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Taylor, E. and Slatter, T. orcid.org/0000-0002-0485-4615 (2017) Role of temperature parameters in achieving precision traverse cylindrical grinding of chrome-plated ferrous metal rolls. Journal of Manufacturing Science and Engineering, 139 (12). 121012. ISSN 1087-1357

https://doi.org/10.1115/1.4037889

Role of temperature parameters in achieving precision traverse cylindrical grinding of chrome-plated ferrous metal rolls

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ABSTRACT

This work considered the finishing precision grinding process at a small ferrous metal roll manufacturer. A design of experiments methodology was used to evaluate the process and ascertain whether the degree of confidence gained from the process offers an acceptable level of risk in the conformance of end products to customer requirements.

A thorough identification of the process variables and measurement considerations relevant to the process was carried out, before assessing and categorizing these variables using the grinding cycle as a 'black box' system.

Coolant temperature, environment temperature, work speed, and traverse speed were all considered against measured size change, surface finish and circular run-out in a full factorial experimental design. The experiments were carried out on a manual cylindrical grinding machine retrofitted with digital

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encoders on the driven axes, with a chrome plated roll 300mm in diameter as the workpiece. Experiments were conducted over a period of 11 months during which the machine used was part of ongoing production environment.

The results show that control of temperature, both of the coolant and of the environment in which the machine was operated, was the most important of the variables studied, but the skill of the machine operator remains dominant in the process overall.

Keywords: Grinding and Abrasive Processes, Precision and Ultra-Precision Machining, Temperature

INTRODUCTION

Small (volume) precision grinding job shops have a market differential in their ability to process a wide variety of customer needs and types of work. In the case of producing ferrous metal rolls (referred to as the “workpiece” throughout this paper) for industries as diverse as paper and laminate film processing to power generation, the work carried out can be either the refurbishment of a used roll or the final stages of the workpiece’s initial production. The operations performed are typically a finish grind followed by polishing, but these processes are carried out on a wide range of workpiece sizes (diameter/length) with many different cylindricity and surface finish requirements. This paucity of repeatable work means analysis of the process in an experimental sense is a difficult task.

To enable such analyses, identification of the process variables that are most dominant in all jobs is necessary. The use of a robust design of experiments (DoE) methodology [1] allows the process of "precision grinding" to be broken down and analysed with the aim of improving knowledge about the outcome of such a grinding process.

The work presented here describes a methodology to define and optimise the finish grinding process to characterise a job shop's capability of consistently achieving the lowest tolerances in precision grinding regardless of job type. Also identified is what is needed to control and minimise the uncertainty [2] in processing and measurement to improve the chance of achieving product conformance and finally ascertain the capability and confidence level in the lowest achievable tolerances through defining and optimising the grinding process [3], [4].

Speeds and Forces

The cutting dynamics of the system are affected by the traverse speed, with chatter most likely to occur at lower traverse speeds due to instability [5], [6]. As the wheel traverses across the work the wheel wears away, therefore a smaller cut depth is expected at the end of the traverse. Attempts to mitigate this have been made by wheel in-feed during grinding, adjusting the machine table to be closer to the wheel at the non-starting end, or starting grinding at alternative ends [7]. These are all difficult to achieve when considering the small diametrical tolerance required in this process relative to the skill of a machine operator or the resolution of any automatic system.

Generally increasing the traverse speed will increase productivity, however it can adversely affect the surface finish and size control [8], with a disproportionate influence in precision grinding.

Problems can arise in any grinding process when the grinding wheel rotational speed is an integer multiple of the work rotational speed. This is because any wheel run-out due to wheel imbalance or other cause will be imposed at the same positions on the workpiece in a repetitive action [5].

Similarly, workpiece deflections, and the resulting lack of workpiece-machine axial alignment, due to the normal force exerted by the grinding wheel on the workpiece are generally greater in the middle [6].

Temperature

In grinding, the mechanisms which take place in the contact area (plastic deformation, friction and surface generation) result in an almost complete conversion of mechanical energy into heat [9]. The energy associated with sliding and ploughing is conducted to the workpiece as heat (energy partition) [10] and is typically 60-85% of the heat generated in shallow cut grinding [11].

Temperature is an important parameter in grinding where the required tolerances have the same order of magnitude as the thermal expansion/contraction rates of the workpiece. As virtually all of the energy expended by grinding is converted to heat, an increase in the wheel speed will produce an increase in temperature, depth of cut and increase in number of cutting edges per unit time [5]. A larger workpiece means the load is distributed across more abrasive grains and therefore heat generation is reduced and the increased contact area improves the heat distribution.

It is well known that temperature and humidity influence size measurements of metallic components due to thermal expansion and changes in humidity causing measurement variations [16]. The change in bulk temperature of the workpiece is the main cause of its thermal expansions and distortions, and coolant temperature plays a large part in controlling this. For example, during the winter months in northern Europe, if coolant temperatures drop to 15°C from a nominal ambient temperature of 20°C, the linear measurements of a 300mm steel roll are smaller by 18µm. AS13003 [3] acknowledges that it is difficult to accurately maintain a temperature of 20°C within a typical production environment and recognises that environmental variables influencing measurement should be monitored and taken in to consideration. This means that the temperature of the workpiece and the environment in which it is processed needs to be understood before final measurement is taken to ensure the best certainty of measurement.

DEVELOPMENT OF METHODOLOGY

Process Review

A Design of Experiments methodology, including cause and effect analysis and process flowcharts, was used as the basis of this work. A series of tests were carried out to identify and discount factors that are insignificant, to ensure the process is operating in the optimal range, and to identify any trends in the outputs. The existing process flow (Figure 1) was identified by shopfloor interviews with machine operators. Likely sources of error at each of these stages were recorded because of their potential role in reducing the conformity of a finished workpiece.

It is clear from review of this process that there are two feedback loops: one associated with the cut itself and whether the operator is satisfied with the chosen parameters for the cut, and the second related to the assessment of the end product. These feedback loops rely on the operators experience and “feel”. Beyond the operators control is the temperature, both ambient and of the coolant, and is shown in literature to be important [7], [10], [12].

A cause and effect analysis was then completed and identified variables that may have an effect on the final size of the shaft. The variables that were identified as influencing the quality of the end product/shaft are shown in Table 1.

Classification of the process variables

A systems methodology, in order to assess and categorise the process variables [13], was used to represent the grinding process as a “black box” with inputs and disturbances having an effect on the grinding process. For the grinding process, a categorisation of these has been attempted and is shown in Table 2. Comments have also been made which gives an outline of their significance and how it is expected they will be measured and/or controlled during experimental procedures.

Selection of factors and responses

The kinematics of grinding (traverse speed, wheel/workpiece relative surface speed), coolant temperature, and dressing type were initially selected as the parameters to be studied. These parameters were ranked as being the most influential, by the experienced precision grinding operators consulted during this study, against the criteria of having the greatest impact on the responses of interest; size, circular run-out and surface finish (R_a).

