Defining tolerances in assembly process with the aid of simulation

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Abstract. Analysis and allocation of tolerance are the typical problems in tolerance planning for the assembly and its components. This paper presents the developed simulator which is able to assist in solving tolerance planning problems in production processes, both in manufacturing and assembly processes. The paper also shows the benefits of this simulator which leads to quality characterisation and improvement, cost reduction and shorter design and planning phases.

Keywords: Tolerancing for assembly, Tolerance planning, Assembly process, Simulation

1 Introduction

Nowadays it is unlikely that any producer or manufacturer will produce their products without any assembly process. The more usual case is that a producer will have several components manufactured by themselves or suppliers and then assembled together. With the introduction of tolerances, it becomes possible to join these components together by the assembly process, since the specification of required tolerances assures that the components will fall within certain cut-off dimensions and fit together. The requirements from the engineering and manufacturing sides are not in the parallel direction. Engineers like tight tolerances to assure fit and function of their designs, however, these can result in excessive process costs. Manufacturers prefer loose tolerances which make parts easier and less expensive to produce. But these may lead to increased waste and assembly problem. Therefore, tolerances must be planned carefully in order to provide a common meeting ground where competing requirements can be solved. The task of tolerance planning is the finding of the optimum where the product can fulfil customer’s requirement with optimum cost and time [6].

Planning tolerances for a finished product consists of many components created by different processes is not an easy task since the quality of assemblies depends on the quality of the manufactured components to be assembled. When the components do not fall within the tolerance, the difficulties can occur in one of the two following ways. Firstly, the intended components cannot be assembled together. Secondly, even though the intended components can be assembled together, the assembly process may require a longer processing time than expected. This would result in the higher production cost. Therefore, the planner has to determine which combination of component tolerances is the best. Simulation is chosen in this research as an approach to evaluate the tolerance planning for products which are produced particularly by manufacturing and assembly processes. The evaluation aims to improve overall quality, cost, and time in the production.

The paper explains the basic background and the concept of the developed simulator. Before ending the paper with the conclusion, the validation result of the simulator is presented.

2 Tolerance Planning

There are two main types of problem in tolerance planning; tolerance analysis and tolerance allocation. In tolerance analysis, the component tolerances are all known or specified and the resulting assembly variation is calculated by summing the component tolerances to determine the assembly variation. In tolerance allocation the assembly tolerance is known from design requirements, whereas the magnitudes of the component tolerances to meet these requirements are unknown. The available assembly tolerance must be distributed or allocated among the components in some rational ways [1].

Simulation can help in tolerance analysis by, for example, simulating the effects of manufacturing variations on assemblies to obtain the assembly function. The assembly tolerance can be determined from this assembly function based on the required yield or acceptance fraction.

For tolerance allocation, the component tolerances can be adjusted until the desired assembly’s quality is acquired. Many researchers such as Wu [7] and Jeang [4] used simulation with other algorithms such as design of experiment to determine the optimal tolerance design in an assembly.

This section has shown that simulation can be used as a helping tool in tolerance planning and tolerancing problem solving. The simulator, which is the outcome of this research, can help as well in tolerance planning and tolerancing problem solving. It provides the opportunity to analyse both individual component or part and the whole assembly by taken quality, cost, and time into account. In order to achieve the most benefit in production, tolerance adjustment should be done together with implementing a good inspection strategy. With this simulator, the tolerance planning can be done at the same time as inspection planning.

3 Simulator for Tolerance and Inspection Planning

The simulator was developed to be able to model each production process and to simulate the quality characteristics which are produced by each process. A mathematical model was developed and integrated into the simulator in order to include the effect of manufacturing process on assembly process.

The new developed simulator focuses on the tolerance and inspection planning and their influences on the production processes. It is designed to investigate the impact of different component's tolerances and inspection strategies on overall production cost, cycle time, and product quality. The flow chart of SixSigma components is shown in Figure 1. SixSigma consists of three components, which are Manufacturing, Assembly, and Inspection process.

