Mobility and Kinematics Analysis of a Novel 5-DOF Hybrid Manipulator for Reconditioning of Mould and Die Tools: Part 1

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***Abstract*- In this paper, the requirements for a mechanical manipulator for achieving reconditioning of mould and die tools are determined. Reconditioning of mould and die tools involves the following manufacturing processes; identification of defects, cleaning of mould/die tool, deposition of material (metal), welding of material (TIG/laser), rough machining and finishing to specs, polishing and heat treatment, in sequential order. Current technology trends in the reconditioning of mould and dies is presented. The different defects that occur in mould and die tools that can be repaired such as wear, craters, chipping, etc are presented.**

Using the knowledge of the different manufacturing process and defects that occur in mould and die tools, specifications of a mechanical manipulator for reconditioning of mold and dies are determined.

Finally, suitability of 5-axis milling machine technology for re-conditioning of mould and die tools is evaluated. This is done by presenting current 5-axis milling technology.

Key words: Parallel kinematics manipulator, serial manipulator, hybrid manipulators, reconditioning of mould and die tools, 5-axis milling.

I. INTRODUCTION

Die and mould repair and refurbishing operations form an integral part of the day to day running of businesses involved with die and mould manufacture and production. Repair and refurbishing operations are never taken lightly by industry, due to the uniqueness of each part produced. The risk or degree of difficulty is highlighted by the span of specialist know-how and variety of human skills required to successfully undertake the correction or repair. These specialist skills include know-how on metallurgy applied to die construction materials, process materials behavior and rheology, CAD and CAM data manipulation and creation, material addition (welding) and removal operations, surface finishing, etc [1].

Automation of some of the manufacturing processes used in repair and reconditioning of mould and die tool can improve cycle times. In this paper, an overview of the most relevant issues and technologies used to fulfill the current repair and refurbishing needs of the mould and die tools reconditioning industry are presented.

Using general terms, the process of repairing or refurbishing dies and moulds can be surmised as follows and this document will assist in all the steps [1]:

-Notice and/or identify the problem.
-Establish the cause.
-Create a plan of corrective actions.
-Apply the actions.
-Apply systematic quality checks and evaluate effectiveness of each action.

In this paper, specifications for a mechanical manipulator that can be used for reconditioning of mould and die tools is presented. The format of the final manuscript that will be submitted will be as follows:

II. Failure modes of mould and die tools, III. Manufacturing processes for reconditioning of mould and die tools, IV. Suitability of 5-axis milling machine technology for reconditioning of mould and with tools, V. Some commercially off-shelve systems, VI. Specification of a manipulator for reconditioning of mould and die tools, and VII. Conclusion

II. FAILURE MODES OF MOULD AND DIE TOOLS.

Typical failures of moulds and dies are;

- Wear which is caused by the abrasive nature of materials being processed flowing over a particular area.

Craters, caused by weakness on die /mould areas subjected to abrasive process material flow.

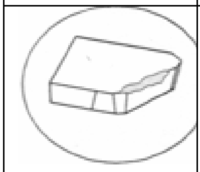
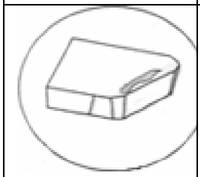
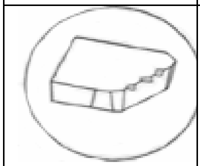
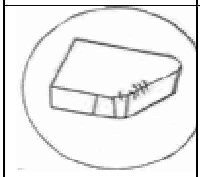
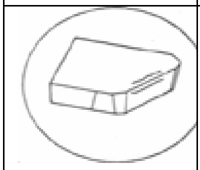
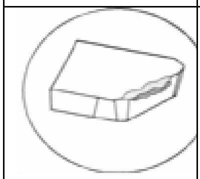
- Chipping, caused by sharp edges subjected to wrong tempering and heat treatment, micro cracks on very hard substrates are susceptible to chip under variable heat and pressure shock processing conditions.