In this industrial context, the dressing type parameter is simply viewed as a qualitative measure (fine/smooth). In order to develop a robust quantitative analysis of the effect of dressing type, a large number of additional process variables (traverse speed of dressing tool against the wheel, dressing depth, wheel rotation speed, number of dressing passes, final dressing pass direction) would need to be considered even before accounting for different wheels (material, grit type/size). Including these would double the complexity of the experiment with little improvement in the desired responses. That said, throughout this work the dressing strategy used was typical to this process in industry and was controlled to be consistent across all experiments performed. The remaining three parameters (traverse speed, wheel/workpiece relative surface speed, and coolant temperature) were then taken forward to be used in the experiments.

Various component features and tolerance types are of significance to different jobs, therefore full consideration of these must be taken before deciding on the responses to be measured in the experiments. In this work the features and types initially considered were; diameter size, roundness and circular run-out, cylindricity, concentricity/coaxiality, total radial run-out, and surface finish.

These measurements were evaluated against the requirements from typical customers in this sector, technology availability, and capability to measure in a timely manner during production. Circular run-out, diameter (size measurement) and surface finish were chosen as parameters to be measured in the experiments.

EXPERIMENTAL PROCEDURE

Baseline machine assessment

Prior to carrying out the experiments, two different tests were carried out on the selected machine to produce a baseline. Firstly, measurements of the rotational speed of the workhead were performed using a calibrated tachometer. A centred thread was then produced and placed at the centre point of the workhead plate. Measurements of the workhead rotational speed were then mapped to the expected gear speed based on machine settings. Secondly, tests to calculate the traverse speed of the bed over the slides were carried out. This was achieved by measuring the time taken for the bed to travel a set distance, marked on the bed, at each of the arbitrary machine settings.

Design of Experiments

The design space for the experiment was a full factorial, resolution VI model with three centre points (normal conditions of grinding). A resolution VI was used to prevent the aliasing of the two-way interactions between the factors. Figure 2 shows the parameter matrix levels of the factors that were studied. The experiment consistent of 11 runs (eight for the corner points and three centre), repeated three times.

To reduce the time taken for the experimental work, the temperature was set up in blocks and within each temperature the run-order was randomised. Centre points were used to account for possible non-linearity of the response effects. The parameter levels were selected based upon typical operating conditions of the grinding wheel used, historical data (coolant temperature) and the norm in this industrial sector.

Selecting the levels for the factors

As the experiment considered the finish grinding process only, the centre points were chosen to reflect typical parameters used in industrial finish grinding. Available work speeds for the experiment were limited by the gearing of the machine and Table 3 shows those used.

The wheel speed used in the experiments was fixed at 25.4 m/s (5000 ft/min) equating to a rotating speed of 779 rpm for the 0.623 m diameter wheel used in this work. The maximum surface speed, stipulated by military standard for grinding of chrome is 6500 ft/min[14]. Due to the limitations of the fixed gearing of the machine used in this work the centre points of the design were run at the gear nearest to the centre 0.353 m/s, not the actual centre point of 0.3485 m/s.

Grinding

A chrome plated steel cylindrical workpiece was setup between two revolving centres of a traverse cylindrical grinding machine as shown in Figure 3. The wheel and cutting conditions used throughout this work are shown in Table 4.

After the workpiece was set-up, the parallelism to the grinding wheel was established by adjusting the swing of the table. This was achieved by touching the grinding wheel on to the extremes of the face to be ground, and making note of the infeed point of the grinding wheel, and diameter of the ground workpiece. Iterative adjustments of the bed were made until the diameter differences and infeed position differences of the wheel were minimised.

The coolant temperature was adjusted using a simple 3 kW immersion heater placed in the clean end section of the sump tank. The temperature of the coolant was maintained at the desired level through use of a thermocouple-based closed loop control system. Once the coolant was at the correct temperature, the wheel was dressed using the settings shown in Table 5.

During the cut, and traversing along the ground face of the workpiece, the amount of power drawn by the wheel was noted using an ammeter mounted to the current supply to the grinding wheel spindle. This was done to monitor the consistency of the cutting conditions. To prevent deflections of the workpiece and improve the dynamic stability, steadies were positioned on pre-ground journal faces at either end of the workpiece.

The ambient temperature in the factory, in which the machine used was located, was recorded between July 2015 and June 2016 (11 months total). All experiments described in this paper were conducted during this period. The temperature was recorded by placing thermocouples at strategic positions around the factory and recording data every 15 minutes using data loggers.

Workpiece Measurements

Upon completion of each grinding cut the following measurements were taken. Initially, diameter measurements were taken at five locations across the body, and at three locations around the diameter. Additionally, at each of the five locations across the body, measurements of surface roughness (R_a) and circular run-out were also taken.

The diameter measurements were taken using an interchangeable anvil digital micrometer. Surface roughness measurements were made with a handheld profilometer in the longitudinal direction across the lay of the roughness. The run-out measurements were made using LVDT probes. Good measurement practice of; taking readings as close to centre height as possible, at the same points across the body, and perpendicular to the surface, ensured accurate and consistent readings were achieved. This is illustrated in Figure 4 and Figure 5.

Although the focus of this study included the role of ambient temperature changes on the size of the roll, the effect of those changes on the measurement process were minimised by always using the same micrometer and ensuring that its temperature during use matched that of the workpiece. The micrometer was calibrated at 20°C ±1°C.

EXPERIMENTAL RESULTS

Roll Diameter

Figure 6 shows the data obtained from each of the 33 runs carried out. For the various speeds and feeds chosen, the applied depth of cut 10 μm was constant. This is shown by the decline in the data for the workpiece diameter. The outliers (runs 7, 8, 31 and 32) are considered to be due to a random error occurring during these measurements. A step increase in the workpiece diameter data is shown from run 23 onwards. This is characteristic of a different day of measurement, where temperature is influencing, because of this influence in temperature, the size change of the workpiece was analysed.

The significance of the grinding variables on each of the selected responses were evaluated using ANOVA. A confidence limit of 5% (p value = 0.05) was used to assess significance of the effect. This confidence level was chosen as it is typically used for practical experiments of all kinds, across many disciplines. There is little justification for choosing a higher confidence level as the results of the experiments are not to be used in a safety critical application.

This response evaluates how much, as a percentage, of the cut is removed when a diameter cut of 10μm is applied. The Pareto chart for the size change for a given cut depth of 10μm (Figure 7a) shows that the traverse speed, work rotational speed and their interactions with the coolant temperature have the most significance. However, their significance is not enough to exceed the 5% threshold stipulated. The main effects chart (Figure 7b) shows that with increases in traverse speed and work speed the mean size change of the workpiece increases, as expected [8], [15].

