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Fostering in-process inspection during process planning using tolerance charting

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Abstract

Integrated development of machining and inspection plans is essential in dynamic manufacturing environments, especially when right first time manufacturing is required. In this work, a methodology, based on a new and extended use of tolerance charting, that allows incorporation of in-process inspection operations to improve process plans is presented. The methodology proposes the transfer of the manufacturing specification tolerance between surfaces to specification tolerances established between these surfaces and a common reference system. In this way, all variability sources originated by part locating and fixturing can be separately considered from the ones originated by the process-machine system. This circumstance allows a more accurate calculation of operation capability indexes and eases the analysis and improvement of critical operations. To prove methodology potential, an application case is showed.

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1. Introduction

Traditionally, process tolerance charting has been used to generate and validate process plans. This graphic tool aids to assure that most appropriate working tolerances are assigned for a specific machining process in order to meet part blueprint specifications (Jeang, 2011). In first stages of process planning, when machining processes and

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methods are determined, meeting blueprint tolerances is the most important factor, but as process planning progresses, other important criteria must also be taken into account, such as total manufacturing cost (machining and inspection) and quality loss (Huang et al., 2005). However, no evidence has been found where tolerance charting is used to refine manufacturing plans by including in-process inspection operations that will condition the plan itself.

Nowadays, in-process inspection is considered very important, especially with the development of on machine integrated inspection technologies. But to take advantage of these new technological possibilities elaboration of machining processes that integrate inspection operations is essential. To achieve this integration new analysis and synthesis methods are required, so that machining operations, inspection operations and their interactions are processed in a unified manner. This approach is even more important in highly competitive environments, such as One Kind of a Product (OKP) manufacturing, where small or one unit lots are used and where right first time manufacturing is crucial.

To assure right first time manufacturing is important to elaborate an appropriate process plan, resulting from an accurate work where all uncertainty sources must be thoroughly analyzed and all preventive and/or corrective actions to achieve this objective must be considered. For this purpose it is essential to have not only precise and disaggregated information about machine and process capability, but it is also necessary to have information about the execution of machining operations. In-process inspection operations are the ones that provide this information about part and process state and, therefore, allow the decision making that every plan execution should consider, such as typical process corrections (tool path, part zero, tool correction, etc.) or decisions related to part acceptance, rejection or possible rework.

To make this approach feasible a methodology that allows the incorporation of new machining and/or inspection operations is proposed. This methodology serves as a means of improving the elaboration of process plans and is especially adequate in the abovementioned contexts. In the next section the methodology is described and, in order to better understand it, in the following section an application example is explained. Finally, main conclusions and future work will be shortly enlightened.

2. Methodology

The proposal is based on authors' previous work (Romero et al., 2011), where a methodology applicable during the stage of locating and fixturing surfaces (setup) selection and that allows the establishment of manufacturing specifications between active surfaces in the setup being detailed was proposed. Active surfaces are both, the ones generated in the machining/inspection operation by the interaction with machining tool/probe, and also the ones used for part locating by the interaction with fixtures. The procedure incorporates a stage aimed at validating that selected locating surfaces are appropriate by assuring that manufacturing specifications are met when comparing them with dimensional and geometrical capabilities of the process-machine system for the setup solution adopted.

Additionally, and opposite to other classical approaches, the methodology sets out that selection and validation of reference systems for part locating must be done in a back to front manner, beginning in the last process plan setup and ending in the first one. With this approach, effects of variability transmission between setups is taken into account, since a specific setup can cause additional manufacturing specifications to the previous ones and necessary to assure the fulfillment of dimensional and geometrical specifications related to the geometries to be obtained in that setup. In this way, a better and more complete fulfillment of design specifications is ensured.

