwards (in Z axis) which was almost a constant amount for every extra 10 Nm of clamping torque as measured. Which needs to be considered also in the simulations to be identical to reality. Also, the effect of hammering the workpiece was measured as it showed translation of the surface downwards (in Z axis) by few microns parallel to its original location. By calculating the machining force, we can determine the proper clamping force therefore the torque and reduce the effect of extra tightening on the workpiece.

Based on the results of the study there is a possibility to prepare a useful database with proper steps in order to ensure the right torque values for the predefined tolerance field due to machining forces. This can be uploaded into the company's MES or any standardised database and should be well maintained. These results and experiments are well usable for the follower studies, where more complex part will be examined.

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