Run-out

Figure 8 shows the mean of the circular run-out at the five measurement locations for each run. The circular run-out change is also presented. Irrespective of the speed and feed selection, the circular run-out falls in the first 12 runs, after this a constant value of 5µm is achieved, from which point further reduction is relatively small.

The main influencing factor on the change in circular run-out of the shaft is the coolant temperature, shown in the Pareto plot (Figure 9a). No factors have shown to be highly significant as they do not reach the 5% significance level.

The main effects plots, shown in Figure 9b, shows that there is a largely non-linear relationship of each of the factors on the response and the centre points show that the largest impact is on the mean circular run-out of the shaft.

Surface roughness

Figure 10, the data captured for the surface roughness (R_a) for each run shows random readings with no bias over time. It can be inferred that the results show dependency only on the tested factors, with little chance of external factors influencing the results.

Analysis of the data captured for the surface finish, R_a has shown that the most significant effect is the coolant temperature, with the significance level set at 5%. The second influencing factor is the work speed/coolant temperature interaction.

Figure 11 shows the Pareto and main effects plots for the three factors on the achievable surface finish. The coolant temperature has the greatest effect on the surface finish producing a large range of surface finishes. The centre point is the highest point on the response for all of the three factors, quite clearly indicating that this combination of factors gives the roughest surface finish, and improvements in surface finish would be seen by operating at parameters other than this.

Temperature

Data captured from two thermocouple locations are presented in Figure 12 and Figure 13. Figure 12 shows data obtained from the measurement room, and Figure 13 a location close to the machine on which the experiments were conducted. Both graphs follow the same trend, with three clear sections; a decline in the temperature to November, a steady temperature between the months of November and April, and an increase in temperature from April to June.

When compared with the local atmospheric temperature data (Figure 14), the trends in the measured results appear to show similar correlation. During the winter months, November to April, the temperature remains below 19°C. Larger fluctuations are seen on the machine graph and these are due to the use of radiant heaters throughout the factory to increase temperatures to comfortable levels for machine operators. These fluctuations are larger during winter months because of the colder temperatures at night.

The measurement room is a small enclosed space within the factory where measurement equipment is stored when not in use, and, although large fluctuations were not observed, there are some temperature differences between this room and the factory (largest being January (7°C)).

Outside the winter months, when the heaters are not in use, a general increase was recorded with a peak in temperatures in August. The mean temperatures, represented by the smooth line, correlate closely between the measurement room and the shopfloor, but on a day to day basis (the high frequency data) greater fluctuations can be seen on the shopfloor due to localised temperature effects (draughts, direct sunlight).

During the experiments it was observed that the bulk coolant temperature was consistently 2°C lower than the ambient temperature, regardless of the time of year.

DISCUSSION

Significance of results

The results show that for the size (depth of cut confidence) and the run-out responses when a cut depth of 10μm is applied and traversed across a length of chrome plated steel, all of the factors have some contributory effect on the achievable response. For the surface finish response, coolant temperature was found to have the most impact on the surface finish, with a high coolant temperature giving the lowest roughness.

The traverse speed influencing the diameter the greatest is in agreement with the abrasive material removal theory presented by Kruszyński and Lajmert [17] and Farago [15], where a high traverse speed influences the finished size of the workpiece and causes difficult grinding conditions, possibly due to the imparting of heat in to work. The lowest traverse speed removed the most material because of the increased time in cut, allowing more material to be removed, and the wheel acting “harder” and thus not wearing as quickly. This implies, however, that the cut is deeper than that intended, therefore reducing confidence in the process at this position.

The traverse speed was found to have a non-linear effect on the run-out of the shaft, with relatively small readings recorded at the high and low parameter values, whereas high run-out values were recorded at the intermediate parameter value. This is likely to have been caused by the inconsistent starting value of run-out (as the same workpiece was used) prior to each run influencing the reduction in the run-out possible in the subsequent test.

Literature has shown that as traverse speed is increases, the surface roughness also increases, and to a greater extent at lower surface speeds [17]. The results from this work are in agreement up to the intermediate parameter value but have shown that roughness drops as it is increased further.

Similarly, theoretical models have shown that by increasing the work speed the surface roughness increases but the results from these experiments have shown that the surface roughness decreases, albeit after an initial increase, when the work speed is increased. Although not selected as a parameter in this study, this trend is in agreement with the overlap ratio recommendations from literature where a higher overlap ratio is recommended for finishing passes [17]. It has also been proposed that depth of cut has the largest impact on surface finish [18].

During these experiments, increasing the work speed was observed to promote an increase in the depth of cut by the operator (i.e. to offset the temporary expansion of the workpiece) resulting in workpiece being undersize. This is attributed to the higher work speed heating the workpiece due to the larger apparent depth of cut with the increased work speed.

Little evidence of the coolant temperature effects on grinding has been identified in literature. The results show that the coolant temperature had little impact on the size change, but was seen as the most influential factor on both run-out and surface finish. When the coolant temperature was at the highest parameter level (20°C) the surface finish and run-out achieved were the most favourable. This contradicts the common pretence in industry which would be coolant as cool as possible in order to remove the most amount of heat generated locally at the grinding zone. But, as Malkin points out [19], the coolant has little effect on the maximum temperature at the grinding area when applied conventionally as flood.

Errors

Three main aspects have been identified which may have contributed to errors in this work:

1. Alignment of the grinding table.
2. Uncontrollable variability in the wheel head cut depth, through touching on error and the apparent cut increasing during the grind seen through and increases on the DRO.
3. Errors in the measurement system.

Other aspects such as dressing depth variability and variations in the concentration and supply of the coolant may also play a role in the variability of the results.

Axial alignment of the machine table

It was observed that more material was being removed from the workpiece at the beginning of the traverse length, than at the end and also more material was being removed at the start of the grinding process, compared to at the end. This unwanted taper is attributed to the necessary use of “touching on” where the grinding wheel is traversed across a small (typically a distance twice the width the wheel) the workpiece, with coolant running, prior to the commencement of a cut. There is also a risk of the workpiece moving in the centres, or the alignment of the machine table not being parallel to the traverse direction. In practice, it would be difficult to always use a machine with perfect alignment, so these errors could be mitigated by using an acoustic emission (or similar) sensing technique to accurately assess the point of “touching on” in order to establish an improved datum.

Cut creepage

As the wheel traverses across the surface the wheelhead was observed to slightly (microns) move into the workpiece. It was expected that this movement would result in a larger cut being taken at the end of the first pass, but was not distinguishable in the experimental results data. In practice this small discrepancy could be due to; wheel wear, a workpiece being adjusted for parallel in-process to facilitate parallel grinding, or the error in any on-machine measurement system.

