

Process-based tolerance assessment of connecting rod machining process

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Abstract Process tolerancing based on the process capability studies is the optimistic and pragmatic approach of determining the manufacturing process tolerances. On adopting the define–measure–analyze–improve–control approach, the process potential capability index (C_p) and the process performance capability index (C_{pk}) values of identified process characteristics of connecting rod machining process are achieved to be greater than the industry benchmark of 1.33, i.e., four sigma level. The tolerance chain diagram methodology is applied to the connecting rod in order to verify the manufacturing process tolerances at various operations of the connecting rod manufacturing process. This paper bridges the gap between the existing dimensional tolerances obtained via tolerance charting and process capability studies of the connecting rod component. Finally, the process tolerancing comparison has been done by adopting a tolerance capability expert software.

Keywords Process tolerancing · Tolerance chart · DMAIC · Process capability · Dimensioning and tolerancing · Dimensional mapping

Introduction

The vital governing factor influencing the machining excellence is the geometric and dimensional tolerance embedded into the product as well as into the process. The two main facets of tolerancing include the arithmetic and statistical tolerancing. In arithmetic tolerancing it is assumed that the detail part dimension can have any value but within the tolerance range; whereas, in the statistical tolerancing scheme, it is assumed that detail part dimensions vary randomly according to a normal distribution, centered at the mid-point of the tolerance range and with its $\pm 3\sigma$ spread covering the tolerance interval.

The main disadvantage of arithmetic tolerancing or worst-case tolerancing is that it does not follow any trend or pattern within the tolerance zone and part dimensions resulting from the machining process can possess any value within the tolerance zone. This results in checking up of each individual dimension for its correctness within the tolerance zone, which is impractical in mass production. The statistical tolerance overcomes this drawback of arithmetic tolerance and facilitates the machining to yield dimensions according to a normal distribution. Also statistical tolerancing allows some cancellation of variation from normal distribution. Hence, this paper in essence reflects the theme of statistical tolerancing.

The structure of paper is as follows. The first introduction part of the paper discusses the required introductory theoretical domain on tolerancing methods. This is followed by a literature review on the process tolerancing. A

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tolerance stack analysis with tolerance chain of the connecting rod machining is then presented. The tolerances obtained from tolerance stack are put to test for process capability studies (Sharma and Rao 2013). Then the

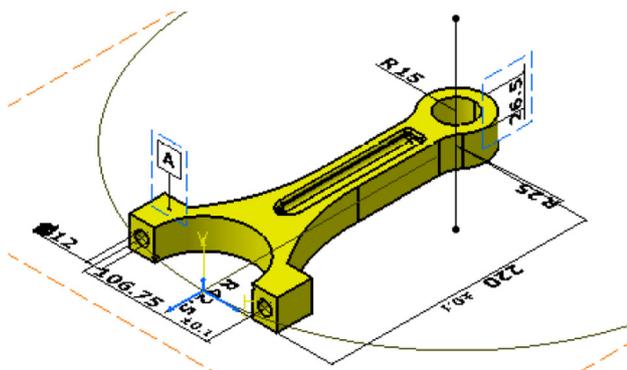


Fig. 1 Dimensioned part model of rod-end of connecting rod in CATIA V5 R14 software

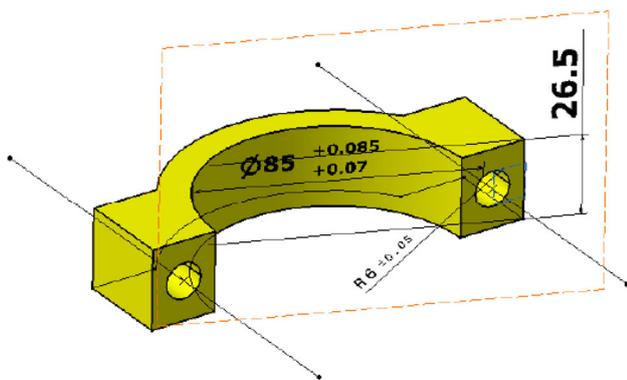


Fig. 2 Dimensioned part model of cap-end of connecting rod in CATIA V5 R14 software

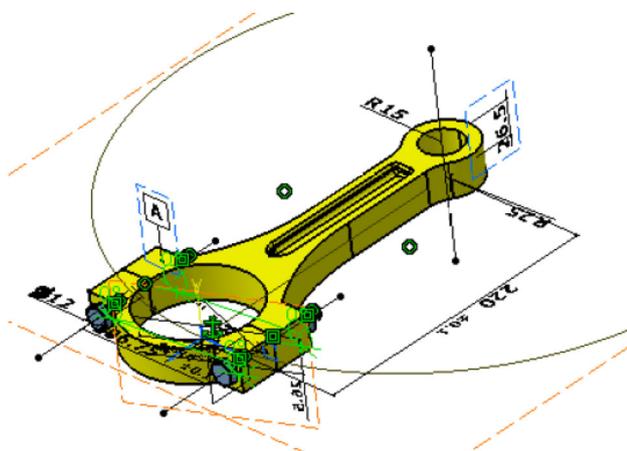


Fig. 3 Dimensioned part model of assembled view with tolerance annotations of connecting rod in CATIA V5 R14 software

