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Reaming process improvement and control: An application of statistical engineering

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A B S T R A C T

A reaming operation had to be performed within given technological and economical constraints. Process improvement under realistic conditions was the goal of a statistical engineering project, supported by a comprehensive experimental investigation providing detailed information on single and combined effects of several parameters on key responses. Results supported selection of production parameters meeting specified quality and cost targets, as well as substantial improvements.

Keywords:
Reaming
Surface roughness
Hole diameter
Quality control
Statistical engineering
Process improvement

1. Introduction

Specifications for a steel bushing, to be produced in small batches, include dimensional and surface finish tolerances on bore [1], namely diameter 10.22 H7 and Ra $\leq$ 0.5 μm. Batch size and other considerations pointed towards finishing by machining, to be performed on a general purpose, low cost machine tool. Reaming was retained for finishing, as a process capable of yielding required results when performed on inexpensive machine tools such as a drill press with simple fixtures. The process is furthermore well suited for medium to small batch production typical of job shops, facing the challenge of meeting specifications at competitive costs. A previous investigation carried out on similar workpieces yielded resultsdescribedin Fig.1,aclassicShewhartcontrolchart[2], showing capability rather far from target. Substantial room for process improvements on several counts being however anticipat-ed, a comprehensive investigation was embarked upon, aimed at supportingprocessimprovementwithasystematicproblem solving approach[3,4].

Bore quality was deemed to be affected mainly, albeit not exclusively,byreamer'sproperties,processparametersand machine tool signature, see Fig. 2. Single and combined effects, and related uncertainties,ofsuchparametersonsurfacefinishand boregeometry werethereforeinvestigatedwithintheframework of an experimental investigation. Improved understanding of apparently minor influences led to enhanced process control, and substantially better results at no extra cost.

Considerations supporting selection of machine tool on account of technical and economic factors are summarized. In a nutshell, productionofpartswithinconformancezone(ASME B89.7.3.1:2001 [5]; ISO 14253-1:1998 [6]) – determined in terms of both specificationsandmeasurementuncertainty–depends uponcritical properties of production and measurement processes, in terms of performances, and costs. A trade-off between characteristics provided by different systems leads to identifica-tion of preferred operating range. Cost analysis may be readily performed in terms of simple models, supporting in the case at hand adequacy of machine tool selected and of measurement equipment for off-line quality control.

2. Statistical engineering approach

A comprehensive approach was selected, drawing upon quality tools and planned experiments to enhance specific knowledge as required to support systematic process improvement [3]. Current operating conditions provided a reference level to assess improvements obtained according to a given testing strategy, aimed at identifying combinations of process parameters meeting specifications in a cost effective way. Extraction of relevant information from the process through a designed pattern of tests, evaluation of results in terms of technical significance taking into account uncertainty budgets, identification of process parameters meeting technical and economical requirements, validated by ad hoc tests, made up the road map selected.

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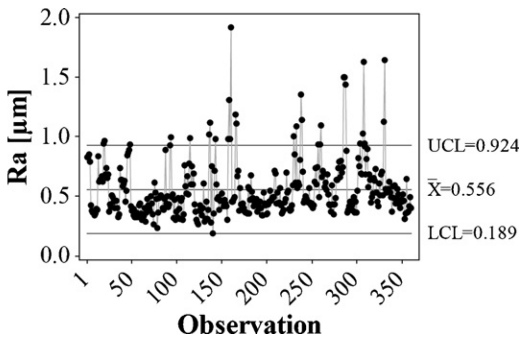

Fig. 1. Control chart for surface roughness parameter Ra, obtained in a previous investigation.

2.1. Designed experimentation

A budget accommodating four sets of tests, carried out on as many days, was allotted to experimental work, permitting a fair amount of replication, particularly desirable when dealing with surface roughness measurements, often affected by substantial scatter and occasionally by outliers. Selection of factors and levels, and testing strategy, was based on previous experience in reaming austenitic stainless steel [7–9].