One of the characteristics of this methodology is that it considers only the transfer of extrinsic specifications from design to manufacturing. This circumstance makes it necessary to compare the latter with dimensional and/or geometrical capabilities representative of the selected process-machine-setup. These capabilities must be expressed in an aggregate way, similar to the specification tolerance, and must gather all sources that can cause an error in the locating and orientation of active surfaces in a machining operation (deviation) and that, therefore, will limit the achievable tolerance in the process specification relating active surfaces in that operation. The fact that normally available aggregate capabilities are of not very good quality -since they establish very wide ranges representing the generalization of many process-machine-setup systems- has made authors think that the use of tolerance charting during detailed process planning could be improved if reasoning related to validation would be carried out on the

deviations that reference systems associated to active surface could undergo in relation to a common reference system. In this way, by working at a surface level, reasoning carried out by the planner can be improved, since likely uncertainty sources can be foreseen and solutions to remove or lessen them can be explored, using a more detailed and accurate information about capabilities and supported by advanced techniques for part quality prediction and improvement. Among these techniques, the Stream of Variation (SoV) model and the Model of Manufactured Part (MoMP) should be highlighted, both based on matrix transformations (Abellán et al., 2013; Abellán et al., 2012).

The proposal that is now being described begins with process specifications established according to the methodology that has been summarized and suggests three new steps, aimed at analyzing and refining the plan when difficulties to meet any process specification are foreseen or when the plan wants to be improved.

Step 1. Transfer of specification tolerances between surfaces to specification tolerances of surfaces in relation to a common reference.

Once the selected technological solution for the setup being studied has been validated and process extrinsic specifications tolerances have been determined, the latter are transferred to tolerances that will restrict location and/or orientation of the reference systems linked to active surfaces in the operation. The transfer leads to, as it can be seen in the example figure, to one specification between common reference and machined surfaces, and to one specification between common reference and locating surfaces. The first one limits all errors causing that generated geometries in the operation deviate from the nominal orientation and/or location in relation with a common reference system, such as the ones produced by tool wear and/or deflection, machine deformations, etc. In a similar way, the second one limits all errors that influence location surfaces, such as the ones produced by fixturing wear, wrong fixturing alignment, etc.

In order to correctly interpret the example illustrations, it must be taken into account that in the charts used in the methodology all surfaces machined in the same operation will be designated as Machining Feature (MF). These MF contain all real surfaces generated by tool movements, all ideal geometrical elements associated to them and, if appropriate, all derived ideal geometrical elements. It must also be considered that, since reasoning at this stage is limited to extrinsic specifications between MF, geometries taken into account in this methodology are the associated and/or derived ones, since form errors do not take part.

The distribution of the specification tolerance that is being transferred to two specifications in relation to a common reference will be carried out taking into account both, process-tool-machine subsystem and setup-part-machine subsystem capabilities. By breaking down the specification it is easier to compare, in the following step, the required process tolerance with a more disaggregated and of better quality capabilities, since they can be the specific ones for the selected solution.

Step 2. Process capability analysis and, if appropriate, improvement of proposed solution.

For every specification resulting from the transfer carried out in the previous step, the capability index will be calculated and a difficulty and cost analysis will be done. With this information, critical operations will be determined and will be candidates for a thorough study that could lead to changes in the initial plan.

This study can foster, for example, the incorporation of additional rough and/or semi finish operations to assure that later operations will be executed in a more favorable way (e.g. with even machining allowances), and also they can be used for incorporating in-process inspection operations, more particularly using on machine integrated probes. Incorporating in-process inspection operations, according to setup state, allows the inclusion of new machining operations conditioned to the information resulting from measuring. These additional operations, of conditioned execution, can be of different types: a) adjustment or preparation operations, such as a reference system shift or tool correction in CNC machining; and b) machining operations, incorporating semi finish or rework operations.

As it will be seen in the example, in order to foster plan improvements, it is necessary to work with specifications relating active surfaces with common reference systems, since this eases the thorough analysis of influence factors when obtaining specifications and, therefore, plan refinement is encouraged taking advantage of in-process inspection.

