Part Distortion Compensation

Introduction

Mann Engineering is an engineering company manufacturing precision components on various types of CNC machine tool. They currently manufacture a family of parts which, due to the shape and material of the component, are prone to distortion and therefore the current method of manufacturing requires the parts to be produced using multiple operations. This requires a full-time operator to move the part between operation and is very laborious. The recent Covid situation has also added to the need for Mann to look at reviewing how these parts are manufactured to see if the manufacturing process can be controlled enough to allow automation and maintain part quality. They are looking to utilise existing equipment and if it can be confirmed that the part can be manufactured in less operations, they would look to implement automated machining of these parts.

Material distortion

The process of machining raw materials into designed finished products can generate forces and these inherently can cause material distortion which is difficult to control and can determine the manufacturing process and overall component cost. There are a number of factors which can directly contribute to the level of distortion observed. Firstly the material type, stainless steels for example, are widely known for distorting and once the machining process has begun the level of distortion can be difficult to control and is one of the reasons machining of stainless steel can be considered costly. When machining of these types of materials it is common practice to rough machine the part and then remove from the machining process to allow "resting" whereby excess material is left on the part surfaces to allow max distortion to occur. The part is then brought back into the machine tool for finished processing. This concept of removing and final machining of parts can guarantee part accuracy but can be a very costly exercise.
It should be noted that where residual stress is in the material, before machining or following a roughing step, a stress relieving processes may be required regardless of part distortion to prevent further distortion during the life of the component.

Secondly, in most cases the method of holding the work piece can play a big part in the variations within the material. To achieve an optimal machining rates, the raw material needs to be clamped securely. This clamping force can contribute to the distortion observed. It is common practice to apply a two-stage clamping pressure to reduce some of the forces applied for the roughing stage before finish machining is carried out. Where milling is concerned, and the part is held in a vice, there is little opportunity to reduce the clamping force automatically during the machining process to assist in reducing part distortion. Where large parts are concerned, which may be clamped to a working table, it is even more difficult to reduce distortion.
The requirement of changing of the clamping method during machining introduces a manual step which can prohibit automating the manufacture of some of these parts.
Third consideration is the type of cutting tool being used. Cutting tools which are typically used to achieve high metal removal rates during the machining process but these exert large forces which may directly affect the distortion of the material. However, the use of tools which reduce the amount of force generated during machining can significantly increase the machining time and in turn part cost.
If the distortion can be measured during the machining, it can be compensated for autonomously by adjusting the finishing strategy and potentially the part can be finished on one operation.
In the case of this project, the proposed component is being produced using a multi-step process where the part is roughed, leaving material on all surfaces and then brought back into the machining process for finishing to achieve the required

tolerances. The research is aimed at identifying an opportunity to manufacture the part in one operation, maintaining required specifications. It was proposed that this could be done by measuring the distortion during the machining process and automatically compensating for it. If this can be achieved, the process of manufacturing these parts could be automated, greatly reducing the cost per part.

Proposed Testing

For the partner company to be able to adopt any potential solution, it was agreed that we needed to conduct tests which would give solutions attainable to the partner company. Firstly, we needed to identify a machining approach which would allow the component to be manufactured in one operation without operator intervention. Following a team review of the component, it was agreed to machine the part on IMR's Doosan Puma 2600SY II machine tool. The machine is equipped with bar feed and parts catcher capabilities which would demonstrate some of the automation possibilities. We would rough machine and finish the part outer sizes and inner bore on the main spindle and then propose that, if the partner company were to adopt this potential solution, they would use an expanding mandrel system on their sub spindle. For the purpose of the research, we would not deploy an expanding mandrel, but we would engage with equipment suppliers' engineers to validate our proposal as a method of manufacture.

Figure 1 Doosan Puma 2600SY with Hydrafeed used for testing

Secondly, we needed to identify the amount of distortion being observed during the different stages of the machining process. To achieve a consistent process for measuring the distortion, we used the Doosan Pumas Renishaw OLP 40 probing system. A program was created which could be run at any stage during in the machining process. This data was captured and compared as different strategies were applied. Figure 3 shows the probing in operation inspecting one of the parts. Once a clear method of measuring the part distortion was identified, we looked at applying closed loop strategy whereby we looked to either update the amount of material being left on for a finishing pass to remove any distortion or automatically update the finishing tools compensation values to achieve desired results.