A 2^3 full factorial design with 3 factors at 2 levels each was selected, i.e. lubricant, feed and spindle speed (see Table 1). Lubricant being far more "hard-to-change" than feed and speed –whose sequence was readily randomized– test layout was adapted accordingly, resulting in a split-plot arrangement [10] in which lubricant was changed only once in every day of testing. The inherently larger uncertainty thus affecting estimates of lubricant effect on responses did in fact hardly matter, since that effect proved to be the largest on roughness, as expected [1,7–9]. Day of testing was dealt with a covariate, accounting for drift due, e.g. to tool wear.

Sixteen workpieces were reamed in each set of tests, a randomly selected batch of eight with a cutting fluid followed by another batch of eight with the other one, after thorough cleaning of setup. The sequence was repeated on four days, yielding 64 finished bores, on each of which six roughness measurement were taken, for a total of 384 recorded values. Furthermore, after every series of sixteen specimens reamed using Reamer 1, two additional, randomly picked parts were reamed for reference purposes using Reamer 2 at conservative cutting conditions (feed = 0.1 mm/rev, spindle speed = 140 rpm), as tests in these conditions were found to be the least affected by uncontrolled disturbances.

Table 1
Factors and levels.

Factor	Level	
	–	+
Feed, f [mm/rev]	0.1	0.3
Spindle speed, N [rpm]	140	640
Lubricant	W1	M

Tests were carried out on DTU's 3.7 kW Modig drilling machine. Two nominally identical high speed steel 6-flute left hand helix reamers were used, namely DIN 212 – F1352 TITEX, mounted in a floating holder SK30 x MK3 Gewefa, with run-out of less than 4 µm. Reamer 1 was used throughout all tests, while Reamer 2 provided a reference substantially unaffected by wear. Both were initially run-in by machining five workpieces, and carefully checked for wear before and after the tests on a toolmaker's microscope.

Workpiece material was austenitic stainless steel AISI 316L (hardness 258 HV20), rather hard to machine due to its ductility, high strain hardening and low thermal conductivity. Cylindrical specimens 15 mm long by 29 mm OD with pilot holes 9.9 mm dia., machined under closely controlled conditions, were used for tests. Workpieces were clamped in a precision chuck, fully immersed in the cutting fluid, aligned with tool holder using a lever-type dial gauge. Two cutting fluids were used in tests, namely a straight mineral oil, undiluted (M), and an amine-free water-based cooling lubricant (Rhenus) at 1% concentration (W1).