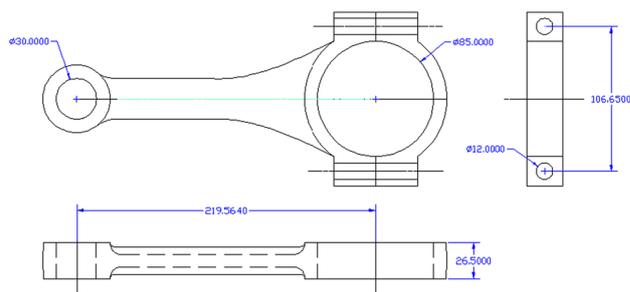


Fig. 4 Product drawing

improved C_p and C_{pk} values obtained are compared for optimum tolerance value using a tolerance capability expert software. Finally, the paper is concluded with a discussion on the results obtained.

Figures 1 and 2 show the part model rod and cap portions of the connecting rod, respectively. Figure 3 shows the assembled view of the connecting rod and Fig. 4 depicts the orthographic projection of the connecting rod product drawing.

Literature review

Primitive studies on process tolerancing were introduced through graphical representation of machining tolerance charting (Irani et al. 1989). The graphical approach and rooted tree diagram were adopted for tolerance charting (Whybrew et al. 1990). A tree theoretical representation for a tolerance chart was presented from the part blue print dimensions, stock removals and working dimensions (Ji 1993). The manufacturing process sequence was determined by using a profile representation method which incorporates a two-dimensional matrix containing a number coding system to represent the part profile (Ngoi and Ong 1993). A mathematical rooted tree model incorporating the linkage between the capability of manufacturing process and tolerance chart balancing was developed (Wei and Lee 1995). Geometrical control requirements were expressed as equivalent linear dimensions and then applied to a tolerance chart (Ngoi and Tan 1995). A backward derivation approach was traced for determining the machining tolerances starting from the last operation and computing machining allowances backwardly till the first machining operation (Ji 1996). A graphical method for presenting the process link and for obtaining the necessary working dimensions and tolerances was introduced (Ngoi and Tan 1997).

Process capability of machinery was taken into consideration for standardization of tolerances, through a non-linear programming model (Lee and Wei 1998). This minimized the total manufacturing loss occurring due to



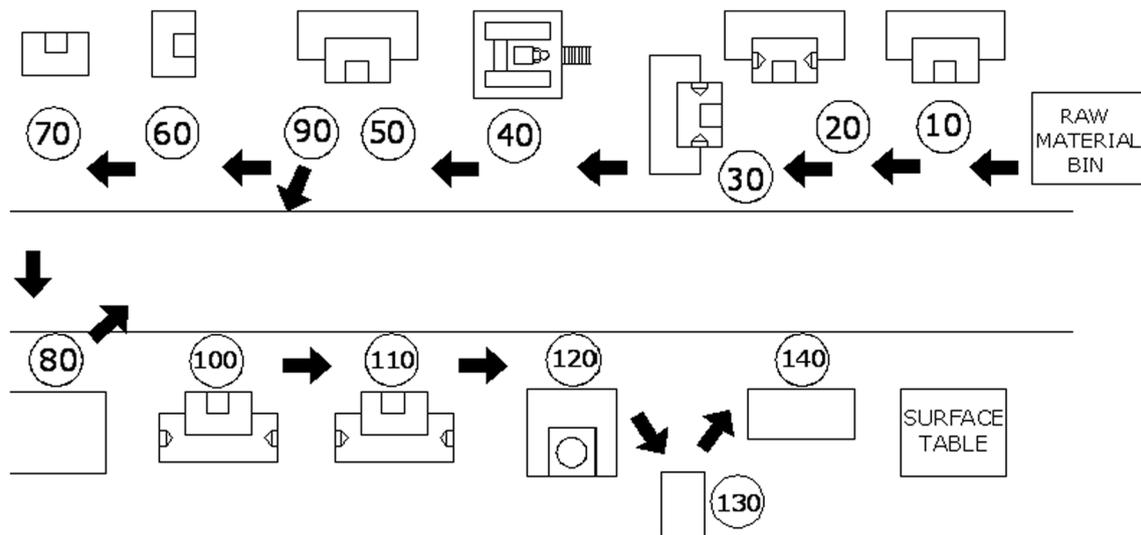


Fig. 5 Process flow chart of connecting rod manufacturing cell. Refer to Table 1 for corresponding description of connecting rod machining operations and their dimensional values

non-conforming parts. A continuous, multi-level approach to design tolerancing of electro-mechanical assemblies was outlined, wherein the assembly models for tolerancing, best practices for tolerancing, and the design process are integrated (Narahari et al. 1999). Manufacturing tolerances were allocated from forward dimensional chains, while the reverse dimensional chains were used to determine the nominal dimensions directly (Ji 1999).