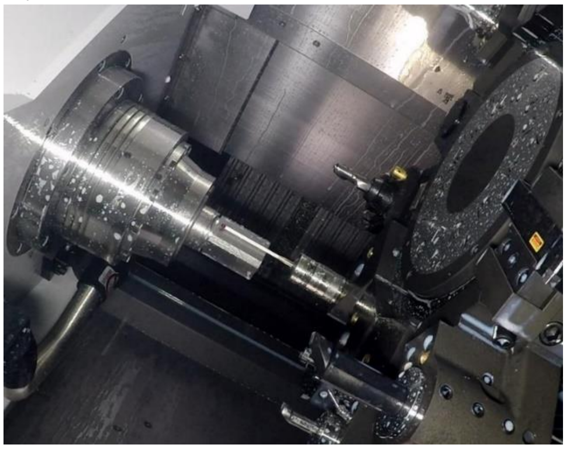


Figure 2 Part probing on the Puma using an OPL40

For the partner company, the problem identified relates to a family of parts and therefore it was agreed to use two of the part types for testing to validate the solution. An example of the parts to be machined is seen in Figure 4 below.

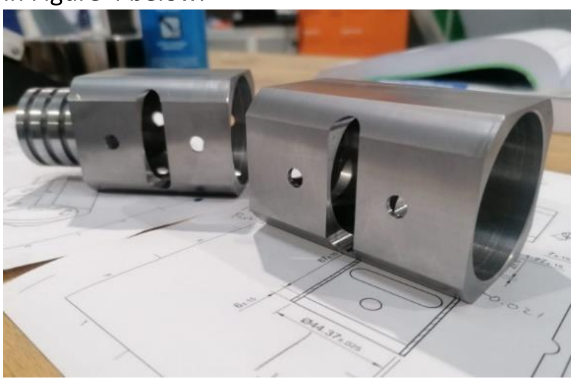


Figure 3 Example of parts to be machined

Testing and Results

We decided, for initial tests, to apply two strategies. The details and sequencing for the machining of these are detailed in tables in Figure 5 & 6 below. For Test 1, the main features were rough cut and then finished directly after. Using an approach such as this would normally encourage distortion as there are additional roughing operations to be carried out. A more typical strategy would be that of Test 2 whereby all features are rough cut and then finished once any potential distortion has taken place. Measurements were taken for test 1 following the roughing cycles. The aim here is to identify if there is a consistent observed distortion between parts which may need to be controlled. Also for Test 2, measurements were taken following the finishing cycles but before smaller holes and slots were added to identify what level of distortion was observed.

Test #1					
No.	Operation	TOOL	Part Number	Make	Supplier
1	Releive groove	Cut off blade	150.10A-20-3	Seco	Flatley Engineering
2	Face/rough OD stock	WNMG Rougher	WNMG 08 04 08-QM H13A	Sandvik	Flatley Engineering
3	Rough and Finish Flats	40mm Facemill	TPD05R040M22.0E08	Tungaloy	MTT
4	Drill Large Bore	32mm U-Drill	DS20-D3200L40-04	Sandvik	Flatley Engineering
5	Rough Large Bore	32mm U-Drill	DS20-D3200L40-04	Sandvik	Flatley Engineering
6	Finish Bore	DNMG	DNMG 11 04 04-SM H13A	Sandvik	Flatley Engineering
7	4mm Pilot	Drill	K/P 19595893	Hartner	Hard Metal
8	4mm Long Drill	Drill	K/P 20001687	Hartner	Hard Metal
9	Drill 8mm holes	Drill	K/P 19202951	Hartner	Hard Metal
10	Mill Slots	6mm Endmill	EC-H4S 06-06C06CF-E50 900	Iscar	Hard Metal
11	Drill 20mm Hole	12mm U-Drill	880-D1270L20-04	Sandvik	Flatley Engineering
12	Bore 20mm hole	12mm U-Drill	880-D1270L20-04	Sandvik	Flatley Engineering
13	Finish outside rads	WNMG Rougher	WNMG 08 04 08-QM H13A	Sandvik	Flatley Engineering
14	Probe #1	Probe	OLP40	Renishaw	Mills
15	Deepen Relief groove	Cut off blade	150.10A-20-3	Seco	Flatley Engineering
16	Probe #2	Probe	OLP40	Renishaw	Mills
17	Rebore Tolerance	DNMG	DNMG 11 04 04-SM H13A	Sandvik	Flatley Engineering
18	Part off	Cut off blade	150.10A-20-3	Seco	Flatley Engineering