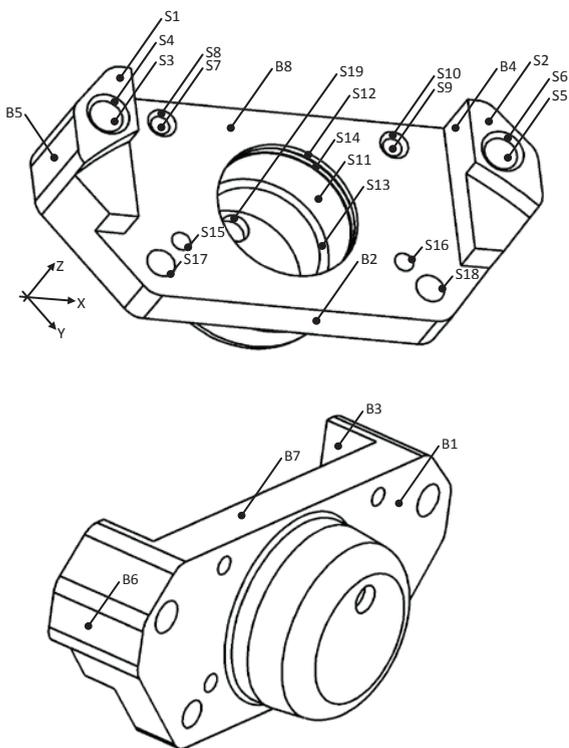
Step 3. Validation of in-process inspection plan.

If in the previous step any in-process inspection operation has been planned, and with the aim of determining the location and/or orientation of a geometrical element and based on the results obtained from measuring being able to suggest some adjustment or machining additional operation, it will be essential to validate that the measuring process has the required accuracy to assure the specification tolerance under study. To do that, necessary transfer process will be carried out and resulting variability will be compared with machining process capabilities, measuring process uncertainty and, if appropriate, adjustment process capability (machine setup, understood as a reference system shift or tool correction; fixture or tool mechanical correction) and uncertainty of association and/or derivation operations involved in measuring.

3. Example

Once the methodology has been described, in this section it will be applied to the process planning of a kart brake calliper. Figure 1 shows the part with all active surfaces during machining numbered and the elaborated machining process plan.

As it can be seen, machining is carried out on a blank obtained by a permanent mold casting process and has two phases: a first one carried out in a CNC machining centre and a second one carried out in a threading station. In the table all machining operations are listed according to the order of execution and it can be seen that only one setup is considered in each machine. It can also be noticed that to refer to operations in the charts a numbering related to the concept of MF is going to be used, followed by a “r” or a “f” to distinguish between MF rough (or previous) and finish (or final) geometry. MF_X denotes the machining feature that is obtained with the corresponding machining operation and will be one of the types considered within the library by ISO 10303-224 (1996).



MANUFACTURING PLAN		
Part: Kart brake calliper		
Material: A356 T61		
Blank obtained by a permanent mold casting process		
MACHINE 1 Machining centre		
Setup 1.1		
Op. N.	Chart operation reference	Description
1.1.1	MF_01 r	Rough face milling (S1, S2)
1.1.2	MF_01 f	Finish face milling (S1, S2)
1.1.3	MF_04	Rectangular pattern, drilling (S3, S5) and countersink (S4, S6)
1.1.4	MF_07 r	Rectangular pattern, drilling (S7, S9) and countersink (S8, S10)
1.1.5	MF_07 f	Rectangular pattern, reaming (S7, S9)
1.1.6	MF_08-09 r	Rough boring and internal facing (S11, S12, S13)
1.1.7	MF_08-09 f	Finish boring and internal facing (S11, S12, S13)
1.1.8	MF_10	Grooving S14
1.1.9	MF_13 r	Rectangular pattern, drilling (S15, S16)
1.1.10	MF_16 r	Rectangular pattern, drilling (S17, S18)
1.1.11	MF_17 r	Drilling S19
MACHINE 2 Threading station		
Setup 2.1		
Op. N.	Chart operation reference	Description
2.1.1	MF_13 f	Rectangular pattern, threading (S15, S16)
2.1.2	MF_16 f	Rectangular pattern, threading (S17, S18)
2.1.3	MF_17 f	Threading S19

Fig. 1. Part surfaces numbering and machining plan.