- Fissures, these can be cracks either perpendicular to the edge, in line with material process flow or horizontally i.e. perpendicular to the material process flow. These appear due to variations in process die/mould temperature revealing defective removal of machining induced stresses.

- Embossing, deformity caused by loss of die/mould substrate hardness and associated bearing strength due to combination of defective heat treatment or loss there off due to high process temperatures and pressure.

- Burr, incrustation of the material being processed due to heat checking or same die material components rubbing on each other.

TABLE I
LIST OF TYPES OF DEFECTS FOUND IN MOULD AND DIES, AND SUGGESTED REPAIRS.

Picture	Defect	Suggested repair solution
	Wear	Build up : Large – Conventional Tig weld Small – Micro Tig weld Finish off to required dimension and surface condition, consider coating or surface treatment of area
	Craters	Build up : Large – Conventional Tig weld Small – Micro Tig weld Finish off to required dimensions and surface condition, consider coating or surface treatment of areas
	Chipping	Remove brittle affected areas and than build up: Large – Conventional Tig weld Small – Micro Tig weld Finish off to required dimension and surface condition, consider coating or surface treatment of area
	Fissures, Crack lines horizonta l	Remove cracks affected areas and than build up: Large – Conventional Tig weld Small – Micro Tig weld Finish off to required dimension and surface condition, stress relieve and heat treat
	Fissures, Crack lines vertical	Remove cracks affected areas and than build up: Large – Conventional Tig weld Small – Micro Tig weld Finish off to required dimensions and surface condition, stress relieve and heat treat
	Embossi ng , denting or sinking	Remove sink affected areas and than build up : Large – Conventional Tig weld Small – Micro Tig weld Finish off to required dimension and surface condition, stress relive and heat treat

III. MANUFACTURING PROCESSES FOR RECONDITIONING MOULDS AND DIES.

In order to generate requirements for a mechanical manipulator to be used for reconditioning of moulds and dies, it is necessary to know the processes involved in order to design a manipulator capable of undertaking these tasks. Once the defect has been identified, the processes that follow are;

- Grinding /machining: this is required in order to clean the affected area before it can be repaired.

- Deposition of material: this can be achieved by either conventional TIG welding or micro TIG welding, depending on the size of the weld and the time. Larger welds are generally not good candidates for micro TIG welding because of the welds produced using a micro torch. Micro TIG welding seldom causes sink marks that compromise the base material because the weld is completed at a lower temperature. Micro TIG amps can be adjusted by 0.5 amps at a time, going as low as 0.5 amps. Conventional TIG welding might start at 20 amps. Micro TIG welding also requires the use of a microscope and a micro-sized torch head that is much smaller than used in conventional TIG welding, allowing for greater control of weld placement, especially in tight spots. Finishing a welded area or restoring the original finish, micro TIG welding saves time over conventional TIG welding. When done properly, micro TIG leaves no sink marks around the welded area and the part can then be hand-stoned and polished to required tolerance. While conventional TIG welding, on the other hand, requires some form of machining operation (EDM, milling or grinding), to achieve desired tolerance.

- Finishing: this is done to achieve the required texture for the part. It can be accomplished by electro spark deposition process (ESD), polishing or milling.

IV. SUITABILITY OF 5-AXIS MILLING MACHINE TECHNOLOGY FOR RECONDITIONING OFMOULDS AND DIES.

The process of reconditioning moulds and dies requires highly dexterous, mechanically reconfigurable and high stiffness machinery. This is what brings us to evaluate the suitability of 5-axis milling machines for this process. 5-axis milling machines make suitable candidates for the reconditioning process, as they tend to have high stiffness and are kinematically flexible, though in most cases not structurally flexible or mechanically reconfigurable.

