Abstract: The paper presents the automation of analysis and verification process of clamping devices, suitable for fixing of thin-wall workpieces. These workpieces will likely undergo deformations due to clamping and cutting forces during machining, which are the result of inconsiderate fixture design. An automation program has been made for the evaluation of fixtures intended for clamping of prismatic and rotational products, for determination of the optimum magnitude and positioning of clamping forces, required to enable the workpiece to be safely clamped during machining. The automation procedure ensures reduction of fixture planning process and prevention of defects and deformation during the machining process.

Key words: fixtures, milling, automation, clamping force.

1. INTRODUCTION

The developed system is of great importance for designing fixtures since it can routinely determine within a short time the optimum sizes, direction and application points of clamping and locating forces for different cases of clamping. The purpose of the procedure is to improve the design of fixture and thus to increase the geometrical accuracy of the thin-wall product made. Designing of fixtures is a complex and intuitive process for which an experienced technologist is required. For each workpiece there are several possible solutions of the design of modular fixtures, therefore the scope of possible solutions is large.

The development of the artificial intelligence has contributed to limiting the scope of possible solutions and, consequently, to achieving better designs. Developed automation procedure (Figure 1) contains the fixture design, analysis, optimization and simulation module. The highly capable structure offers also the possibility of rationalization and visualization of the fixture solution obtained. It is important to consider the cutting forces, the clamping forces, the friction forces and the dimensions and availability of fixtures as well as the space on the machine limiting the possibility of clamping. The designing and manufacturing costs of the fixture amount even to 18% of the total production costs [1]. In addition to searching for the mathematical solution for positioning and clamping of workpieces the development is oriented towards searching for the solutions by means of the computer routine. Researches [2] proposed the model “workpiece-fixture” based on the screw theory and used the linear programming method for determination of clamping forces. By the use of the non-linear programming method the quadratic model for verification of the fixture configuration is derived [3]. Mittal [4] proposes the dynamic model “fixture-workpiece” for the determination of the required clamping forces ensuring the equilibrium of the workpiece during machining. All the above mentioned methods use simplified models which do not take the friction into account in their calculations [5].

2. ASSUMPTION IN MAKING THE AUTOMATION PROCESS

When making the automation programme it was assumed that the workpiece would be fixed by a flexible modular fixture ensuring clamping of workpieces of different shapes. The worked out programme works on the (industrial computer) IPC and is programmed in the C++ programme language. The developed programme determines [6]:

- Minimum number and position of locating and clamping elements,
- Motion allowed by locating elements,
- Reactions at the places of the contact “workpiece-fixture” (locating forces),
- Minimal clamping forces required for balancing of cutting forces,
- Collision detection system,
- Fixture cost calculation system,
- The cost of fixture automation (pneumatic in combination with hydraulic) [7],
- Animation of fixture assembling, machining [8],
- Visualization of clamping control.

The clamping forces on the workpiece must not create internal stresses and must not damage or deform the workpiece surface. This argument affords great importance to the model made since it specifies the minimum required clamping forces, their application points and orientations with which the workpiece is still safely clamped. The purpose of the Force analysis is to find out whether the workpiece will lose the contact with the locating and positioning elements during machining due to cutting forces and moments.

3. CLAMPING SCHEME ANALYSIS AND OPTIMIZATION

The scene is more complex when friction between
the workpiece and fixture is taken into account (Fig. 2).

Fig. 1. Block diagram of the automated system for selection, analysis, optimization and visualisation of fixtures.

Fig. 2. Forces on workpiece during the milling process
Where:
- \((F_1, F_6)\) - reactions acting on locating elements (N)
- \((C_1, C_2, C_3)\) - clamping forces acting in the direction of the normal onto positioning planes (N)
- \((F_i, F_x, F_y)\) - components of cutting force \(F_i\) (N)
- \((M_c, M_y, M_z)\) - components of cutting moment \(M_c\) (Nm)
- \(f_i\ (i=1...6)\) - resulting friction forces in contact points (N)
- \(F_{fr}\) - force of workpiece weight (N)
- \(\mu\) - friction coefficient

In general when the friction forces are taken into account, the number of unknowns is far more than that of the equilibrium equations. In order to solve for clamping forces the case must be simplified, and an iteration method is used in the force analysis routine. The workpiece is located on the six-point \(P_1-P_6\), and an iteration method is used in the force analysis routine.

The workpiece is located on the six-point \(P_1-P_6\), and the equilibrium equations are written in matrix form:

\[
[A]_{lok} \cdot [F]_{lok} + [w] = 0
\]  

The normalized geometrical matrix \([A]_{lok}\) is as followed:

\[
[F]_{lok}^T = [F_1 \ F_2 \ F_3 \ F_4 \ F_5 \ F_6] \quad (5)
\]

Because of the numerical solving of the problem the equilibrium equations are written in matrix form:

\[
[A]_{lok} \cdot [F]_{lok} + [w] = 0
\]  

The normalised geometrical matrix \([A]_{lok}\) and the vector of external forces \([w]\) into the Equation 3 the clamping and locating forces are calculated.