Since it is not possible to detail the complete process plan, attention will be paid to setup 1.1, which is being carried out in a machining centre and includes 11 operations. After applying the methodology proposed in a previous work to this setup (Romero et al., 2011), it was determined that the setup to be used in this case is the one illustrated in Figure 2, where part locating and fixturing is indicated using the AFNOR AF E 04-013 (1985) symbols. This setup solution can also be seen in the tolerance charting used for its selection and validation (Figure 3), where dimensional and geometrical manufacturing specifications resulting from methodology application are also shown.

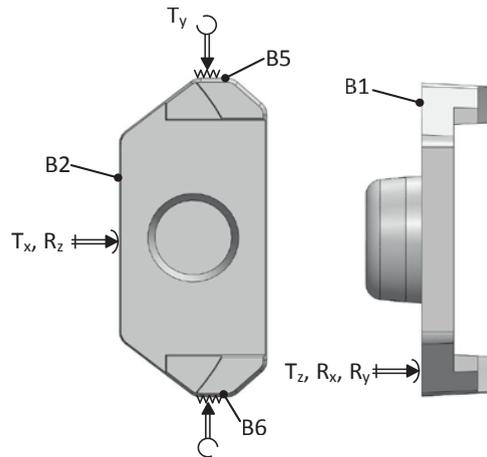


Fig. 2. Representation of setup 1.1 (AFNOR AF E 04-013).

In this chart, blank specifications refer to process specifications that fit in with the design ones, circumstance that happens when these design specifications correspond to two surfaces obtained in the same setup or when one of the surfaces is used for part locating. On the other hand, shaded specifications correspond to process specifications resulting from transfers carried out during process plan elaboration according to the mentioned methodology. In this case, manufacturing specifications 1, 2 and 3 are the result of transferring specifications relating surfaces machined in setup 1.1 that are not directly related with any of the surfaces used for part locating. Manufacturing specification 3 appears as a consequence of the need to meet an intrinsic cylindricity design specification that, in turn, requires concentricity between the intermediate surface obtained by the rough operation and the previous blank surface.

To illustrate the application of the proposed methodological approach, the highlighted case corresponding to manufacturing specification 4 in Figure 3 will be explained, which together with the concentricity tolerance, is one of the critical tolerances and, therefore, it requires a more detailed analysis in order to validate process plan capability.

On the upper part of Figure 4 the origin of manufacturing specification 4 is shown, being the reason that surfaces B5-B6 used for part setup do not correspond to the datum for hole axis S3 and S5 location specification. Design specification restricting every hole axis S3 and S5 location is transferred to manufacturing specification 4, that restricts the location of these axis in relation to the median plane derived from blank surfaces B3-B4, and to the symmetry specification between median planes derived from surfaces B5-B6 and B3-B4, that is required to the blank coming from the permanent mold casting process. More particularly, the tolerance value, $\varnothing 0,7$ mm, is assigned as follows: 0,6 mm for the symmetry specification and $\varnothing 0,1$ mm for the new hole axis location specification. This transfer was carried out considering just the direction with the most influence and in the asymmetrical tolerance assignment general capabilities of the two selected process were used, assigning a higher value to the symmetry specification that is obtained by casting. Plan capability will not only be limited by how

alternative to be considered can be the incorporation in the same setup of an additional machining operation of blank surfaces B3-B4. Another alternative, that would not require additional machining and could take advantage of the CNC machine measuring possibilities, could be to include an inspection (measuring) operation, previous to the machining of holes S3 and S5, of surfaces B3-B4 that would allow, by means of a reference system shift (part zero correction), the reduction of the uncertainty in B3-B4 surfaces location in relation to the common reference system.