Xue and Ji (2001) proposed a methodology for dealing with angular features in tolerance charting. Ji and Xue (2002) obtained the mean working dimensions from the reverse chain matrix containing reverse tolerance chains. Huang et al. (2005) devised a procedure for determining the process tolerances directly from multiple correlated critical tolerances in an assembly. Process-oriented tolerancing was focused upon, by considering all the variations arising due to tool wear, measurement device fluctuations, tolerance stack-up propagation (Ding et al. 2005). A process optimization model was introduced which considers process means and process tolerances simultaneously, with sequential operation adjustment to reduce process variability, and with part compensation to offset process shifting (Jeang et al. 2007). Peng et al. (2008) derived quality loss function of interrelated critical-to-quality dimensions. Through this quality loss function, the design-tolerances of the component are determined for achieving an improved product as well as process quality. The tolerance chart balancing was mathematically modeled for minimizing the manufacturing cost and quality loss (Jeang 2011). Concurrent tolerancing was identified as an optimization problem and a feasible solution for systematically distributing the process tolerances within the design

constraints was proposed (Sivakumar et al. 2012). Contreras (2013) proposed simplification of tolerance chains through a surface position tolerance (SPT) method for tolerance chart balancing. Chen et al. (2013) optimized the process parameters for the plastic injection molding. An improvement in the process potential capability index (C_p) and process performance capability index (C_{pk}) was registered through process capability improvement studies on thrust face thickness characteristic of connecting rod (Sharma and Rao 2013).

Recent works on tolerancing include tolerance analysis simulation during the initial design phase by a computer-aided tolerancing software (Barbero et al. 2015). The design tolerances estimated through this simulation subsequently determine the manufacturing tolerances. In another approach, complex workpiece with intricate shapes are classified based on its overall discrete geometry and tolerance analysis is performed on this overall part geometry (Schleich and Wartzack 2014). This simplifies the tolerance analysis for non-ideal complex workpiece shapes. Louhichi et al. (2015) performed realistic part tolerancing taking CAD part geometrical discrepancies into consideration. They identified the future research work as tolerance allocation by taking the manufacturing variations into consideration, which is also addressed in this paper. Considering this literature review, it can be summarized that the works on process tolerancing concentrated on the aspects of tolerance synthesis through tolerance chain and tolerance charting. In the pursuit for striking the balance between the conflicting issues of quality and cost, part tolerancing is optimized keeping the manufacturing process into consideration.

Table 1 Description of connecting rod machining operations

Machining operation number	Machining operation description	Dimensional value of machining characteristic (in mm)
10	Thrust face width rough grinding	27.250 ± 0.250
20	Gudgeon pin diameter rough boring	$\text{Ø}25.000 \pm 0.200$
30	Crank pin diameter rough boring	$\text{Ø}80.000 \pm 0.200$
40	Side face width broaching	128.300 ± 0.500
50	Thrust face width finish grinding on separate rod- and cap-end parts	26.800 ± 0.200
60	Bolt hole diameter drilling and reaming	$\text{Ø}6.000 \pm 0.200$
70	Key way slot milling	
80	Assembly of rod- and cap-end parts	
90	Thrust face width finish grinding of rod and cap connecting rod assembly	26.500 ± 0.050
100	Finish boring of gudgeon pin bore diameter	$\text{Ø}30.000 \pm 0.200$
110	Finish boring of crank pin bore diameter	$\text{Ø}84.090 \pm 0.050$
120	Crank pin bore diameter honing	$\text{Ø}85.077 \pm 0.015$
130	Magnetic crack detection	
140	Final quality check, set making and dispatch to engine assembly line	

The process capability studies on thrust face thickness, bolt hole center distance and crank pin bore diameter critical-to-quality characteristics of connecting rod were performed. After making the process capable through DMAIC approach, the end results of these process capability studies in the form of process capability values and tolerances obtained from tolerance charting of connecting rod machining process are compared with a tolerance capability expert software (Tec-ease.com 2014) and the results are documented.

Process sequence

The connecting rod manufacturing process sequence is depicted in the process flow diagram as shown in Fig. 5. The raw material from the raw material bin is the starting point of the connecting rod manufacturing process. The first roughing operation is operation no. 10 followed by a sequence of operations. The final operation is operation no. 140 where final quality check, set making and dispatch to engine assembly line are carried out. Table 1 gives the corresponding description of connecting rod machining operations.