Figure 4

Test #2					
No.	Operation	TOOL	Part Number	Make	Supplier
1	Relief Groove	Cut off blade	150.10A-20-3	Seco	Flatley Engineering
2	Rough Turn face and OD	WNMG Rougher	WNMG 08 04 08-QM H13A	Sandvik	Flatley Engineering
3	Pilot Drill 4mm Holes	Drill	K/P 19595893	Hartner	Hard Metal
4	Deep Drill 4mm holes	Drill	K/P 20001687	Hartner	Hard Metal
5	Rough Flat Detail - leave 0.2mm per side	40mm Facemill	TPD05R040M22.0E08	Tungaloy	MTT
6	Drill Large Bore	32mm U-Drill	DS20-D3200L40-04	Sandvik	Flatley Engineering
7	Rough Bore - leave 0.2mm on ID	32mm U-Drill	DS20-D3200L40-04	Sandvik	Flatley Engineering
8	Probe #1	Probe	OLP40	Renishaw	Mills
9	Drill 8mm Holes	Drill	K/P 19202951	Hartner	Hard Metal
10	Mill Slots	6mm Endmill	EC-H4S 06-06C06CF-E50 900	Iscar	Hard Metal
11	Finish Flat Details	40mm Facemill	TPD05R040M22.0E08	Tungaloy	MTT
12	Drill 20mm Hole	12mm U-Drill	880-D1270L20-04	Sandvik	Flatley Engineering
13	Bore 20mm hole	12mm U-Drill	880-D1270L20-04	Sandvik	Flatley Engineering
14	Finish Bore and Detail	DNMG	DNMG 11 04 04-SM H13A	Sandvik	Flatley Engineering
15	Finish OD Rad	WNMG Rougher	WNMG 08 04 08-QM H13A	Sandvik	Flatley Engineering
16	Probe #2	Probe	OLP40	Renishaw	Mills
18	Part Off	Cut off blade	150.10A-20-3	Seco	Flatley Engineering

Figure 5

Measurements were taken from both test pieces during the machining process to measure the level of distortion. As expected, Test 1 exhibited a much larger distortion value than that of Test 2. Figure 7 below shows the amount of distortion measured during the machining process and at the end of the process. It is clear that the level of distortion causes multiple tolerances to be out of specification.

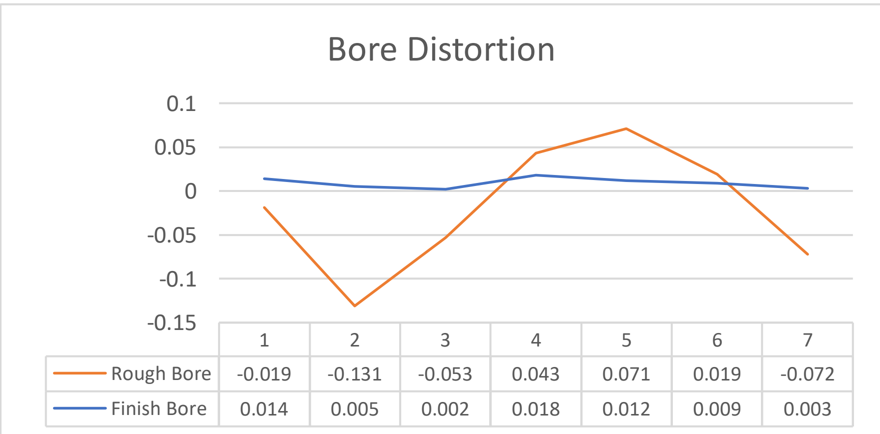
Measurement Results										
						Test #1 Part #1				
						Probe #1		Probe #2		
Feature number	Part #1	Nominal	Tol	Min	Max	Actual	Deviation from Nomonal	Actual	In/Out Tol	Variance
1	MAIN BORE DIAMTER Back	44.27	0.02	44.27	44.29	44.089	-0.181	44.089	-0.181	0
2	MAIN BORE DIAMTER Front	44.27	0.02	44.27	44.29	44.22	-0.05	44.225	-0.045	-0.005
3	LARGER BORE DIAMETER	44.37	0.02	44.37	44.39	44.295	-0.075	44.295	-0.075	0
4	DISTANCE ACROSS FLATS Y AXIS BACK ED	47.7	0.12	47.64	47.76	47.648	-0.052	47.645	-0.055	0.003
5	DISTANCE ACROSS FLAT X AXIS BACK EDG	47.7	0.12	47.64	47.76	47.622	-0.078	47.616	-0.084	0.006
6	DISTANCE ACROSS FLATS Y AXIS FRONT E	47.7	0.12	47.64	47.76	47.645	-0.055	47.643	-0.057	0.002
7	DISTANCE ACROSS FLAT X AXIS FRONT ED	47.7	0.12	47.64	47.76	47.591	-0.109	47.587	-0.113	0.004
					Bore Taper	-0.131		-0.136		
					Y Axis Taper	0.003		0.002		
					X Axis Taper	0.031		0.029		

Figure 6 Results of Test 1

The table in Figure 8 below displays the inspections taken from Test 2. Again it is clear that the part is distorting following the roughing phase but each dimension is corrected and well within tolerance following the finishing pass. Following trials, measurements from both strategies were analysed and compared. To demonstrate repeatability of the process, we machined a number of parts using the strategy used in Test 2 and measurements from these are detailed in table below.