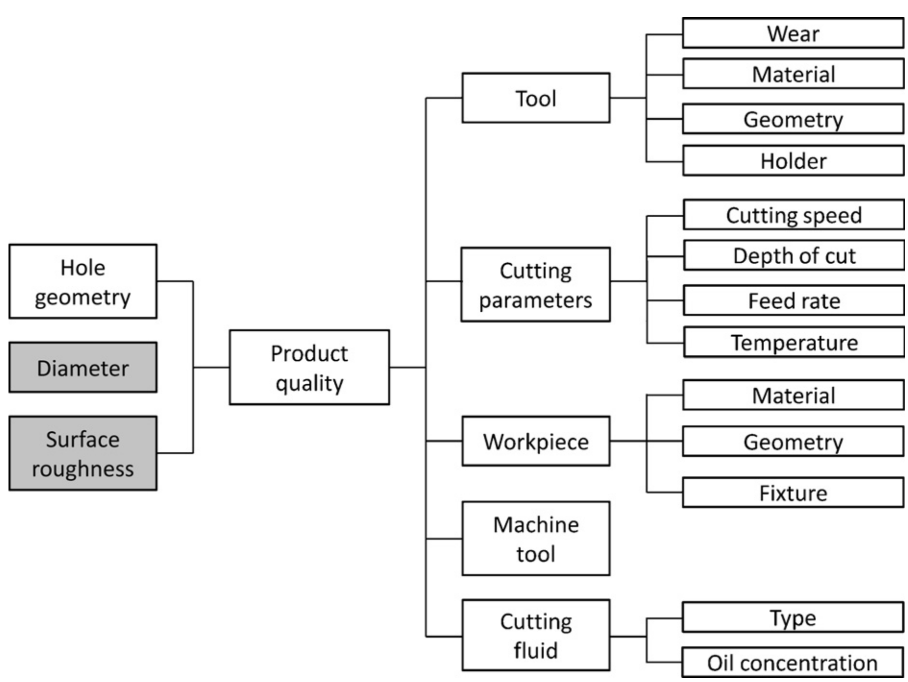

Fig. 2. Process parameters in reaming (right) and performance criteria (left) for product quality [20]. The highlighted are those considered in this work.

3. Surface roughness and hole diameter measurements

A conventional parameter, Ra (ISO 4287:1997 [11]), was used to characterize surface roughness. Measurements were carried out using a skid stylus roughness tester with a resolution of 1 nm, Taylor Hobson Surtronic 4 equipped with a 2 μm radius tip (ISO 3274:1975 [12]).Evaluationlengthln=4mm,low-passλ_s =0mm andhigh-passλ_c = 0.8 mm profile filtering (ISO 3274:1996 [13]), were applied. Six profiles were recorded for each specimen at three different positions, equallydistributedonboresurfaceat eitherend.

Bore diameters were measured after completing a batch of 18 specimens (16 test specimens with Reamer 1 and 2 reference specimens with Reamer 2) using a 3-tip TESA bore gauge with a resolution of 1 μm. Measured were taken at either end of bore, with three replications. Bore gauge was regularly checked for bias on a reference ring of calibrated diameter 9.999 mm, and measurements corrected accordingly as required. Some considerations follow concerning uncertainty of surface roughness and bore diameter measurements.

3.1. Uncertainty of roughness measurements

Uncertainty using stylus tester was assessed taking into account instrument calibration and variability of machined surface. The instrument was calibrated using an ISO type C2 standard (ISO 5436-1:2000[14]),anduncertaintywascalculated as:

$$U_{\text{inst}} = k\sqrt{u_n^2 + u_r^2 + u_b^2} \quad (1)$$

where U_{inst} is the expanded uncertainty of stylus instrument; k the coverage factor (k = 2 for a confidence level ≈ 95%); u_n the standard calibration uncertainty of roughness standard; u_r the instrument repeatability, calculated as standard deviation of the mean of repeated measurements on roughness standard; u_b is the standard uncertainty due to instrument's background noise, calculated as standard deviation of repeated roughness measurements on an optical flat.

Individual uncertainty contributions being respectively u_n = 6 nm, $u_r < 1$ nm, u_b = 4 nm, expanded uncertainty relevant to calibration of stylus instrument is U_{inst} = 15 nm.

The uncertainty budget (Table 2) of roughness measurement process was calculated according to GUM (JCGM 100:2008 [15]), taking into account both instrument's calibration and roughness variability on reamed surface, the latter assessed through repeated measurements at different locations. The uncertainty was calculated as:

$$U_{\text{roughness}} = k\sqrt{u_{\text{inst}}^2 + u_s^2} \quad (2)$$

where $U_{\text{roughness}}$ is the expanded uncertainty of roughness measurement process; k the coverage factor (k = 2 for a confidence level ≈ 95%); u_{inst} the instrument standard uncertainty; u_s the measurement uncertainty caused by local roughness variations; $u_s = s_s/\sqrt{n}$, where n is number of measurements carried out with standard deviation s_s.

Table 2
Uncertainty budget for the roughness measurement process.