Tolerance stack analysis of the connecting rod machining

Before proceeding to the process capability-based tolerancing study it is necessary to thoroughly examine the tolerance stack-up of the various machining processes involved in the manufacture of connecting rod. Figure 6

shows graphical representation of the tolerance chain associated with the machining of connecting rod.

The tolerance chain in the tolerance chart depicts the sequel of machining operations and their working dimensions. The tolerance stack-up and selection of reference surfaces for the subsequent machining operations is inferred from the diagram. Subsequently, the tolerances over the dimensions and the stock removal on the machining operation are also derived.

Process capability tolerancing of connecting rod

Based on the process capability improvement studies, the identified critical-to-quality characteristics in the machining of connecting rod and their initial and improved process capability values are tabulated in Table 2.

Comparison using tolerance capability expert software

The dimensional tolerances and C_{pk} values of the quality characteristic from Table 2 are the inputs into the database of the tolerance capability expert (TCE) software. In the TCE software, the worst case of manufacturing is considered, i.e., manufacturing machinery is not modern and not in good condition.

The following are the assumptions considered while using tolerance capability expert software.

1. The component or tooling used has repetitive features over a multiple references.



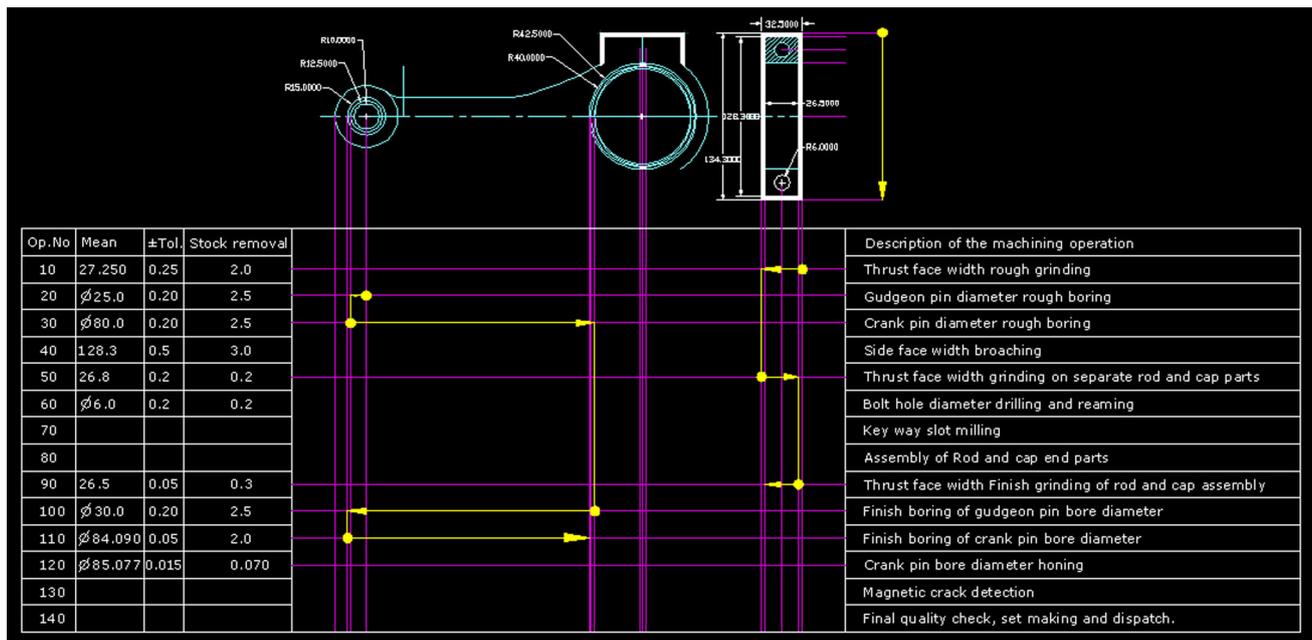


Fig. 6 Tolerance chain diagram of connecting rod in AutoCAD version 2005 software

Table 2 Process capability values of critical-to-quality characteristics of connecting rod machining process

S. no.	Quality characteristic	Dimension	Initial value			Final value		
			σ	C_p	C_{pk}	σ	C_p	C_{pk}
1	Thrust face thickness after thrust face width rough grinding	27.250 ± 0.250	0.48	0.12	0.12	0.048	1.72	1.37
2	Bolt hole center distance after bolt hole diameter drilling and reaming	106.750 ± 0.100	0.017	0.97	0.57	0.009	1.77	1.49
3	Gudgeon pin bore diameter after finish boring operation	30.000 ± 0.200	0.004	1.28	0.33	0.002	2.03	1.45
4	Crank pin bore diameter after honing operation	85.077 ± 0.015	0.005	0.5	0.34	0.002	1.52	1.45

