1. INTRODUCTION

Flexible fixturing has a strong potential to reduce capital-investment costs by as much as 30% per machining system [1]. In standard production the classical fixtures are controlled and monitored by operators. In Intelligent Fixturing System (IFS), fixtures must work automatically, without operator intervention and cooperate with other devices of production system. The main elements of the IFS include a vision system, a universal clamping system, a part location system, and a micropositioner that positions the fixture so that the workpiece is precisely aligned with the machine tool's axes. The process begins when a part is loaded on a pallet and moves to a vision station. The vision station identifies the part and communicates part details to the appropriate stations that will be required to process it. A manipulator removes the part from the vision station and inserts it in a flexible workholding fixture. No effort is made to precisely locate the part in the fixture. After the part is secured, the entire fixture is transported to a station that locates the spatial position of the part. Accordingly, the part location data is communicated to a device called a Part Micropositioner, which adjusts the fixture to bring the part into the desired position [2]. Finally, the adjusted fixture is transferred via conveyor to a machining cell.

Intelligent clamping fixtures besides the base functions provide also some “intelligent” functions: control of clamping forces/torques acting on workpiece, monitoring of clamping operations and elements of fixtures [1], readjustment of locators and change of clamping elements [3]. The aim of force control is to decrease the workpiece deformation and workpiece surface damage. Typically, once a workpiece is being fixed in the fixturing system, the clamping forces applied to the workpiece are not changed during the entire machining. The application of clamping forces has been largely experience-based. Improper or inadequate fixturing process could result in elastic/plastic deformation, and static/elastic displacement that can significantly affect the final part accuracy. On the other hand, insufficient clamping may permit the part to slip or detach from the locator during the machining process, causing the fixturing system to lose its effectiveness. Especially in cases of machining of thin-walled and large-size aerospace components and other precision components, deformation and distortion can be minimised by optimising the location and magnitude of clamping forces. At some positions along the tool path, small forces may be adequate, but large forces may be required at others. Hence, our attention is focused on the force distribution. In an ideal intelligent fixturing system, both the location and magnitude of clamping forces have to be controlled in real time depending upon the geometry of the workpiece and cutting forces. The major disadvantages of an intelligent fixturing system where both location and magnitude of clamping force are controllable are very high cost and limited accessibility to the workpiece [4]. Another more cost-effective approach is to use off-line optimisation of the location of the clamps and on-line optimisation of clamping force magnitude. An attempt was made to design an Intelligent Fixturing System (IFS) such that the fixture elements can be manipulated to provide dynamic clamping forces during the entire machining and fixturing process. For the proposed IFS in this paper, the clamping forces are adaptively adjusted to optimal values according to the cutter position and the cutting forces during machining with the objective of minimizing workpiece distortion while ensuring that it is adequately secured. In proposed system, a machine tool equipped with a CNC controller is considered. Three components of cutting forces in end-milling are calculated using the force prediction model developed by [5]. The clamping force optimisation algorithm calculates the optimal values of clamping forces considering the cutter location, the three cutting force components and the results of fixture stability model. These values are provided for a hydraulic clamping
system. The values of clamping force thus calculated are reference values for the force control loop. To develop the efficient optimization control algorithm is essential to realize the real-time control of this intelligent fixturing system. The optimization algorithms were reported since 1980s [6]. However, these models are too complex and computationally lengthy; hence, are not suitable for real-time control. In this paper, an effective algorithm and approach have been established for the on-line control of an intelligent fixturing system.

The proposed IFS is characterized by on-line monitoring, dynamic clamping forces, and real-time fixturing process control. At the conceptual design stage, electro-pneumatic, electro-hydraulic and electro-mechanical clamping devices have been compared in terms of force range, response time, working environment, size and cost. Finally electro-hydraulic controlled clamping elements are selected.

2. CLOSED-LOOP IFS

Based upon the above-mentioned facts, an intelligent fixturing system is developed (Figure 1). It adjusts the clamping forces adaptively as the position and the magnitude of the cutting forces vary during machining to achieve the minimum deformation of the workpiece. Proposed system is able to perform the following operations: monitor the clamping forces, monitor the machining forces and adjust the clamping forces according to the change in geometry of the workpiece. All the above operations have been designed into the presented fixturing system. To ensure that the controller has a sufficiently short response time, the models should be as simple as possible, and yet effective. Adjustment of the clamping forces during machining requires the control system to be responsive to the change in workpiece dimensions. This can be achieved by using a closed loop control using the parameter identification of adaptive control theory. The application of adaptive control theory in this research led to an intelligent clamping system. The framework of the system is shown in Figure 1. The structure consists of the modular fixturing system, fixturing stability model, clamping optimization algorithm, clamping control system, force monitoring module and communications with CNC machine tool.

At the beginning of the machining, reaction forces are measured through the sensors embedded in locators. This is a cylindrical locator assembly with built-in ring type force sensor (Kistler). The data are sent via force monitoring module to the fixture stability model.