Day #	Standard uncertainty components [μm]		Expanded uncertainty [μm]	Average A [μm]	$U_{\text{roughness}}/A$ [%]
	u_{inst}	u_s	$U_{\text{roughness}}$		
1	0.007	0.016	0.035	0.39	9.1
2	0.007	0.016	0.035	0.44	8.2
3	0.007	0.018	0.039	0.46	8.5
4	0.007	0.021	0.044	0.50	8.9

3.2. Uncertainty of diameter measurements

Uncertaintyassessmentofthemeasurementsperformedwith the three-tipboregaugewasevaluatedfollowingISO(ISO15530- 3:2011) [16], which describes a method for uncertainty assess-ment based uponrepeatedmeasurementsonacalibrated workpiece–areference ring in the case at hand – under measuring conditions as close as possible to those concerning actual measurands. The uncertainty budget of measurements on reamed holes (U_{diameter}) was calculated accordinglyas:

$$U_{\text{diameter}} = k\sqrt{u_{\text{cal}}^2 + u_p^2 + u_w^2} \quad (3)$$

where U_{diameter} is the expanded uncertainty of measurements on reamed holes; k the coverage factor (k = 2 for a confidence level of approx. 95%); u_{cal} the calibration uncertainty (from reference ring's calibration certificate); u_p the standard uncertainty of measurement procedure, calculated as standard deviation of repeated measurements on reference ring, taking into account variation of measurements performed in different days; u_w is the standard uncertainty resulting from manufacturing variations, evaluated in a worst case condition.

Accordingly, expanded uncertainty for measurements on reamed holes was found to range between 0.01 and 0.02 mm according to days.

4. Results and discussion

Exploratory data analysis [17] highlights some features of surface roughness and bore diameter measurements. Box-plots in Fig. 3 suggest compatibility among Ra values measured on bores machined with Reamer 1 over the four days, within the uncertainty estimates referredtoabove.Eachbox-plotincludesatotalof96Ra values,coming from 8 treatment combinations replicated twice, with 3 replicated measurements at both ends. An increasing trend in Ra values appears for both central tendency and scatter, likely to be due to accumulated tool wear. The distribution pertaining to each box-plot appears approximately lognormal, as expected Ra being inherently positive. Evidence of several outliers, detected at EDA level, is upheld by tests suchasmodifiedIQR[18].

Results obtained with Reamer 2 are compatible with those pertaining to Reamer 1 for Day 1; over the following days accumulated wear on Reamer 1 contribute to observable differences. Boxplots of Fig. 4 pertain to measured values of Ra parameter on bores finished with Reamer 1 on Day 1 split by lubricant, feed and speed. BoxplotsequenceforLubricantW1

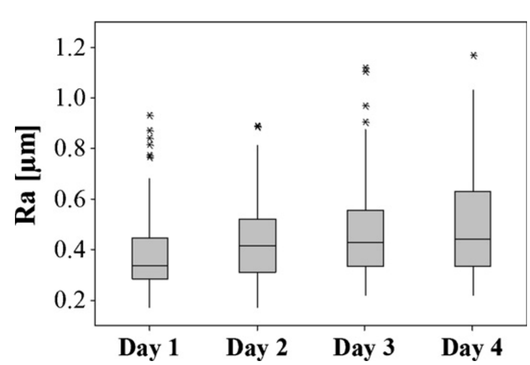

Fig. 3. Box-plot of measured values of Ra parameter for the four days, pertaining to bores finished with Reamer 1.

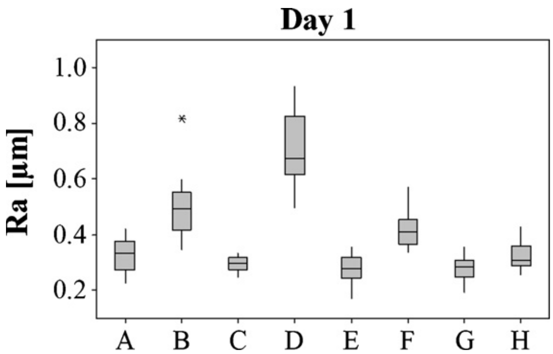

Fig. 4. Box-plots of measured values of Ra parameter on Day 1. Symbols identify cutting conditions (lubricant-feed-speed) as follows: A = W1-0.1-140; B = W1-0.1-640; C = W1-0.3-140; D = W1-0.3-640; E = M-0.1-140; F = M-0.1-640; G = M-0.3-140; H = M-0.3-640.