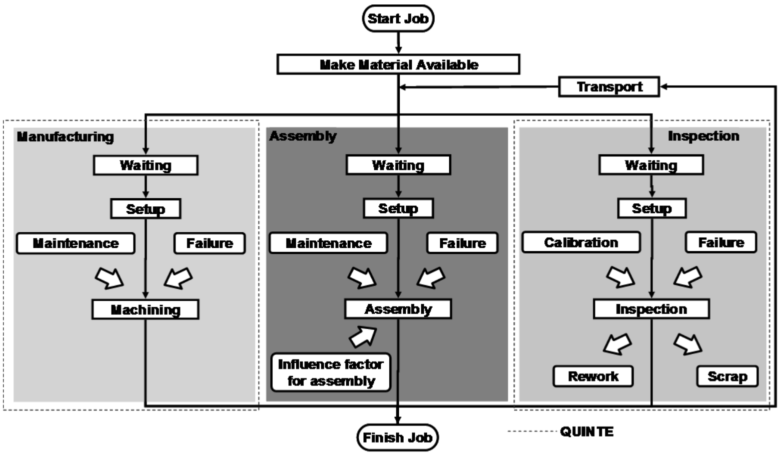

Fig. 1. Components of SixSigma simulator, showing as well the processes derived from QUINTE simulator

The concept of the manufacturing and inspection processes are taken from another simulator called QUINTE and adapted into SixSigma simulator. QUINTE was built to simulate the machining and inspection in a detailed way. It aimed to investigate the impact of different inspection strategies on manufacturing cost, cycle time, and product quality [2].

3.1 Manufacturing Process

Initially, the model of machining process is characterized by its own statistical distribution depending on the current process capability. Then, from this model, SixSigma randomly simulates the quality characteristic value of the given process. SixSigma models the distributions dynamically since the process capability is not constant over time. This phenomenon was described by Nürnberg [6]. The expected value can glide from its original value or the deviation can increase because of failure, wear of the tool, etc. This changed distribution can be restored or improved by setting up and maintenance.

From this dynamic model, the simulator generates a random number belonging to the specified distribution at the time of simulation. The obtained characteristic value denotes the actual value of a manufactured part's characteristic.

3.2 Assembly Process

The quality characteristics from assembly process can also be presented with statistical distributions. The accuracy of most assemblies is determined primarily by the accuracies of the individual components to be assembled. Therefore, these effects of the components' quality which have on the quality of the assemblies are necessary to be included in the simulator.

The simulator simulates the characteristic of the assembly in two different cases. The first case applies if the characteristics of all components are conforming. The characteristic of the assembly are randomly generated by simply using the distribution which represents the assembly process in the normal process condition. The second case applies if the characteristic of one component or more is non-conforming. The simulator cannot simulate the characteristic by using either the process's distribution alone. The model which simulates the characteristic must be influenced by the component's quality and the model differs depending on the characteristic type of the component.

For the variable characteristic case, the assumption is that the machined part, which has the characteristic that falls outside the specification limit of the machined part but still inside the acceptable limits, can still be possibly assembled. However, the probability of non-conforming in assembly process increases as compared to the probability in the normal process condition. And the probability keeps on increasing until it reaches the minimum or maximum acceptable limit. Therefore, distance ratio is introduced in order to calculate how the probability of non-conforming characteristic in assembly process changes. The distance ratio from the normal distribution is illustrated in Figure 2 [3].