Measurement

Measurement equipment used to obtain the data presented in this work was representative of equipment used on factory floors for measurements of this scale. While every step was taken to ensure the repeatability of the gauges, through using recently calibrating equipment to monitoring the temperature of the physical gauges, it must be noted that the gauges will still have an uncertainty associated with them. This will inadvertently introduce error in to the results presented here. The uncertainty is much larger than the required tolerance <12.5μm and from an uncertainty budget has been predicted as ±30μm and the digital readout system has an accuracy of ±5μm.

Limitations to study

A broader aim of this study was to attempt to define a set of process parameters to achieve a consistent tolerance on the finished size, run out and surface finish of this type of workpiece and this has not been achieved. The lack of control in the process arises due the particular capabilities of the machine being used (maintenance of set cut depth, repeatability of positioning, workpiece-machine axial alignment). This means that the operator has to actively monitor these parameters during the process through the use of the machine's positioning system, sound and visual cues, and micrometers, which all contribute to the uncertainty of the process.

To further reinforce the findings of this study it is suggested that the following is conducted:

1. Repeat experiments using other workpieces and over a wider range of finished workpiece sizes.
2. Do not remove the work from the machine during the experiments. This is difficult to achieve when experiments are conducted in a production environment.
3. Choose a larger value for the input being measured, for example increase the size of the depth of cut to be significantly larger than any measured error in the machine being used. This is difficult to do when grinding chrome as small depth of cut is required for finish passes in precision grinding.

It is clear that the grinding operator is a fundamental part in achieving the tightest tolerances, and through providing guidelines into best practises, it is possible to be able to hone the skills of the grinding operator. There will always be some variance resulting from the different approaches to working a particular job by even highly skilled operators, however. Variation in process output is also susceptible to being 'masked' by local workplace practices (e.g. pre-warming machines, approach process monitoring and quality).

It must be noted that the results presented here have been produced from mean values with data that has a large amount of variation, due to being conducted in a real production environment, therefore the robustness and repeatability of these parameter settings in producing these favourable outputs is low. Ideally, the process must be controlled as much as possible leaving the variation down to the skill of the operator, and this potential for on-job process variation is key to achieving the desired result.

It should be noted that although this study was performed in a production environment, the machine to be used to conduct the experiments was selected due to its high level of capability and low levels of error (relative to the rest of the precision grinding capability in the UK).

CONCLUSIONS

The results presented here have shown that the coolant temperature is most significant factor in achieving the desired workpiece size, run out and surface finish in precision grinding. It has been found that, for this process, when the ambient temperature is higher than ambient there is an increased risk of machining a component undersize, because measurement has been made when the component is in an expanded state, and will shrink when returned to ambient.

The parameter centre points for both the run-out and surface finish, which are typically used to control the finish of workpiece on shafts of similar size and material, have been shown to be least favourable. By either increasing or decreasing the speeds away from these points, more favourable results have been achieved in this study and the results have also demonstrated the need for active intervention from the machine operator.

Identification of an optimised set of parameters, that will consistently result in achieving the required tolerances, have not being achieved by imposing the tight restrictions in the method of experimentation. Although investment in new/refurbished equipment to arrive at a ‘perfect’ machine would go some way to reducing the effect of disturbances related to alignment and coolant temperature can be removed, machine operator skill remains the dominant factor.

ACKNOWLEDGMENT

The authors would like to acknowledge the support of Innovate UK and BEP Surface Technologies in conducting this work.