(low feed/low speed, low feed/high speed, high feed/low speed, high feed/high speed) is followed by the same succession for Lubricant M. Specification is met with Lubricant W1 at low speed for both high and low feed, and not quite met at high speed. With Lubricant M, specification is always met, Ra is lower at low speed, feed hardly matters. These results were further supported with the analysis of the surface roughness profiles. A good agreement was found between low values of Ra parameter and 2D roughness profiles; low Ra values obtained mainly for lubricant M, low feed, low rotational speed resulted in a reproducible clear cut (Fig. 5, top). On the contrary, cutting conditions represented by lubricant W1, high feed and high rotational speed resulted in remarkable irregularities and a bigger scatter (Fig. 5, bottom).

Results of ANOVA for Ra parameter (see Table 3) clearly show the lubricant being dominant factor having the greatest single effect (27%), followed by spindle speed (18%).

Diameter measurements at EDA level show substantial bell-mouthing, hinting at influence of several parameters. Dotplots of diameters values observed on bores machined with Reamer 1 (Fig. 6) are to be considered in terms of the relevant uncertainty

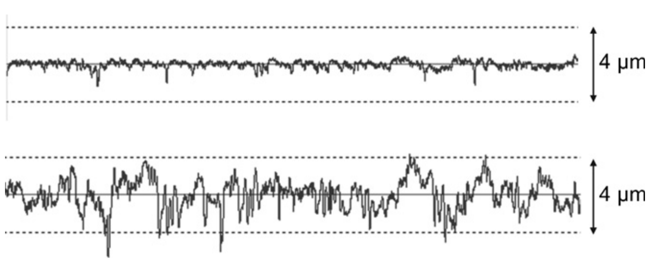

Fig. 5. Surface roughness profile obtained for combination of lubricant M, low feed, low spindle speed showing a reproducible clear cut (top). Profile corresponding to combination of lubricant W1, high feed and high spindle speed exhibits besides larger roughness remarkable irregularities and bigger scatter (bottom).

Table 3
Summary of ANOVA for response Ra.

Source	DF	SS %
Significant effects (6)	**8**	**62**
Lubricant	1	27
Spindle speed	1	18
Feed × spindle speed	1	7
Day	3	4
Feed	1	3
Lubricant × spindle speed	1	3
Non significant effects (7)	**20**	**8**
Error	**355**	**30**
Total	**383**	**100**

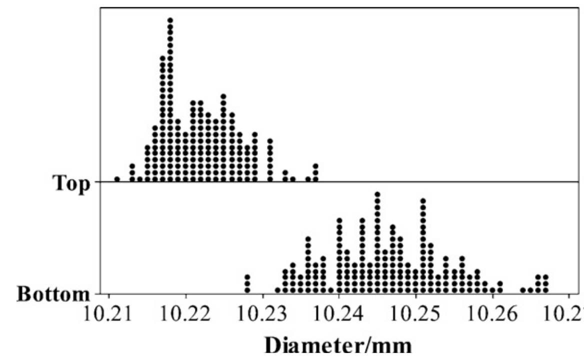

Fig. 6. Dotplots of measured values of diameter at bore's top and bottom.

estimates. Each dotplot includes over 190 diameter values, measured respectively at bore's top (a) and bottom (b), the latter exhibiting fairly larger mean and range.