A minimum of 5 degrees of freedom are required to obtain maximum flexibility in tool work-piece orientation, this means that the tool and work-piece can be oriented relative to each other under any angle. This is one of the analysis undertaken during the design of machine tools, to ensure the kinematics provide sufficient flexibility in orientation and position of tool and part. Some other design specifications of 5-axis machine tools are; orientation and position with the highest possible speed, orientation and positioning with the highest possible accuracy, fast change of tool and work-piece, Safe for the environment and highest possible material removal rate.

To analyze a machine tool, it is necessary to analyze the kinematic structure of the machine tool. To do this, a kinematic chain diagram must be set up, from which two groups of axes can be distinguished: the work-piece carrying axes and the tool carrying axes. In [8], the general case is presented, where the analysis of the kinematic structure and the setting up of kinematic chains in a machine tool can be broken down into four stages;

- proceeding from the shape of the be obtained, the cutting tool to be used and process of shaping the material, the number and type of kinematic groups are determined for the formative, indexing and feed-in motions.
- Knowing the nature of the operative motions, the structure of each kinematic group is examined separately. The internal and external constraints are established in each group, and the devices are found for setting up and regulating the parameters of the operative motion.
- The remainder of the kinematic scheme, usually consisting of the controls and kinematic groups for handling motions, is considered.
- The kinematic chains of the machine tool are set up after deriving the set up formulas for the change-gear sets and certain other setting up devices.

The applications for 5-axis machine tools are classified in positioning and contouring, for more details and difference on the two see [2]. Due to the large number of theoretically possible configurations, a specific 5-axis machine will be most appropriate for a special set of work-pieces.

Five-axis milling offers reduction in a number of set-ups, and this helps to increase the accuracy and reduce the lot size. Some of the disadvantages of 5-axis machines are; high price and additional rotation axes cause additional position error.

The purchase of a 5-axis must be preceded by a profound study of the range of products which have to be machined. This along with a 5-axis machine being most appropriate for a special set of work-pieces and the disadvantages, pose limitations in using 5-axis machine tools in the recondition of moulds and dies process.

V. Some Commercially Off-Shelve Systems

Below some commercially off-shelves systems are presented, in order to identify the current state of technology development in this field.

A. The POM Group Inc.[3]

The POM Group developed a process called Direct Metal Deposition (DMD) that fabricates fully dense metal “from the ground up” using powdered metal and a focused laser. DMD is designed for 3-dimensional, unmanned laser-aided, powdered metal fusion. It automatically constructs 3D components directly from computer aided design (CAD) data. The key to the technology is an optical heat energy source, in this case an industrial laser that is used to directly fabricate metal parts. The laser creates a melt pool on the substrate material into which the additive materials, in powder form, are injected in exactly measured amounts and melted forming a metallurgical bond. The rapid cooling characteristics of DMD create a fine grain microstructure, which results in a fully dense product with superior mechanical and metallurgical properties.

The POM advantage is a patented closed-loop feedback system that ensures product quality and dimensional stability during fabrication. If the actual geometry deviates from the required geometry, this is detected by process sensors developed for DMD Closed Loop Technology. The Closed Loop optical feedback system continuously monitors in real time the size of the weld pool and adjusts process variables such as powder flow rate, CNC velocity and laser power.

The melt pool information for the layering is monitored by 3 CCD cameras. The process PC compares the information about the actual geometry with the desired geometry and controls the layering process accordingly. The use of 3 cameras in a 3x120^{o} array allows a controlled DMD process in 3D mode as well. As a pre-condition for this, it must be possible to observe the melt pool with at least 1 camera (interference contours). POM has 6 and 5-axis systems.

B. Optomec Inc.[4]

This company commercialized the LENS process. The LENS process is a CAD driven, additive manufacturing method where material is deposited layer by layer to build a fully 3D part. First the engineer designs the part using CAD. The resulting STL file is then processed using the proprietary PartPrep software which turns the CAD data into a digital tool path. This tool path drives the laser, at the heart of the LENS process, in 3D space. The LENS Work Station Control software controls the manufacturing process with the ability to adjust processing parameters in real time.