Table 3 Graphical output from tolerance capability expert software

Characteristic	Graphical plot 1 with predicted C_{pk} for predetermined tolerance	Graphical plot 2 with predicted tolerance for predetermined C_{pk}
Thrust face thickness after thrust face width rough grinding with process dimension as 27.250 mm	See Fig. 7	See Fig. 8
Gudgeon pin bore diameter after finish boring operation with process dimension as 30.000 mm	See Fig. 9	See Fig. 10
Crank pin bore diameter after honing operation with process dimension as 85.08 mm	See Fig. 11	See Fig. 12

- The characteristic is not along the die/mould parting line.
- For producing this tolerance, simultaneous grinding of two parallel planes are involved.
- The manufacturing machinery is not modern and in good condition.
- The component size, weight, geometry and material impose additional limitations to the machine capability.
- The feature geometry does not enable the process to be operated under good conditions of practice.
- The process involves additional setups (for producing diesel as well as petrol variants of connecting rod).

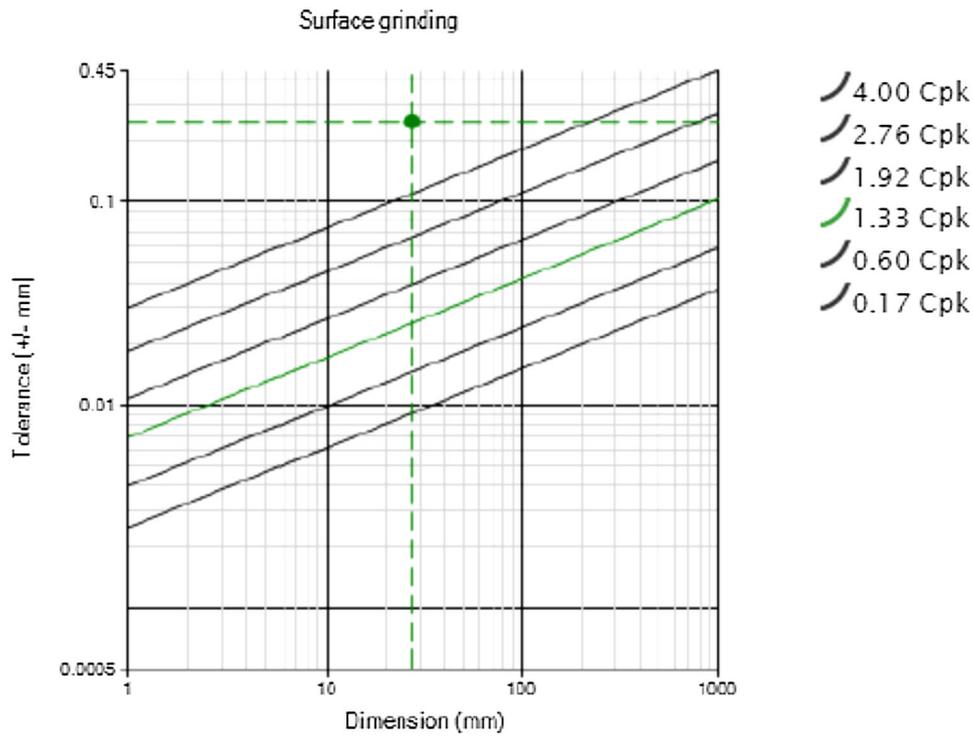


Fig. 7 Predicted C_{pk} for predetermined tolerance of ± 0.250 mm for thrust face width rough grinding dimension of 27.250 mm