ANOVA for bell-mouthing, estimated by the difference ΔD between diameters measured at the bottom and at the top of the bore, singled out spindle speed as the main factor having the largest single effect, accounting for well over a quarter of total sum of squares, followed by three-factor interaction speed-feed-lubricant, and two-factor interaction feed-lubricant, covering together one sixth of total sum of squares. The three factor

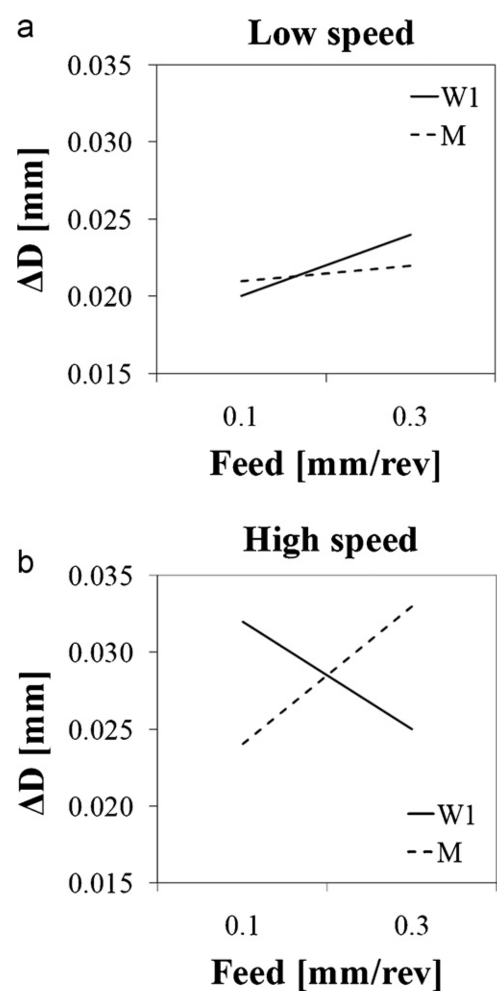

Fig. 7. Three-factor interaction speed–feed–lubricant for bell-mouthing ΔD depicted as interaction between speed – at low (a) and high level (b) – and the two-factor interaction feed–lubricant.

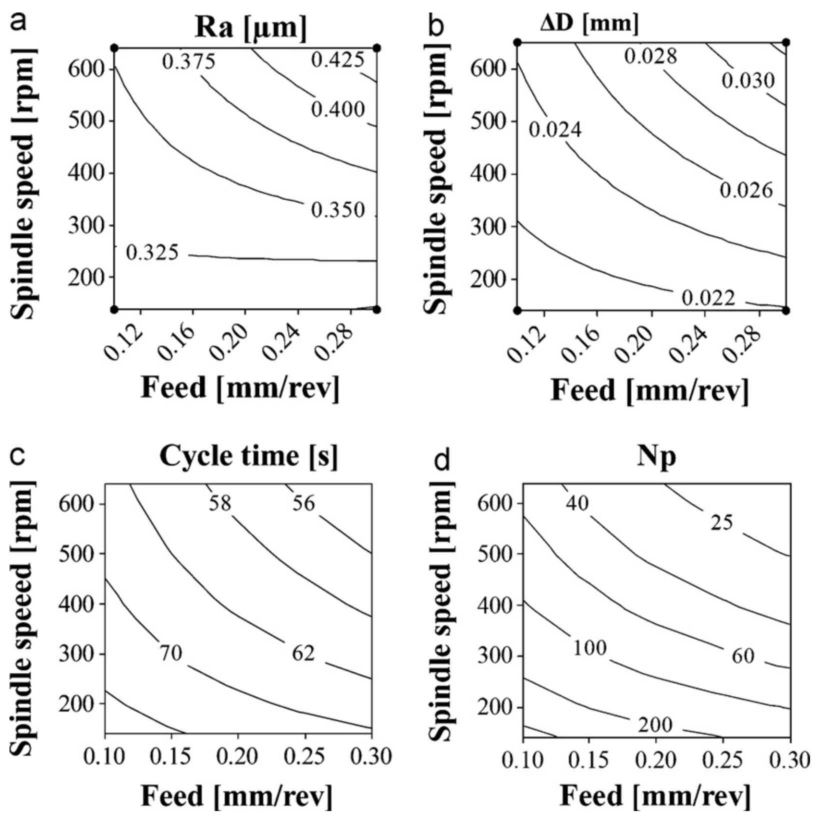

Fig. 8. Contour plots of roughness parameter Ra (a) and bell-mouthing ΔD (b) for data relevant to lubricant M, of cycle time (c), and number of pieces reamed per regrind N_p, versus feed and spindle speed (d).

interaction may be explained as an interaction between a single factor (spindle speed) and a two-factor interaction (feed-lubricant) (see Fig. 7).