The build process uses a high power solid state laser focused onto a metal substrate to create a molten melt pool in a protective Argon atmosphere. Metal powder is then injected into the melt pool to increase the material volume. The substrate is then scanned relative to the deposition apparatus to write lines of the metal with a finite width and thickness. Rastering of the part back and forth creates a pattern and fill to complete the layer of material to be deposited. Finally this process is repeated many times until the entire object represented in 3D CAD model is produced. Optomec Inc. has the LENS 850R and the LENS 750 systems. These systems offer up to 7 Axis of motion.

C. *Trump system Precision Machinery Co., Ltd (TPM) [5]*

This company has the LO 180 and LC 180 Laser deposit Welding Systems. They state that their systems are compact and portable designs, which makes it easy to transport to do service on site. TPM provide special welding materials as well as techniques aimed at avoiding air-holes. They employ amplitude modulation (where the single pulse shape can be modulated), a new and advanced technology which improves the welding quality. The systems are easy to operate and offer large memory for the welding data.

D. *Sciaky Inc.[6]*

They have developed a new generation (NG1) Electron Beam Welder, which provides advantages in energy efficiency, welding rate and cycle time. The improved system elements are;

Control- the new PC based control system uses integrated CNC motion and process controls. With the capability of more than 10 Axis of motion control, the system synchronizes the process parameters. Capabilities include process monitoring with data acquisition, networking and off-line programming. Open architecture allow for easy upgrading. System diagnostics, hard drive and three levels of program access for security are included.

Electron Beam Gun- the electron beam package provides an improved, narrow beam geometry that produces superior depth-to-width ratios and operational stability. The filaments can be changed out in 10 minutes at the end or beginning of any chamber cycle.

Optical Viewing System- this system features high-resolution, precision gun optics with CCD camera and monitor. Optic focus, shutter and iris controls and an electronic adjustable crosshair are built in.

Lean Design- the system has smaller footprint which requires less shop space. Implemented a new, more compact and flexible vacuum system.

VI. Specifications for the Mechanical Manipulator for Reconditioning of Moulds and Dies.

The table below list kinematics and dynamic specifications required for the different manufacturing processes for recondition of moulds and dies. The maximum torque, power and force were calculated using methods and values found in charts in [7].

TABLE II
SPECIFICATIONS FOR MECHANICAL MANIPULATOR

Process	Kinematics	Dynamics
Checking for defects	No. of axis:4-axis Workspace*: (0.6m x 0.9m x 0.6m)	
Cleaning (Grinding/Machining)	No. of axis: 5-axis Workspace*: (0.6m x 0.9m x 0.6m)	Max. Power: 2kW Max. Torque: 30N.m Max. Force:10kN
Welding	No. of axis:4-axis Workspace*:(0.6m x 0.9m x 0.6m)	Max. Power: 2kW Max. Torque: 30N.m Max. Force:10kN
Finishing (Milling/Drilling/Reaming/Tapping/Engraving/etc.)	No. of axis: 5-axis Workspace*: (0.6m x 0.9m x 0.6m)	Max. Power: 2kW Max. Torque: 30N.m Max. Force:10kN
*workspace depends on the size of the work-piece		

VII. Conclusion

Having studied the methods or processes involved in reconditioning of moulds and dies and mechanical capabilities required for machines to be used in the process, specifications for a mechanical manipulator that can be used are presented. The design of the proposed manipulator will be based on optimizing 5-aixs machine tool capabilities and reducing or eliminating its limitations. Based on the design specifications presented in this paper (Mobility and Kinematics Analysis of Novel 5-DOF Manipulators for Mould and Die Tools: Part 1) and recommendations made in [1], conceptual designs for the manipulator are presented in (Mobility and Kinematics Analysis of Novel 5-DOF Manipulators for Mould and Die Tools: Part 2).

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