Summary																	
				Test #2 Part #1		Test #2 Part #2		Test #2 Part #3		Test #2 Part #4		Test #2 Part #5		Test #2 Part #6		Test #2 Part #7	
Feature number	Feature	Nominal		Rough	Finish	Rough	Finish	Rough	Finish	Rough	Finish	Rough	Finish	Rough	Finish	Rough	Finish
1	MAIN BORE DIAMTER Back	44.27		43.84	44.158	44.089	44.26	43.812	44.191	43.892	44.156	43.94	44.2	43.903	44.24	43.775	44.238
2	MAIN BORE DIAMTER Front	44.27		43.859	44.144	44.22	44.255	43.865	44.189	43.849	44.138	43.869	44.188	43.884	44.231	43.847	44.235
3	LARGER BORE DIAMETER	44.37		43.867	44.244	44.295	44.336	43.878	44.324	43.848	44.217	43.879	44.273	43.892	44.322	43.856	44.338
4	DISTANCE ACROSS FLATS Y AXIS BACK EDGE	47.7		47.722	47.574	47.648	47.667	48.086	47.695	48.091	47.681	48.116	47.693	48.116	47.694	48.111	47.688
5	DISTANCE ACROSS FLAT X AXIS BACK EDGE	47.7		47.701	47.551	47.622	47.647	48.066	47.667	48.075	47.654	48.093	47.67	48.091	47.678	48.09	47.665
6	DISTANCE ACROSS FLATS Y AXIS FRONT EDGE	47.7		47.702	47.57	47.645	47.685	48.069	47.694	48.063	47.684	48.089	47.692	48.092	47.697	48.092	47.69
7	DISTANCE ACROSS FLAT X AXIS FRONT EDGE	47.7		47.675	47.541	47.591	47.64	48.041	47.666	48.043	47.663	48.073	47.679	48.075	47.676	48.065	47.672
		Bore Taper		-0.019	0.014	-0.131	0.005	-0.053	0.002	0.043	0.018	0.071	0.012	0.019	0.009	-0.072	0.003
		Y Axis Taper		0.02	0.004	0.003	-0.018	0.017	0.001	0.028	-0.003	0.027	0.001	0.024	-0.003	0.019	-0.002
		X Axis Taper		0.026	0.01	0.031	0.007	0.025	0.001	0.032	-0.009	0.02	-0.009	0.016	0.002	0.025	-0.007

Figure 7 Summary of inspections from Test #2



The graph in Figure 9 across displays the amount of distortion measured within the bore area alone. It is clear that the distortion following the rough machining does not display any consistency across the seven parts machined. The distortion moves from a positive direction to a negative one. Any remaining distortion within the part is within tolerance and under control.

Figure 8 Bore Distortion Graphed

Following the trials, it was apparent that for these parts that the strategy of clamping and machining observed in Test 2 achieves a solution for machining these parts to the required specification without the need for further processes. One of the project objectives is to identify an automated solution of compensating for distortion, we did continue to inspect the distortion level and create strategies which compensated for this distortion. Using the available probing system, we measured the level of distortion and we created a macro program to automatically reduce or increase the offset distance from the feature which was distorted. For example, where the distortion observed was greater across the flat area than a typical finishing pass i.e. 0.1mm, we moved the finishing pass away from the finished surface to reduce cutting pressure on the part to ensure it did not cause further distortion to the internal bore. An example of the program used to achieve this is detailed below. While it may not be necessary for the manufacturing of these parts in the future, it was a very good example of how it this technology might be used.