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Figure Captions List

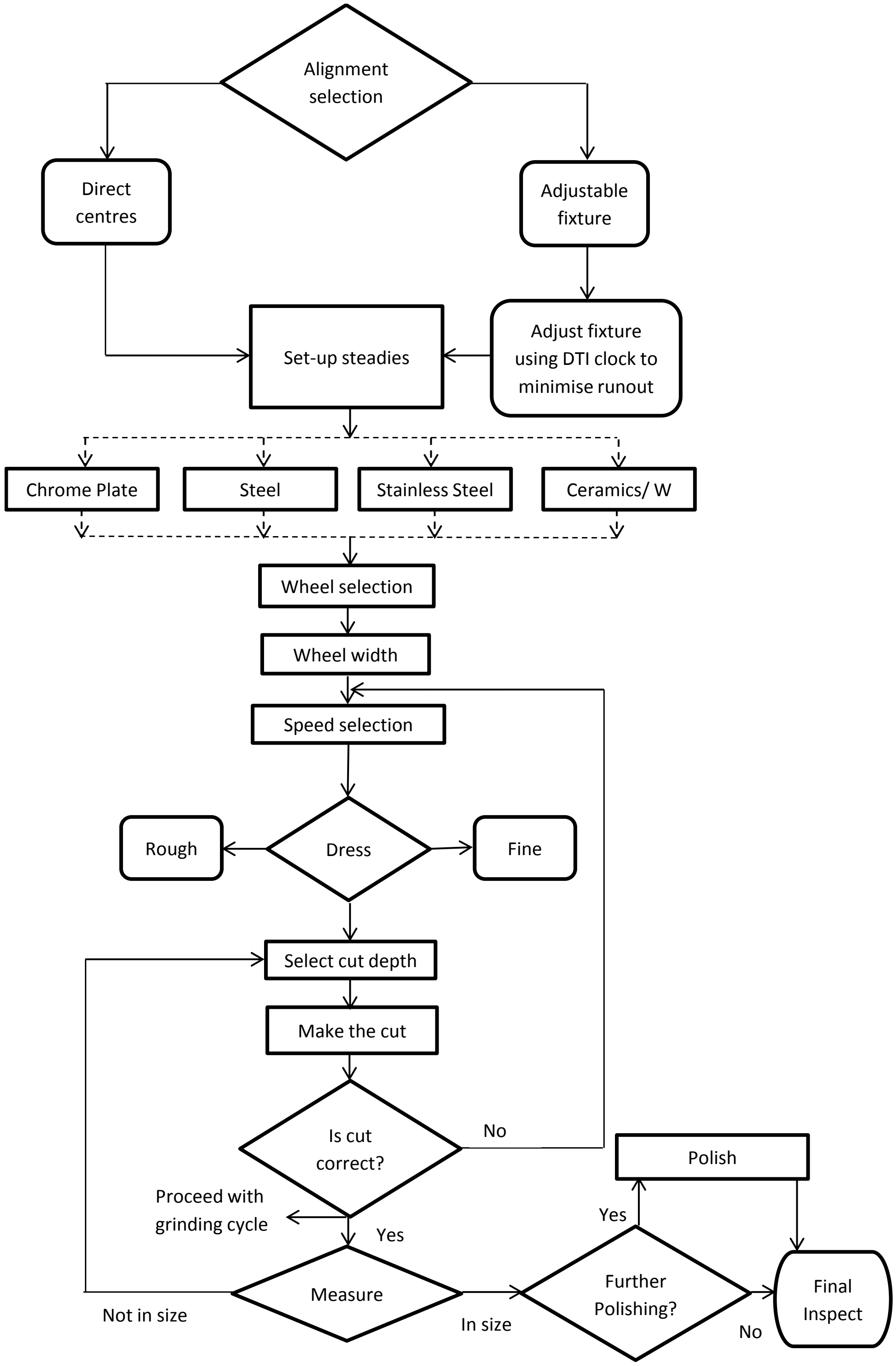


Figure 1- Grinding process used in this work

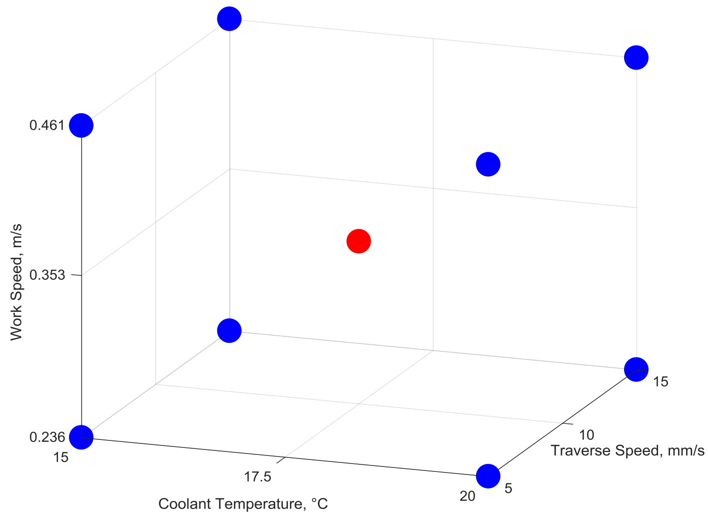


Figure 2- Experimental Run combinations used.

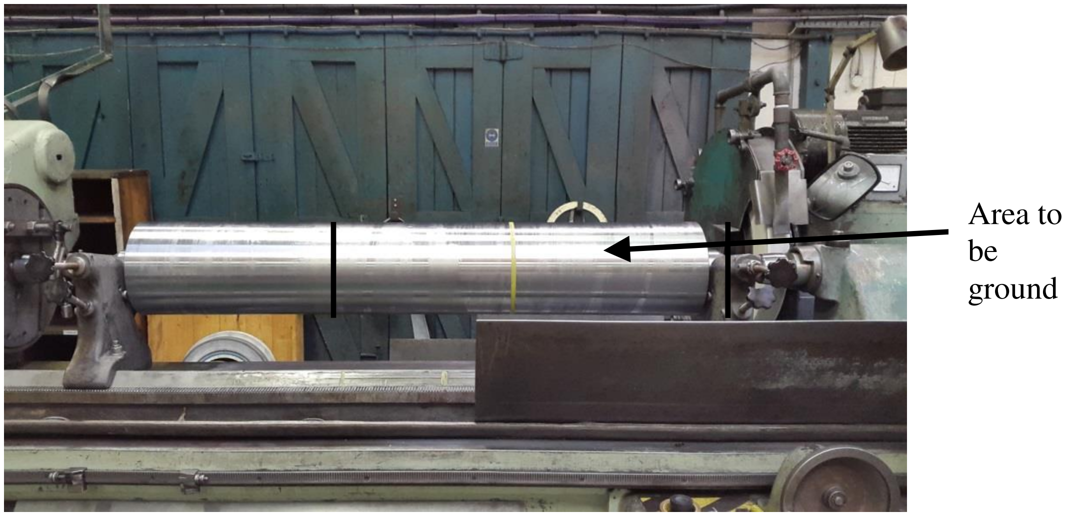


Figure 3- Set-up of chrome test roller between centres.

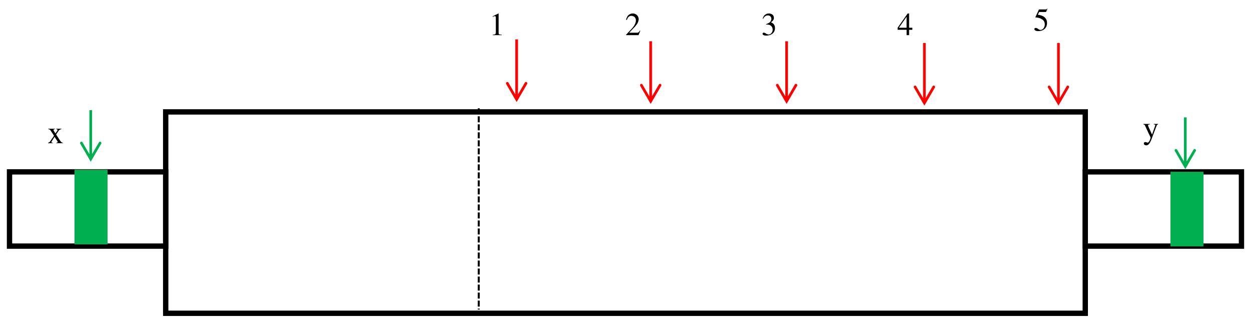


Figure 4- Probe placement and measurement positions schematic.

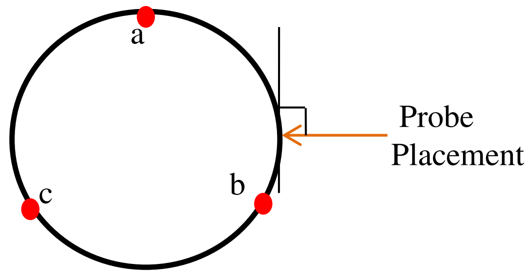


Figure 5- Illustration of the correct probe placement.