The normalized geometrical matrix \([A]_{lok}\) and the vector of external forces \([w]\) are as followed:

\[
[A]_{lok} = \begin{bmatrix}
    f_{x1} & f_{x2} & f_{x3} & -1 & -1 & f_{x6} \\
    f_{y1} & f_{y2} & f_{y3} & f_{y4} & f_{y5} & f_{y6} \\
    1 & 1 & 1 & -f_{x2} & -f_{x3} & -f_{x6} \\
    r_{y1} & r_{y2} & r_{y3} & -f_{y4} \cdot r_{y2} & -f_{y5} \cdot r_{y3} & -f_{y6} \cdot r_{y3} \\
    -r_{x1} & -r_{x2} & -r_{x3} & -f_{y2} + f_{y4} \cdot r_{x2} & -f_{y3} + f_{y4} \cdot r_{x3} & +r_{x3} \\
    -f_{x1} \cdot r_{x1} + f_{y2} \cdot r_{x2} & -f_{x2} \cdot r_{y2} + f_{y3} \cdot r_{x3} & -f_{x3} \cdot r_{y3} + f_{y4} \cdot r_{x4} & +r_{y4} & +f_{y5} \cdot r_{x5} & +r_{x5} \\
    +f_{y5} \cdot r_{x5} & +f_{y5} \cdot r_{x5} & +f_{y5} \cdot r_{x5} & +f_{y5} \cdot r_{x5} & +f_{y5} \cdot r_{x5} & +f_{y5} \cdot r_{x5} \\
\end{bmatrix}
\]  

\[
[w] = \begin{bmatrix}
    f_{y1} + f_{y3} + C_2 + R_x \\
    f_{y2} + f_{y4} + C_3 + R_y \\
    -f_{y2} - f_{y3} - F_y + R_z \\
    -f_{y2} \cdot r_{y2} + f_{y3} \cdot r_{y3} + f_{y4} \cdot r_{y4} + C_1 \cdot r_{y2} - C_1 \cdot r_{y3} - C_1 \cdot r_{y4} - F_y \cdot r_{y0} + M_y \\
    -f_{y2} \cdot r_{y2} + f_{y3} \cdot r_{y3} + f_{y4} \cdot r_{y4} + C_2 \cdot r_{y2} + F_g \cdot r_{y2} + M_y \\
    -f_{y2} \cdot r_{y2} + f_{y3} \cdot r_{y3} + f_{y4} \cdot r_{y4} + C_3 \cdot r_{y2} + C_3 \cdot r_{y3} + C_3 \cdot r_{y4} + M_z
\end{bmatrix}
\]
The Equation 3 is suitable for further numerical solving. The system has the non-trivial solution when the determinant of the system is: $\det[\mathbf{F}] \neq 0$.

By the iteration procedure the Equation 3 is solved; thus the minimum required clamping forces are calculated. The iteration starts with the initial value of clamping force $C_j=0$, $j=1,2,3$, afterwards this value gradually increases incrementally, until all forces $F_i$ are positive. In this way we reach the basic-fundamental solution of the problem. The obtained values of $C_1$, $C_2$ and $C_3$ will be the first set of possible solutions. The basic solution can be optimised in this following way: The value of the basic solution is adapted to the first clamping force whereas the values of the others are gradually increased incrementally until all the calculated locating forces are positive. Then the procedure is repeated for each clamping force.

5. RESULTS AND MODEL EVALUATION

The tests confirmed correctness of the results of the propose automated system. The deviation of the predicted forces from the actual forces is slightly greater only in case of very little coefficient of friction ($0.01 \leq \mu \leq 0.2$) between the workpiece and the fixture. We tried to compensate the deviation of the predicted results in the mathematical model itself, but the corrections made did not improve significantly the values of the predicted forces. Therefore the required correction was made by introducing the artificial neural network into the model.

By using the artificial neural network (ANN) all the influencing factors, not taken into account in the equilibrium matrix equation, are included [9]. Five-layer feed-forward neural network was used. It contained 18 neurons in the input layer, and 9 in the output layer. The input vector consists of components of cutting forces, co-ordinates of point of machining, co-ordinates of position of the clamping and supporting parts, workpiece weight and friction coefficient. The output vector contains 9 corrections factors by which the values of the calculated forces are multiplied. Training was performed with the help of the error back-propagation. The training was supervised; the desired outputs (the nine clamping / locating forces) of the ANN are also being supplied during training.

Training of the ANN was made with experimental data of 1500 full training examples. Additional 800 examples were used to test the trained network.

The data for training and testing are obtained from the experimental measurements on the fixtures already made. Due to the introduction of the ANN the accuracy of the predicted forces was improved for 94% in case of $\mu<0.3$ and for 4% in case of $\mu>0.3$. The average estimation error was about 7.4% which is low compared to the 12.7% estimation error of the analytical model.

6. CONCLUSION

A automation system is presented that considered the effect of frictional forces for verification, rationalization and improvement of a fixture design.

A new iteration method is introduced for determining the clamping and locating forces at more reasonable level. By the system developed we have significantly reduced the time of conceiving the fixture (18%) and we have reached a greater manufacturing accuracy.

By the described model it is possible to anticipate and prevent the defects on the workpiece, fixture and cutting tool during the clamping and machining process.

In the research it has been found out that by taking the friction into account the value of the required clamping force as well as the number of the required clamping elements are strongly decreased.

Automated procedure enables even the inexperienced technologist to prepare high-quality (optimal) fixturing schemes.

7. REFERENCES


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