

Author : Terry-Louise Betambeau P133303

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THE EFFECTS OF SURFACE QUALITY OF MACHINED SPECIMENS FOR TENSILE TESTING ON MECHANICAL PROPERTIES



University of Wales Trinity Saint David
Faculty of Applied Design and Engineering
BEng Materials Science (Hons)

1. Declaration of Authenticity

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

2. Acknowledgements

I would like to thank Kelvin Lake, an excellent project mentor, who gave support and guidance during my project. I am grateful to Shelley Doolan and Daniel Butler for access and support at their facility. I appreciate the interest in my project from Tom Taylor at Tata Steel, and for organising access to testing at Swansea University. I would like to thank Cynthia Traore, for performing analysis and testing.

Many thanks to the technicians at the Metallurgical Laboratory who supported trials and allowed access to equipment, and for their patience with my interference during busy working times. I would like to thank Neil Johnston at Tata Steel for access to the Metallography Laboratory support with testing.

I would like to thank my Line Manager Peter Barnes for his level of support and flexibility during this project.

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3. Abstract

This report details an investigation into the effects of milled surface quality of automotive grades of steel by evaluating tested mechanical properties. Automotive grades account for a significant portion of the Tata Steel order book, and mechanical property specification tolerances required by automotive customers are rigid. It is crucial that the Metallurgical Testing Laboratory has confidence in mechanical properties tested to ensure the products are being manufactured and sold within specification.

This investigation considers any relevant milling factors that affect the surface finish of steel samples prepared, which is evaluated by the method a surface roughness analysis; white light interferometry. This project aims to determine whether the surface finish of milled steel test specimens has an effect on the mechanical properties. Initial trials demonstrated that exaggerated surface defects can cause a tensile test specimen to fracture prematurely, indicating the possibility that smaller defects may affect elongation.

The milling elements explored are tool wear and packing material thickness. Other machining variables such as depth of cut, feed rate and speed rate are not considered, due to previous optimisation.

Analysis determined that tool wear and packing gauge influenced both mild steels selected, DP800 and DX57, although tool wear effects are more significant. Results are affected after the tool wears beyond 0.3mm, particularly for elongation, yet remain consistent for levels of wear below this point. Reduced packing gauge has a similar result, although to a lesser degree. The results correlate with the roughness average results for the same tests, supporting a relationship between surface quality and tensile test performance.

The method of machining is compared with waterjet cutting, which has become more widely used commercially. Waterjet cut samples prepared at Swansea University Trinity and Saint David showed a substantial reduction in some mechanical properties, with elongation being most affected.

Cost analysis presents that approximately £57,000 is possible annual saving that could be achieved by addressing the factors influencing milling quality. Numerous recommendations are presented including options for improved sample clamping, and improved methods for monitoring tool wear and replacing tools at prescribed periods.

Consideration is given throughout to remain within the limits of the testing standards, that sets how test specimens must be prepared, which does introduce some boundaries to this experiment as the testing laboratory cannot adopt any methods that are not compliant to this standard.

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4. Project Plan

<i>Week Number</i>	<i>Task Description</i>
42	Determine main project sections.
43	Write project plan and timelines. Meet with mentor. Obtain research material.
44	Source and prepare material for testing. Organise and plan trials required. Prepare and organise samples.
45	Write introduction. Write contents page. Complete trial for broken ends.
46	Write about milling. Arrange to meet Kelvin next week. Begin trials on material and milling tips.
47	Prepare material. Organise meeting Richard Morgan to discuss milling. Complete literature review.
48	Meet Kelvin. Meet Richard. Write one section. Complete tests good v bad milling.
49	Determine how to measure surface roughness. Decide on tool wear measurement.
50	Prepare Slides for Oral Exam. Arrange to meet waterjet cutting in new year.
51	Oral Exam.
52	Design template for waterjet cutting.
1	Prepare plan for trials. Metallography for crack propagation.
2	Meet with waterjet cutting.
3	Begin section on waterjet cutting.
4	Break for exam.
5	Meet Andrew Wilkes confirm milling set up.
6	Theory milling and surface roughness testing.
7	Break for exam.
8	Decide on analysis tools/technique. Complete trials by preparing samples – milling.
9	Write theory on crack propagation.
10	Collect waterjet samples if ready.
11	
12	Use SEM to analyse samples before tensile testing. Complete analysis of data.
13	Conclusion. Obtain quotes for recommendations.
14	Submit draft dissertation.
15	Proof read report.
16	
17	Review Dissertation.
18	Submit Final Dissertation.
19	Final Oral Preparation.
20	Final Oral Exam.

FIGURE 1 PROJECT PLAN.