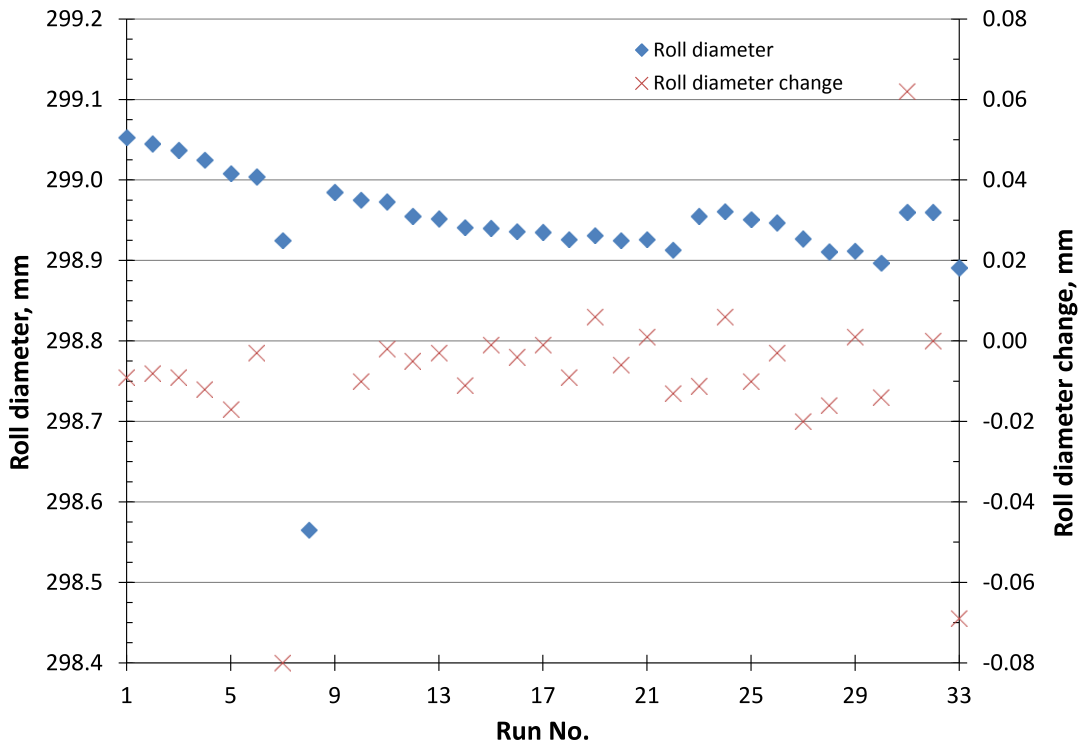
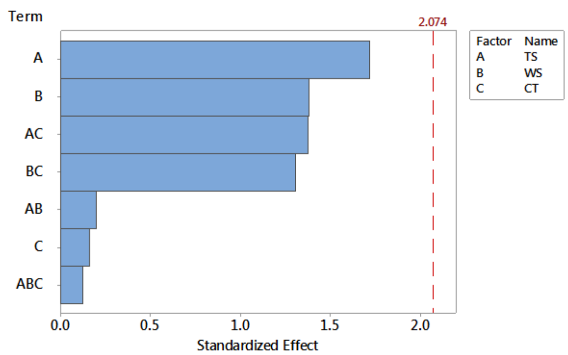


Figure 6- Workpiece diameter and change in roll diameter after each run.



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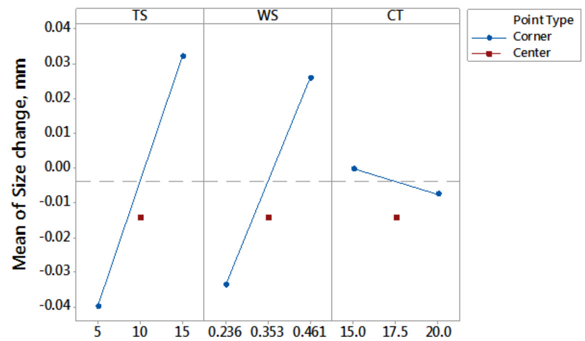


b

Figure 7- (a) Pareto ($\alpha = 0.05$) and (b) main effects chart for size change.

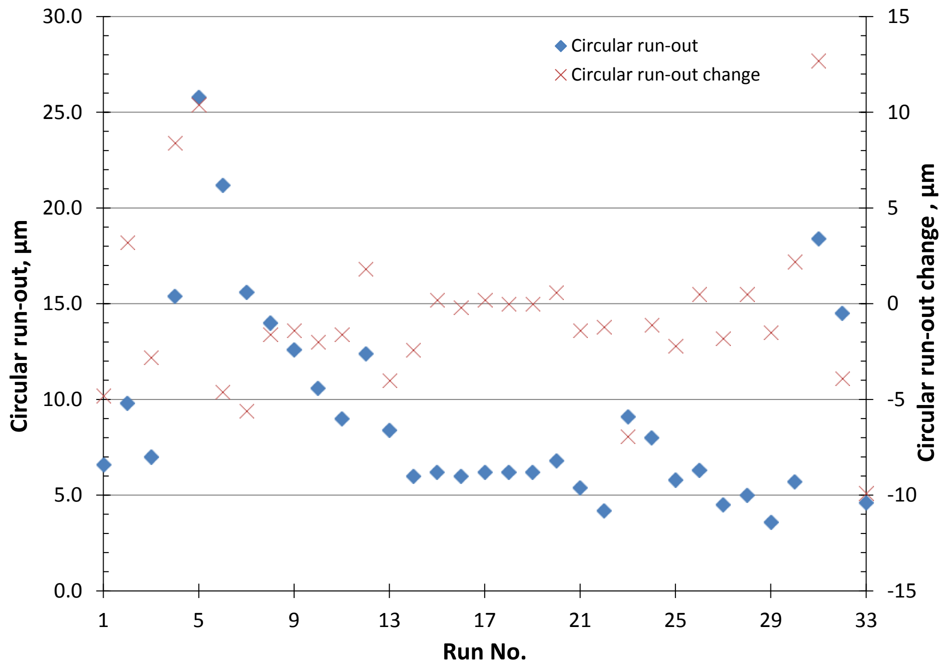
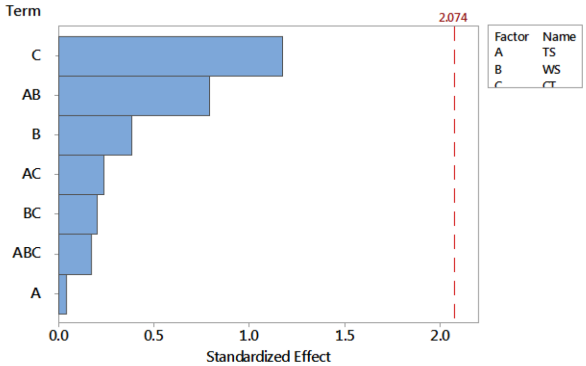
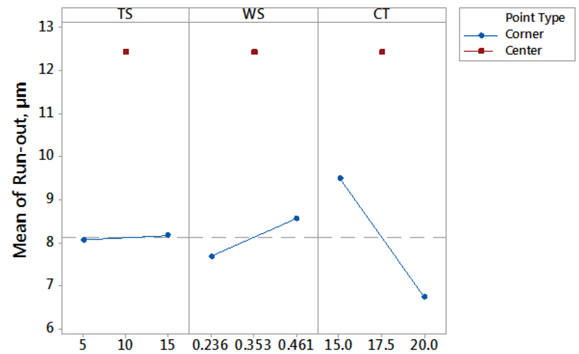


Figure 8- Circular run-out measurements made and the changes between them for each run.



a



b

Figure 9- (a) Pareto ($\alpha = 0.05$) and (b) main effects chart for the run-out.