Part of Program used to automatically compensate for distortion prior to finish machining:

```
#650=2;                       Define variable to use in dividing macro later
#652=0.1;                     Define tolerance of roughing cut

G65 P50 T3;                   Call air blast macro to clean part before probing
G65 P9812 X48.1 Z-71;         Call Renishaw probing macro, measure at Z-71, expected value 48.1mm
#714=#138;                    P9812 writes probed value to #138
#715=#143;                    P9812 writes the out of tolerance value to #143
DPRNT[Distance*across*flats*Y*axis*back*edge*#714 [24]]; Prints probed value to the log file
IF[#715GT#652] THEN #2102=ABS[#715/#650];
IF[#715GT#652] GOTO 12;       If the probed value is out of the tolerance set in #652, the length wear offset value
                              for that tool is updated based off the probed value.

N12 (Correction Roughing cut)
G30 U0;
G30 W0;
M35;
G0 P11 C0;
T0404;
G50 2000;
G98 G97 S675 X48.1 Z10 M7;
G1 Z-86 F770;
G0 X49 Z10;
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Summary

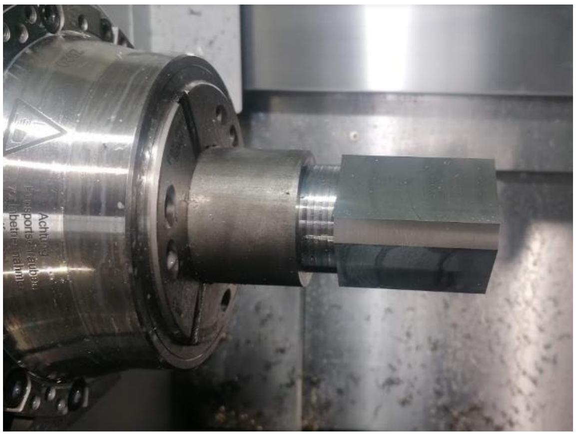
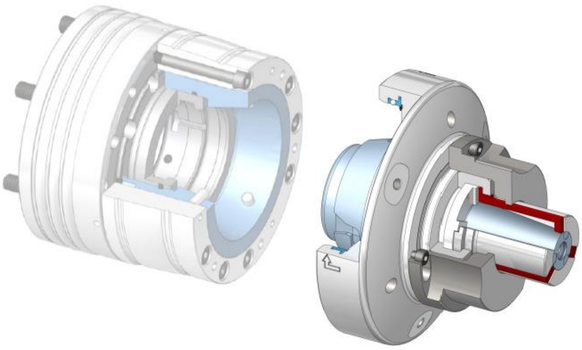


Figure 9 Image of part being held

An overall review of the inspections can only conclude that the strategy applied of moving the machining of these components to a turning type machine, where the raw material has been clamped and not any area of the finished component, can completely remove any distortion. This also leads us to assume that the current method of manufacturing involving clamping of the part in vices, on the finished surfaces is one of the root causes of the distortion. These trials have clearly demonstrated the impact of clamping the raw material can have on this material type. The complete removal of part distortion was an unforeseen but welcome outcome. It did clearly demonstrate the impact of holding the part during the initial rough cut. By holding the part in the lathe, i.e. clamping on the bar on an area which is not machined, Figure 10 and introducing a relief cut, we removed any clamping forces being introduced into the material during the machining process. We did acknowledge that by using this strategy, we marginally reduced the holding capacity and cutting toolpaths cannot be as aggressive, but this is often observed when trying to automate a process. The initial challenge identified of compensating for material distortion, from the testing carried out, it is clear that we have been able to identify a method which eliminated any distortion.

As companies look to move towards more automated solutions, identifying solutions such as we have in this project, will be critical to success in reducing costs. Part distortion would be considered one of the greatest challenges to automation. This is a typical example of a component which, upon review of manufacturing strategy, and with newer technology such as multitasking machines, automation can be achieved. Machining of these types of components will need to be achieved in one operation in order to be cost effective. This project has also demonstrated the opportunity presented through the gathering inspection data, directly at the machine. We were able to, in an automated configuration, demonstrate the stability of the process.

Sub Spindle clamping system



As already mentioned in the report, it was agreed that we would look to use an expanding mandrel system to hold the part for finish machining on a sub spindle. As our existing machine is fitted with a Hainbuch precision clamping system and they are suppliers of expanding mandrels, we consulted with them on whether our proposal is a potentially viable solution. Upon review, they foresaw no challenges with either the holding capacity or distortion of the part. They recommended their MANDO Adapt T812 RD system Est. €3900 Figure 11 (NB: Price was based on supply for a Doosan Puma 2600)

Figure 10 Hainbuchs Expanding Mandrel System

Additional opportunities noted

As we machined the parts, we used the machines inbuilt parts catcher and conveyer to remove parts from the machining area. Combined with the Hydrafeed bar feed system, we were successfully able to demonstrate a completely automated system of producing the parts.

Partner Companies

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