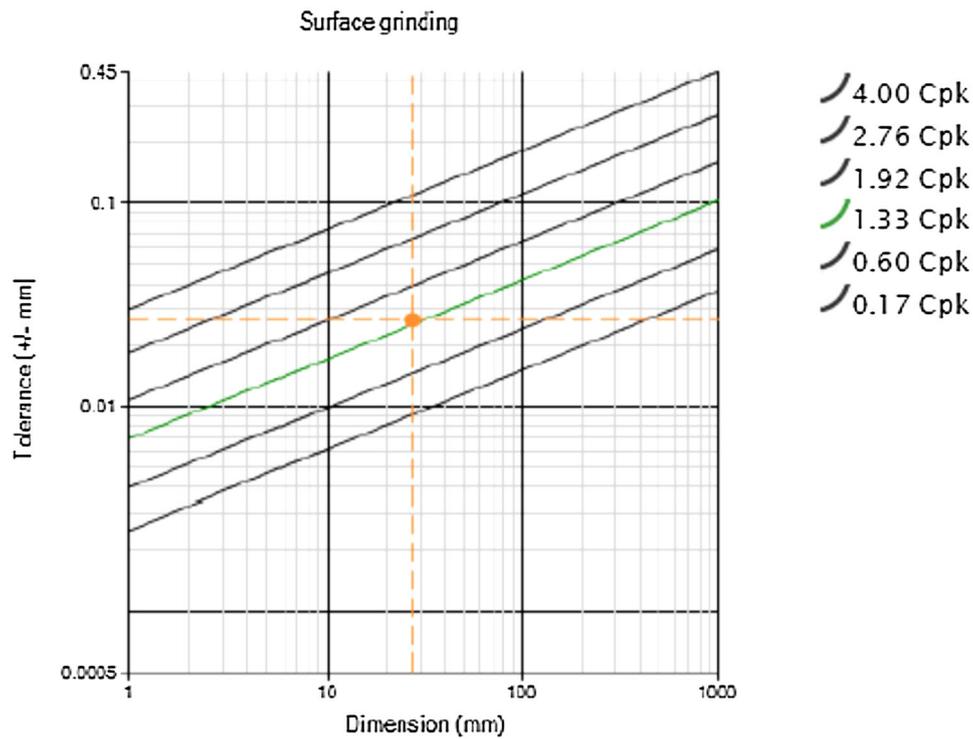


Fig. 8 Predicted tolerance for predetermined C_{pk} of 1.4 (>1.33) for thrust face width rough grinding dimension of 27.250 mm

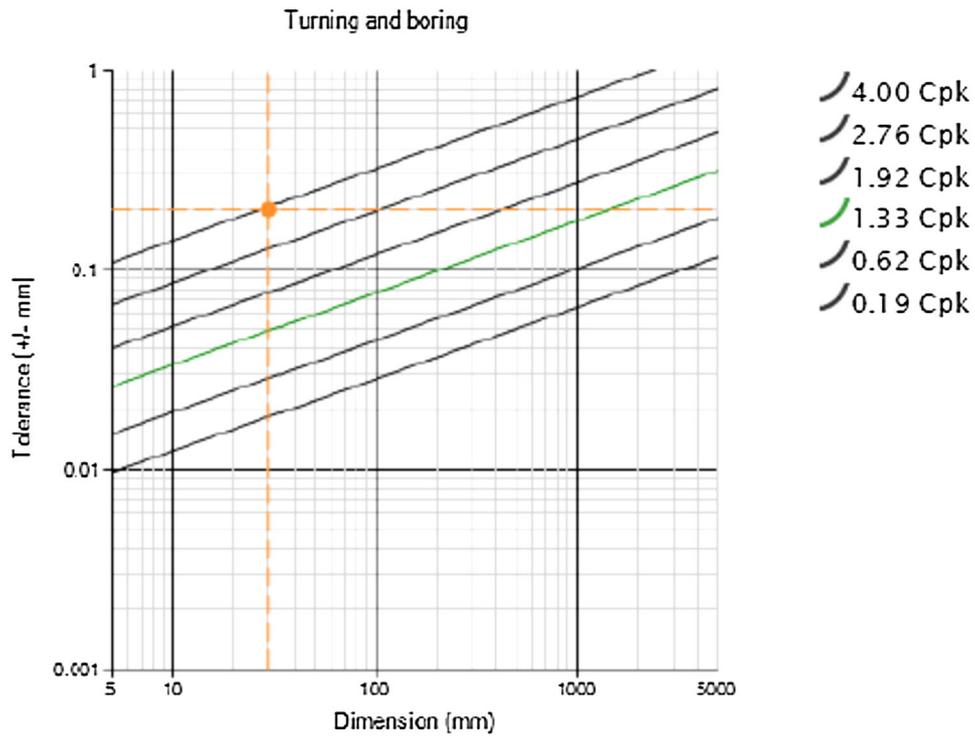


Fig. 9 Predicted C_{pk} for predetermined tolerance of ± 0.200 mm for gudgeon pin bore diameter after finish boring dimension of 30.000 mm