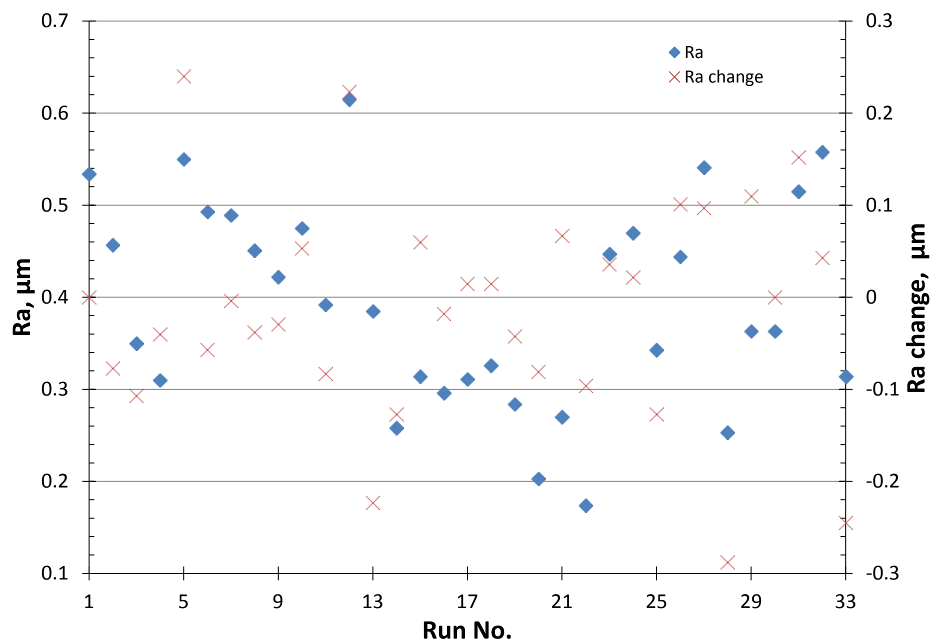
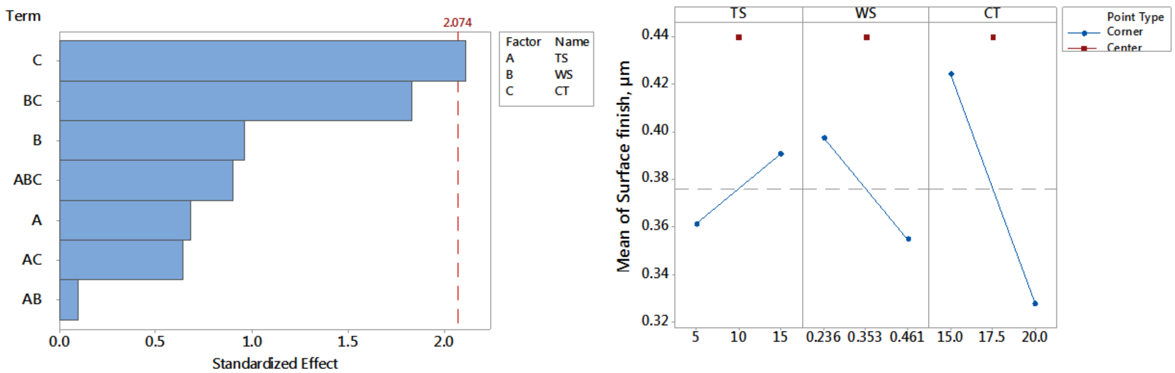


Figure 10- Surface roughness for each run and the change in the surface roughness between each run.



a b

Figure 11- (a) Pareto ($\alpha = 0.05$) and (b) main effects chart for the surface roughness

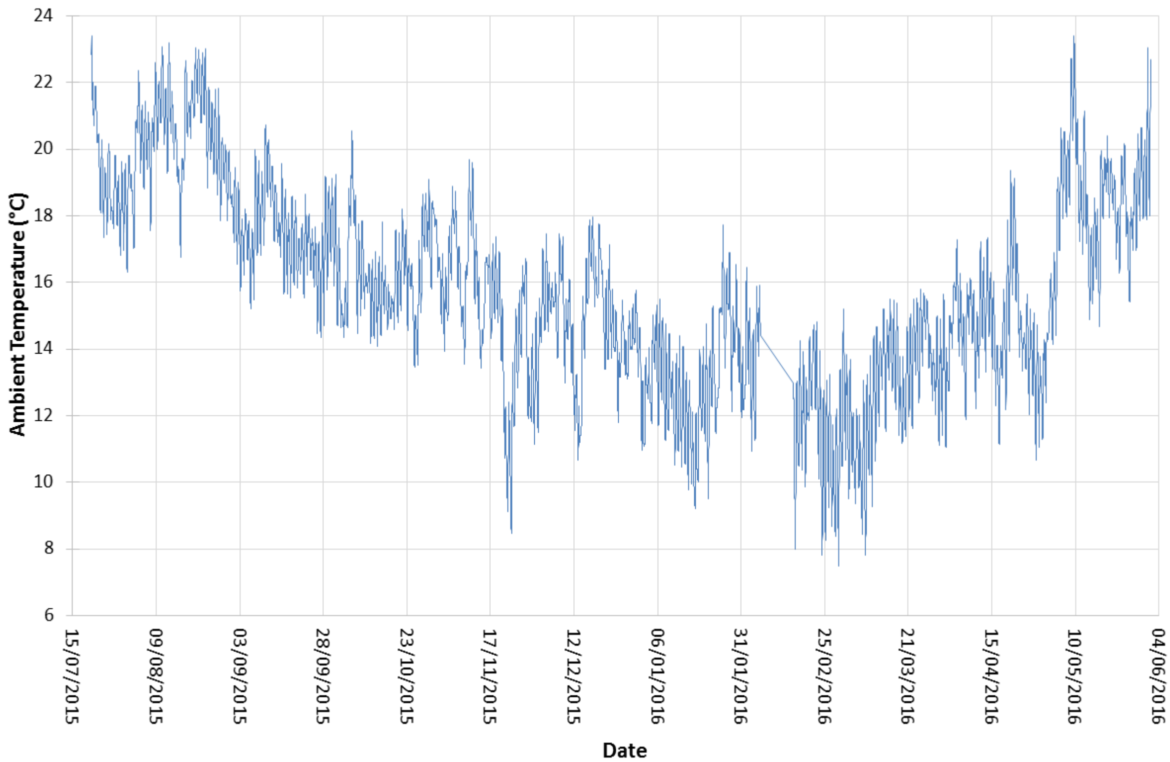


Figure 12- Temperature data for the period July 2015- June 2016 for measurement room