At low spindle speed feed and lubricant show marginal effects only on bell-mouthing ΔD; however at high speed lubricant W1 is associated with significantly lower ΔD at high feed, and worse at low feed, as opposed to lubricant M. Superior cooling properties of W1, and lubricity of M, may explain these effects.

Cycle time is made up by a constant component of 50 s (covering workpiece handling–loading–unloading, tool approach and withdrawal), and a variable component, namely actual machining time – determined by spindle speed and feed – ranging between 5 s and 64 s.

Tool life was also considered among terms entering machining economics. An extended Taylor model, reasonable within the range of considered machining parameters, links tool life T to feed f and speed V:

$$VT^n f^r = C \quad (4)$$

Tool life in terms of number of pieces reamed per regrind N_p, i.e. ratio of tool life T to cutting time per piece t_c, is:

$$N_p = \frac{T}{t_c} = KV^{1-(1/n)} f^{1-(r/n)} \quad (5)$$

where Taylor's constant, bore length, etc. are covered by term K. Given but a limited amount of available tool life data, handbook values are adequate for exponents, whose experimental estimates are affected anyways by quite large uncertainties unless derived from very extended datasets [19].

Contour plots of the four main responses considered: surface finish, bell-mouthing, cycle time, and tool life, shown in Fig. 8(a)–(d), point out to treatment combination "high feed–low speed" as the overall best one also according to minimax criterion, meeting specifications with affordable production rate and tool life. At low speed surface finish is substantially unaffected by feed, and nearly so bell-mouthing, while cycle time is reduced by about one third when moving from low to high feed. Breakdown of cycle time in elementary operations shows that improvements in setup and overall organization offer the best opportunities for improvement of production rate, since with the preferred combination of machining parameters actual reaming accounts for less than one sixth of total cycle time. In terms of tool life high speed is definitely ruled out.

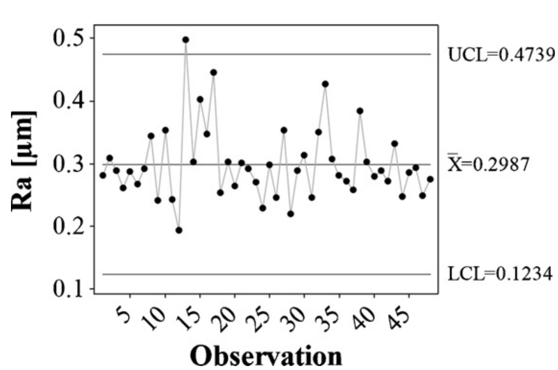

Fig. 9. Control chart for roughness Ra considering high feed and low speed for data relevant to lubricant M.

Results obtained in a confirmatory test run with the "lubricant M – high feed–low speed" combination, selected in the light of experimental investigation (Fig. 9) show full conformance with specifications, along with a substantial improvement in process control, as underlined by comparison with Fig. 1. A corresponding improvement is obtained also concerning bore diameter, also fully under control.

5. Conclusions

Even a simple process as bore reaming may be substantially improved by systematic investigation, with a comprehensive statistical engineering approach. A process barely approaching specifications was readily improved into one fully meeting them, with minor modifications only. Meeting specifications in a cost effective way implies realistic evaluation of both process inherent scatter and of measurement uncertainty, in order to achieve a proper balance, and ensure viable cycle times. Some peculiar combined effects of process parameters may not be unraveled in overly simple terms; however even three factor interaction, while requiring proper statistical tools for detection and evaluation, may be readily explained using simple graphs, providing clues for further investigation.

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