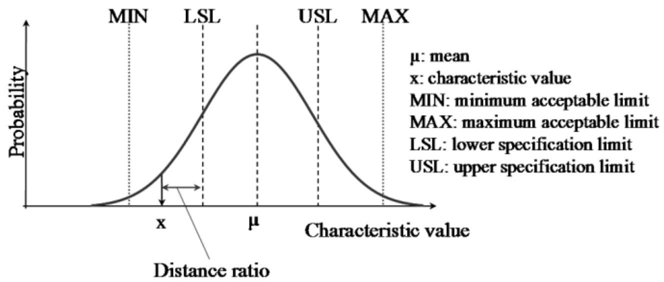

Fig. 2. Figure 2: Example of distance ratio

In the current simulator, it is assumed that the probability of non-conforming in assembly process increases linearly. The ratio of distance of machined characteristic can be calculated by the following equations:

When X is lower than lower specification limit,

$$\text{Distance ratio}_j = (LSL_j - X_j) / (LSL_j - MIN_j)$$

When X is higher than upper specification limit,

$$\text{Distance ratio}_j = (X_j - USL_j) / (MAX_j - USL_j)$$

Where MIN is minimum acceptable limit

MAX is maximum acceptable limit

LSL is lower specification limit

USL is upper specification limit

j is characteristic *j*; for *j* = 1,…,m

The distance ratio gives no effect on the assembly's quality when the component's characteristic falls inside the specification limit. Thus it is set to zero. The assembly part turns out to be a bad part when the distance ratio falls out of the acceptable limit or the distance ratio is set to be equal to one.

Each machined characteristic has different impact on the quality of the assembly. Another variable called importance factor is initiated at this point to integrate these impacts into the model. The importance factor, which can be determined from the historical data, ranges from zero to one. The multiplication of distance ratio and importance factor of characteristic is called the characteristic's influence factor.

The influence factor of the component is the combination of influence factors of related characteristics. Furthermore, the influence factor of the whole assembly can be found from its related components' influence factor. It is assumed that the effects of component characteristics on the assembly are independent from each other, thus the influence factor for component and assembly can be derived from the following formulas:

$$IF_i = 1 - \prod_{j=1}^{m} [1 - (DR_j * ImpF_j)]$$

$$IF \text{ for assembly} = 1 - \prod_{i=1}^{n} [1 - IF_i]$$

Where IF is influence factor
DR is distance ratio
ImpF is importance factor
i is component i; for i = 1,…,n
j is characteristic j; for j = 1,…,m

The influence factor for assembly will affect the model on assembly's process distribution. Besides, the distribution is influenced in time by failure and maintenance as in manufacturing process. Therefore, the assembly can obtain the characteristic value from the new adjusted model.

3.3 Inspection Process

The inspection process is simulated in the similar way as manufacturing process. Due to bias and precision, the value given by the inspection tool may differ from the true value. The capability of the inspection process is described by a statistical distribution, for example, a normal distribution. A standard deviation σinsp and a mean μinsp are assigned for each inspection process. The machined characteristic value is used as a mean for the inspection process. The expected value can glide from its original value or the deviation can increase due to failure. And the distribution can be restored or improved by setting up and calibration.

SixSigma randomly generates inspected value from the specified distribution. The inspected value will be compared with the specification limit, thus deciding whether the part is conforming or not.

After the decision is made, the part, which is declared as a conforming part, continues on its production sequence. Scraps must be sorted out and rework parts can be handled in two ways. The rework parts can be sent back to the preceding process or processes and repeat the operation. Another option is to repair the part at separated rework area.

4 Validation and Implementation

The simulator was validated with both fictional and actual cases [5]. A preliminary validation of the simulator was done with a fictional case to validate the use of simulation in evaluating different tolerances and inspection strategies The result from this preliminary validation, which is shown in Figure 3, is compared with the logical trend.