MACHINE 1									
SETUP 1.0 (PREPARATION)					SETUP 1.1				
Reference system	Location on S B5-B6	Zero S B3-B4	Location on S B2	Location on S B1	IF_01 (S B3-B4)	MF_01 r (S 1-2)	MF_01 f (S 1-2)	MF_04 (S 3-5-4-6)	MF_07 r (S 7-9-8-10)
Ty									
					$\pm \sigma 0,7$				
	$\pm 0,6$								<i>Manufacturing specification 4</i>
					$\pm \sigma 0,1$				
	<i>Machined surfaces tolerance</i>								<i>Application of step 1 of methodology</i>
	<i>Locating surfaces tolerance</i>								
Ty									
					$\pm \sigma 0,7$				
									<i>Possible alternative after applying step 2 and 3 of methodology</i>
					<i>Machined surfaces tolerance</i>				
					<i>Part zero tolerance</i>				
					<i>IF association and derivation uncertainty</i>				
					<i>Machine location and orientation and IF extraction operation uncertainty</i>				

Fig. 4. Chart detail for manufacturing specification 4.

The incorporated inspection operation is referred on the chart in a similar way as it has been done for machining operations, relating it to an Inspection Feature (IF), in this case IF_01, which is proposed as the first setup operation. This operation is aimed at determining the location and orientation of surfaces B3-B4 median plane in relation to the machine coordinate system to make possible a coordinated system shift used as reference system (part zero). In this context, an IF is defined as a part geometry or group of geometries that can interact with one or more specific measuring procedures with the aim of obtaining information about real geometry using GPS operations such as extraction, association, derivation, etc.

Applying the first step of the methodology to the initial design specification ($\varnothing 0,7$ mm), this tolerance is transferred to a tolerance that restricts location and orientation of machined surfaces and of part zero in relation to the machine coordinate system. If as a result of the transfer a tolerance of 0,2 mm is assigned to part zero, remaining for the machining tolerance a generous value that provides a high capability index, now capability of this operation must be validated applying the third step of the methodology. Uncertainty of this operation

considers: the one regarding the extraction process when taking data or measuring; the ones regarding the GPS association and derivation operations, necessary to determine surfaces median plane; and the one regarding the reference system shift. The first of these uncertainties (extraction uncertainty) depends directly on the measuring operation, including uncertainties regarding machine location, probe deflection and contact, etc. The second one refers to the GPS mathematical operations used to obtain (integral or derived) geometries associated to real extracted geometries. The latter is often negligible when compared to the first, and the same happens with the third uncertainty which is normally even smaller than the second, which is the one illustrated on the chart. Assuming this fact, required tolerance for the extraction/measuring process could be around 0,2 mm, which can be easily met by any measuring process using on machine integrated probes.

4. Conclusions

In this work a methodology to validate and improve process plans by fostering integration of in-process inspection operations has been proposed. The proposal is based on a new and extended use of tolerance charting, traditionally used just to generate and validate manufacturing process plans, by transferring aggregate manufacturing tolerances between surfaces to specification between surfaces and a common reference system.

The described methodology also enhances integrated machining and inspection process planning, essential in dynamic manufacturing environments and in line with STEP-NC norm advances. To achieve this, a common and homogeneous approach based on features (MF and IF) is used, incorporating the GPS concepts that allow a unified processing for both process specification operators considered (machining and inspection).

Although in this work post process (off line or in line) inspection is not directly addressed, authors consider that the methodological approach and the process charting could also be used for this type of inspection. This possibility will be examined in future work, since it can help to overcome barriers that still remain between inspection and manufacturing, strengthening in that way the pedagogic value ascribed to the proposal here presented.

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