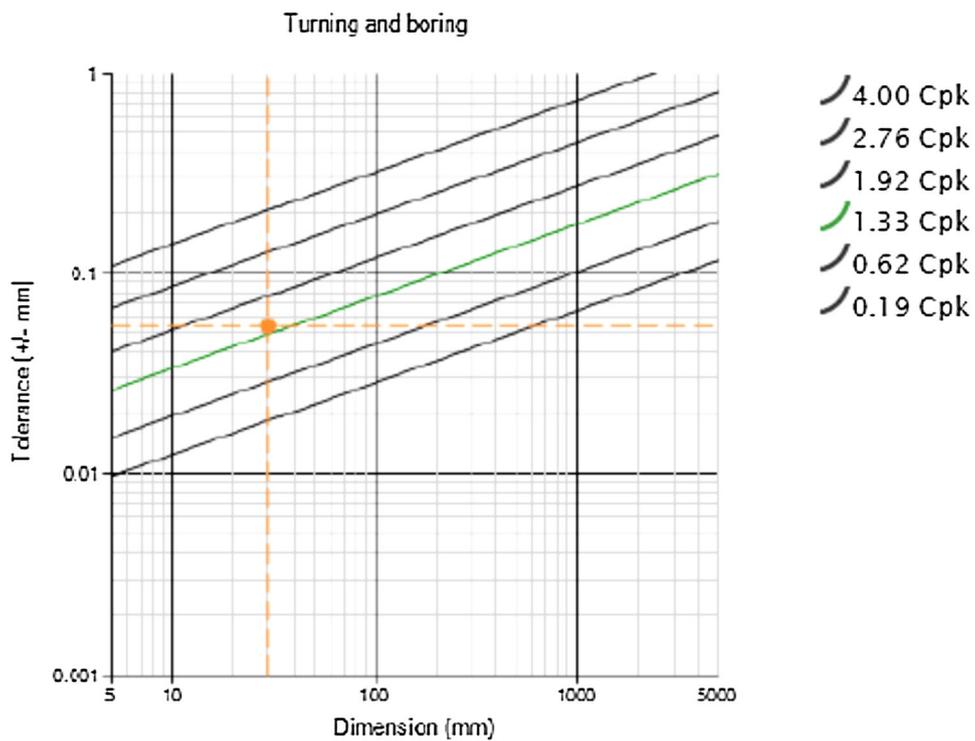


Fig. 10 Predicted tolerance for predetermined C_{pk} of 1.4 (> 1.33) for gudgeon pin bore diameter after finish boring dimension of 30.000 mm

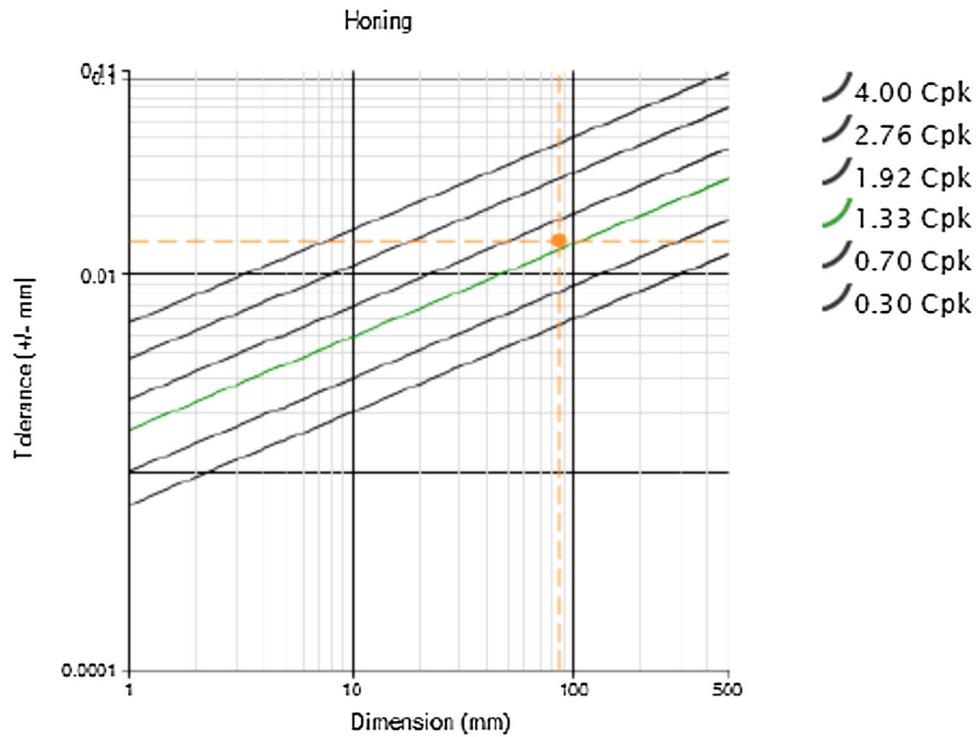


Fig. 11 Predicted C_{pk} for predetermined tolerance of ± 0.015 mm for crank pin bore diameter after honing operation dimension of 85.08 mm