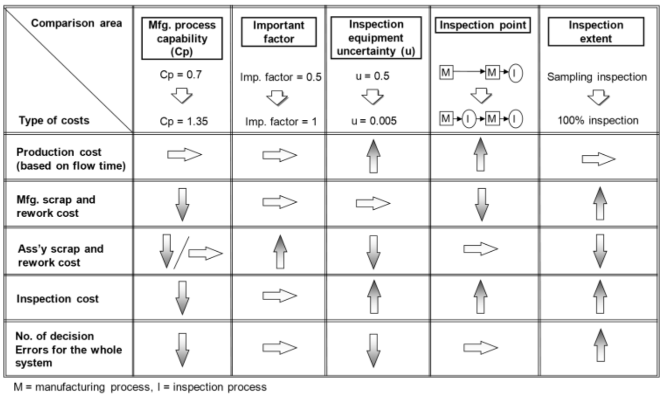

Fig. 3. Simulation results for preliminary validation

The comparisons of the results with the logical trend were done in order to investigate if the simulator is able to simulate the effects of manufacturing process on assembly process or not and how they effect on the assembly process. Additionally, comparisons of different inspection strategy aspects with respect to quality, cost, and time were conducted to investigate how the production performance fluctuates according to the changes in different strategy. The results prove that the model, which assigns an influence factor for each assembly part according to the quality and importance of its manufactured components, was successfully developed and validated.

A more extensive validation was done by implementing the simulator at a pilot company. The simulator was used to identify the optimal tolerance planning and inspection planning of one final product which consists of several components. The actual historical data was used as an input for the simulation. One of the validations was done particularly on the simulator's function in tolerance planning. This validation was experimented on a final product with 2 components (component A and B). The tested strategies were differentiated by the components' tolerances. The result in Figure 4 shows that only the tolerance of component B significantly affects the quality of the finished product. From this investigation, the company can know which component's tolerance they should tighten or improved. In this way, they will be able to properly plan the tolerances of components and achieve the require quality level of the finished product. They can also make the break-even analysis between the investments that they have to make versus the degree of improvement that they can gain.

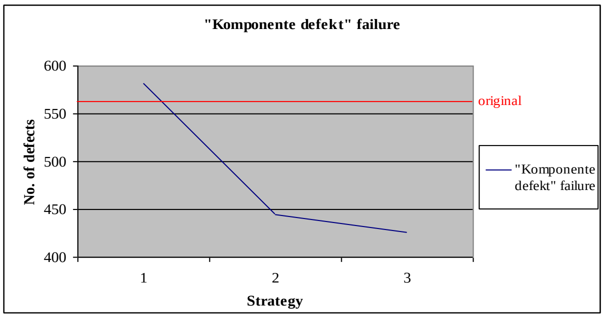

Fig. 4. Comparison on number of defects of different tolerance planning strategies

Moreover, the scenarios with different strategy for tolerance planning and inspection planning were created and ran with the simulation. The simulation gave the result which suggested several improvement points for the company. The company gained the insight of their processes and realized which process they should pay attention to. The output of the simulation were broke down into several types of costs, defects, and time used at each process. Figure 5 shows an example of the simulation result which was obtained from the pilot company case.

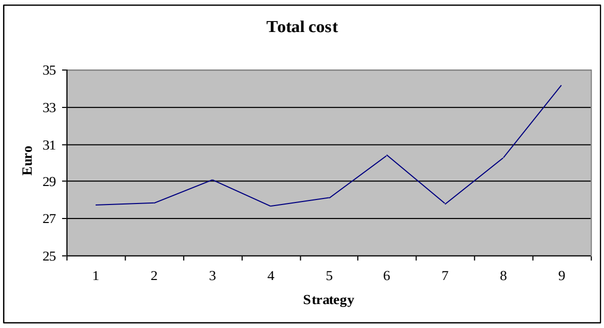

Fig. 5. One of the simulation results of pilot company

5 Conclusion

The validation proved that the simulator can assist in investigation and evaluation of the tolerance and inspection planning, so that the suitable tolerances and inspection strategy can be selected without the risk of trying it out in the real production environment. The output from the investigation leads to quality improvement, cost and time reduction. Usually the three aims are contradictory because a higher product quality causes higher costs and requires more time. Thus, the weights for the single goals must be set by each company individually. In this way, the simulator can help to improve the company's goals regardless whether production cost and cycle time are more important than product quality or vice versa. Moreover, the simulator can support the management in justification of investment in inspection equipment or manufacturing processes, for example, by illustrating the consequences of changes in inspection equipment's uncertainty.

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