The fixture stability model is used to monitor the fixturing stability during the entire machining operation. It is based on static equilibrium analysis. The model is aimed at analysing the configuration of the fixture, confirming or rejecting it, if all the set condition is not fulfilled. A stable fixturing system must hold a workpiece firmly in place during machining. Once instability appears, the module sends a command to the hydraulic system to increase the corresponding clamping force. This process is repeated until the completion of the machining process. Positive reaction forces at the locators ensure that the workpiece maintains contact with all the locators from the beginning of the cut to the end. A negative reaction force at the locator indicates that the workpiece is no longer in contact with the corresponding locators and the fixturing system is considered unstable. This stability criterion has been used by many other researchers [7,8]. The three components of cutting forces in end-milling are predicted using the cutting force model developed by [6]. Many cutting force models have been developed in the past for milling, drilling and other machining processes [9]. In the intelligent fixture system, cutting forces are predicted according to neural network model [6]. Neural networks simplify the determination of the cutting forces. The clamping force optimisation algorithm determines the optimal clamping force values considering the cutter location, the three cutting force components and results of the fixture stability model.

Fig. 1  Model based control scheme of closed-loop IFS
The clamping forces should ideally be just sufficient to constrain and locate the workpiece without causing damage to the workpiece. If the clamping forces are too large, the machined workpiece may warp when released from the fixture. The objective of the optimization algorithm is to minimize all the controllable and reaction forces. This is expressed as the minimization of the sum of the squares of the clamping and reaction forces. Based on the force analysis and rigidity and stability constraints, the algorithm determines the optimal clamping force for every cutter position. The used algorithm [10] is useful for designing fixtures since it can routinely determine the optimum sizes, direction and application points of clamping and reaction forces for different cases of clamping. The predicted optimal clamping forces are then applied in real-time using an electro-hydraulic clamping system. This system is designed to vary clamping forces on the workpiece during the machining process. Soft PLC controls a hydraulic system to apply the required clamping forces as the cutter moves to different locations on the workpiece. The clamping forces are proportional to pressure in hydraulic cylinder. This means, that the clamping forces can be monitored by pressure monitoring in cylinder.

2.1 Integration of the IFS with the machine tool

The machine tool can send commands to the fixturing system, and the fixturing system can send requests and information to the machine tool for certain tasks, such as stopping the machining process, decreasing feedrate. Data communication is achieved through the DNC2 interface (Fagor). The fixturing system communicates with the machining centre and adjusts its clamping accordingly. At the beginning of the machining process, the workpiece is clamped with an optimal clamping force. Once the machining process begins, the fixturing system monitors the clamping forces. Once the forces exceed predetermined thresholds, a feedrate reduction request or stop request is sent to the machine tool from the fixturing system.

3. EXPERIMENTAL SET-UP

To demonstrate the effectiveness of the proposed Intellligent Fixturing System, machining experiments are carried out on a thin-wall workpiece. The control scheme and set-up of the proposed fixturing system is shown on Figure 2.

On a Heller Bea 02 machine tool with Fagor CNC controller it is necessary to make the slot shown in Figure 2. Tool path if marked with arrow from point 1 to point 2). The milling cutter of 16 mm diameter with two cutting inserts (R-216-16 03 M-M) with the following cutting conditions: cutting speed \(v=30\) m/min, feedrate \(f_z=0.02\) mm/tooth, cutting depth \(a=2.7\) mm is used for the experiment. The workpiece material is steel Ck-45. The components of the cutting forces (X, Y, and Z directions) with cutting parameters defined above are calculated on the basis of reaction forces (R1 to R6) measured from the sensors. Piezoelectric sensors are built into six locators to measure reaction forces during machining.

4. RESULTS

The measured reaction forces are shown in Figure 3. It can be seen that the reaction force R1 at some tool position is almost zero, which means that the workpiece in not in equilibrium. This indicates that the fixturing system is not stable under this set of constant clamping forces (C1=300N C2=250N). The clamping forces must be increased until all the reaction forces become positive. Two hydraulic clamping cylinders are employed to clamp the prismatic workpiece. The fluid pressure in each hydraulic cylinder is measured by a pressure gauge.

The optimal clamping forces are shown in Figure 4. The corresponding positive reaction forces are given in Figure 5 that shows the workpiece will not detach from the six locators.

The results show that the clamping forces can be very small by applying varied clamping forces during machining in comparison with fixed clamping scheme. Tests with the prototype show that the fastest response time which can be achieved equals to 200 msec for a force step of 10 N.

The designed and tested system can deliver a maximum of 2500 N clamping force. A force resolution of \(\pm\) 1 N has been achieved.
This error can easily be improved. It is determined by the resolution of the A/D conversion of the force signal, the noise in the force feedback (not filtered) and backlash movements of the actuator.

5. CONCLUSION

This paper presents the development of an intelligent fixturing system. Variable clamping force control is implemented in the IFS. The main task of IFS is to adaptively adjust the clamping forces to achieve minimum deformation of the workpiece according to the cutter position and the cutting forces. The developed system is a solution for force controlled clamping with large force range, good resolution and fast response. The accuracy of the workpiece is improved due to adaptive control of clamping forces and the robustness of the systems to disturbances is also greater. The approach also uses an optimization algorithm to determine optimal clamping forces based on the static equilibrium analysis of the fixture system.

6. REFERENCES


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