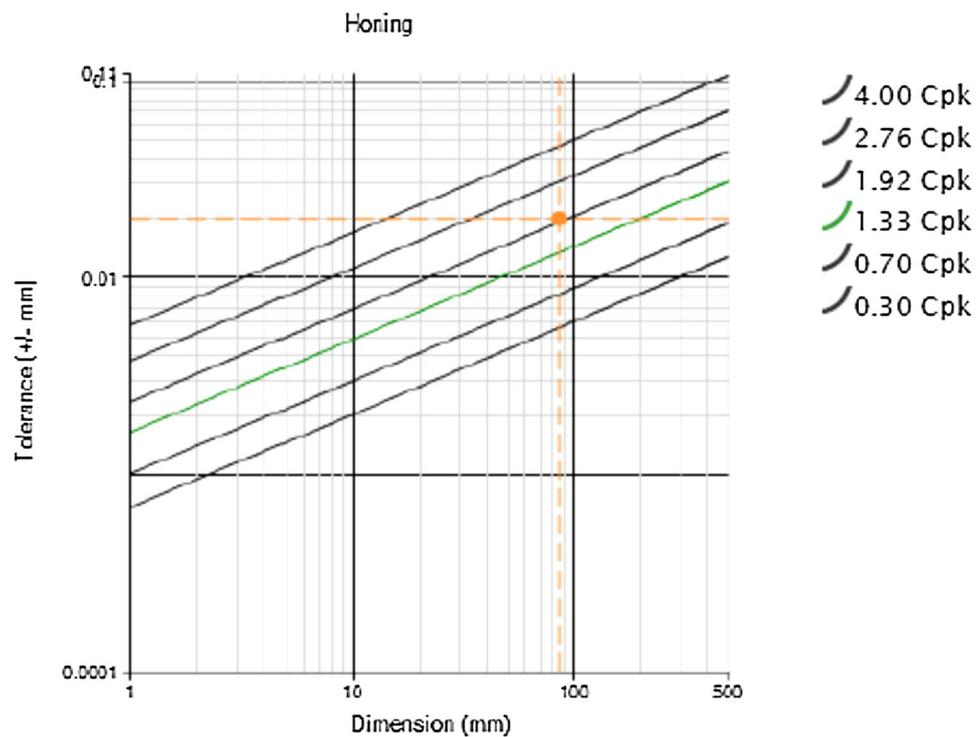


Fig. 12 Predicted tolerance for predetermined C_{pk} of 1.4 (>1.33) for crank pin bore diameter after honing operation dimension of 85.08 mm



Since the TCE software considers worst case of manufacturing, hence the results obtained are reliable with a certain factor of safety tolerance being inherent. The output obtained from the TCE software is tabulated in graphical form in Table 3.

Results and discussion

Table 3 depicts the various graphical outputs from the tolerance capability expert software. The dimension of the thrust face thickness after thrust face width rough grinding is 27.250 mm. Figure 7 shows that for thrust face thickness with a target tolerance of ± 0.250 mm, the predicted C_{pk} lies in the region above 4.00. On the other hand, Fig. 8 shows that for a target C_{pk} of 1.4 (>1.33), the tolerance predicted is 0.027 mm, i.e., about ten times less than that in Fig. 7. The next critical-to-quality characteristic under consideration is the gudgeon pin bore diameter after finish boring operation as 30.000 mm. Figure 9 gives that for a target tolerance of ± 0.200 mm, the predicted C_{pk} is 3.89; whereas, Fig. 10 gives that for a target C_{pk} of 1.45 (>1.33), the tolerance is ± 0.054 mm for gudgeon pin bore diameter, leaving a large scope for improvement in this quality characteristic. The third critical-to-quality characteristic is the crank pin bore diameter after honing operation with process dimension as 85.08 mm concerning Figs. 11 and 12. In Fig. 11 it can be seen that for a target tolerance of ± 0.015 mm, the predicted C_{pk} is 1.5 and from Fig. 12 it can be deciphered that for a target C_{pk} of 2.0, the predicted tolerance is ± 0.020 mm. Figures 11 and 12 show close resemblance to each other and it can be deduced that the values of tolerances and C_{pk} obtained from tolerance sheet and process capability studies are in-phase with the values obtained from the tolerance capability expert software for the crank pin bore diameter after the honing operation.

Conclusion

Optimal values of the dimensional tolerance bandwidth are determined from the statistical process control charts. The process is made capable with the capability indices more than 1.33, i.e., more than a moderate level of 4σ , which is the industrial benchmark. After having made the process capable, the upper and lower tolerance bounds are shrunk to the calculated control limits inherent in the process. With the newly obtained tolerance values, the process is again calculated for its capability to be more than 4σ level. This iterative procedure of process improvement is carried out till the convergence is reached and no further noticeable process improvement is seen. Thus, the dimensional

tolerances are optimized in accordance with the statistical process control improvement studies.

This paper witnesses an application of process tolerancing which proves to be a better way of finding the optimal tolerancing of the part, leading to fewer process rejections and improved quality levels. The end results of the process capability values and tolerances obtained from tolerance charting of connecting rod machining process are compared with a tolerance capability expert software. The results showed further scope of improvement for the thrust face thickness and gudgeon pin bore diameter, whereas the crank pin bore diameter after honing operation showed close resemblance between the values obtained through process capability and tolerance capability expert software.

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