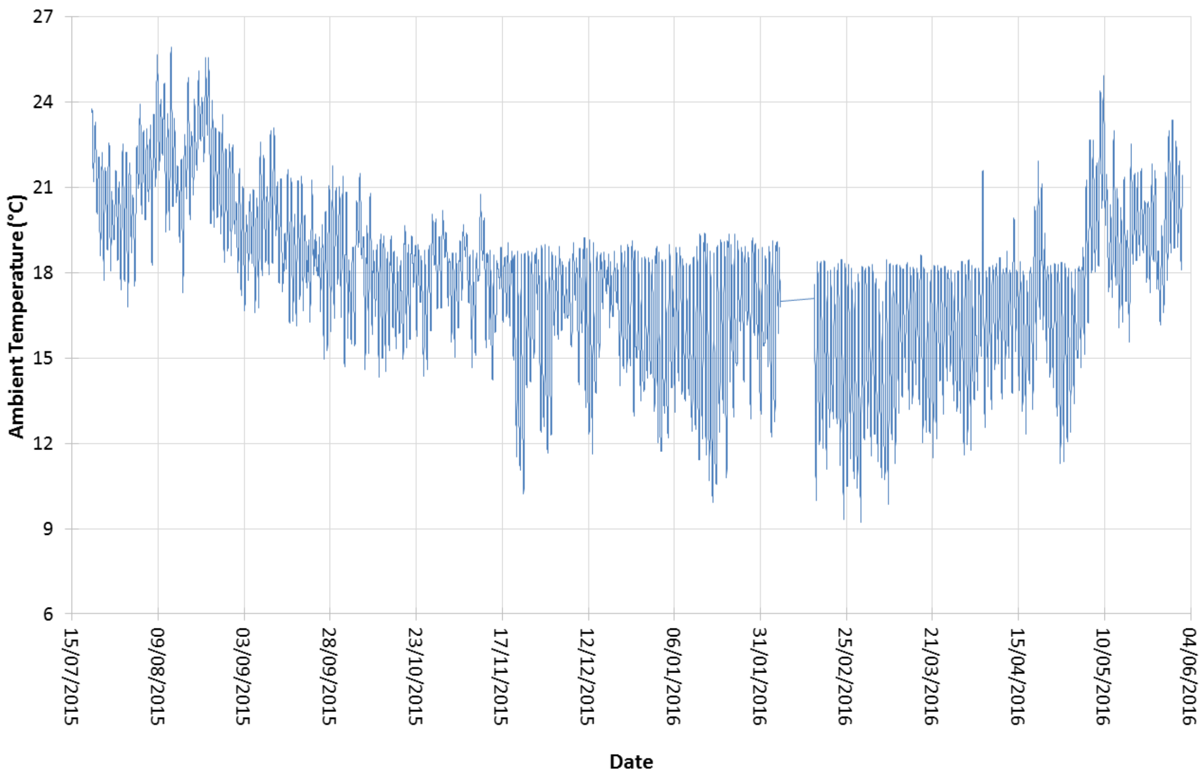


Figure 13- Temperature data for the period July 2015- June 2016 for machine used

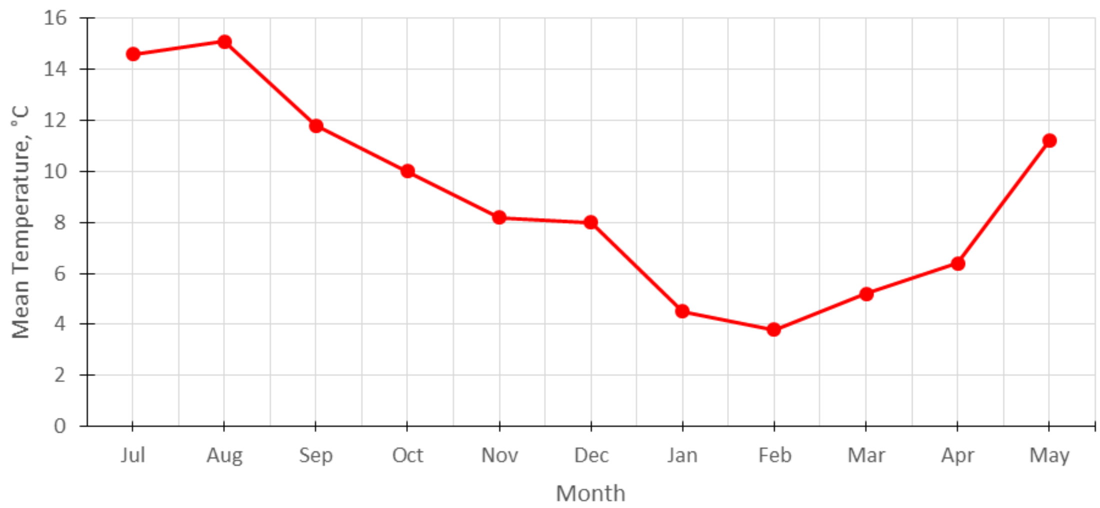


Figure 14- Mean temperature per month for the North of England, modified from [16]

Table Caption List

Machine
• Calibration- straightness of slides, positioning of centres. • Work head power. • Dynamic characteristics (Stiffness, Damping, Mass). • Thermal stability.
Measurements
• Different operators. • Micrometer measurement: expansion/contractions, human operator (feel) • Setting up job and inspection with robust analogue dial gauges.
Coolant
• Debris, fines, oil contaminants contributing to clogging of the wheel. • Condition (age, replenishment schedule, evaporation, mixing). • Temperature. • Flow rate (pressure/velocity). • Positioning and design of outlet nozzle.
Work Alignment
• Centralisation of the work into centres. • Forces exerted by the steadies (affected by steady wear). • Machine wear (particularly the non-uniformity of wear). • Mounting and balancing of the grinding wheel.
Environment
• Temperature variation (over time- seasonal, in-factory locations). • Humidity. • External vibrations (other machinery).
Work-piece
• Material properties. • Surface speed • Length – traverse wheel wear. • Stiffness and mechanical distortions.
Grinding Process
• Grinding wheel selection, dressing. • Wheel diameter and width. • Local heat generation from process. • Workpiece material left prior to finish grind. • Order of operations in process. • Selection of speeds. • Depth of cut.

Table 1- Properties identified to influence the precision of the end product.

Controlled inputs	- Steadies (position, number, forces, cooling) - Wheel (diameter, width, age, wear, grade, grit type/size)) - Dressing (dressing conditions, diamond condition/type) - Grinding cycle - Material - Coolant (type, concentration, level of contamination)
Disturbances	- Misalignment of machine, machine wear, movement of wheel - Ambient temperature fluctuations - External vibrations - Variations in shaft properties, touching on process, grinding wheel properties
Productive Outputs	- Geometric accuracy - Surface finish

Table 2- Categorisation of the various parameters according to the systems model.

Gear, rpm	Actual rotational speed, rpm	Work speed of 300mm diameter, m/s
16	15	0.236
23	22.5	0.353
31	30	0.471

Table 3- Work speed calculation of a 300mm diameter workpiece.

Wheel	White AlOx A60/3J3V
Wheel speed	650 rpm
Wheel diameter	623mm
Cut depth	5µm
Dynamic stability	Two steadies on journal bearings, using soft metal/wood.

Table 4- Wheel and cutting conditions.

Traverse Speed	3.22 mm/s
Depth of dress	5 µm
Wheel Rotation	650 rpm
Number of passes	2
Direction of final pass	Left to right (relative to Figure 3)

Table 5- Parameters used to dress the wheel.