Project Plan Gantt Chart

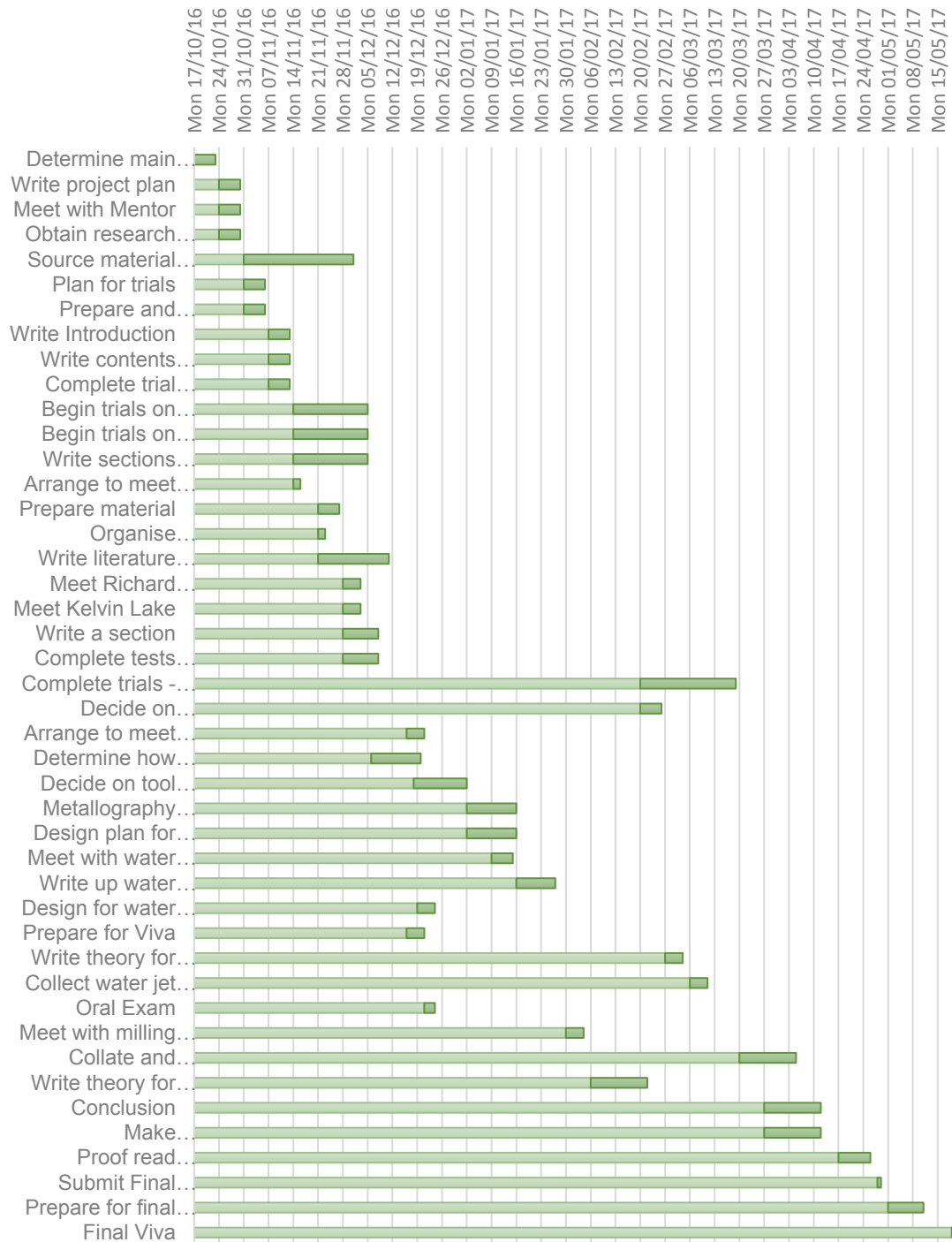


FIGURE 2 PROJECT PLAN GANTT CHART.

5. Acronyms and Abbreviations

TABLE 1 TABLE OF ACRONYMS AND ABBREVIATIONS.

Acronym / Abbreviation	Description
1ACTM	Coil temper mill identified as 1A
ABB robot	Type of polar robot used in automated systems, named after the manufacturer
Arisings	Department of specialists for the disposition of failed material
Aurora	An internal system/database that records mechanical test results and test curves for each tensile tests performed
AWJ	Abrasive waterjet
BOS	Basic oxygen steelmaking
Capex	Capital expenditure (often referring to a project)
CAPL	Continuous annealing process line at Tata Steel
Coil	Unit of produced steel
CR	Cold rolled material (when referring to steel)
CRP	Cold Rolled Products (Tata Steel cold rolling mill)
CTQ	Critical to quality. Key quantifiable requirements of a product which are critical to meet customer expectations
EDM	Electrical discharge machining
FANUC	The FANUC controller is the interface between the waterjet machine and user
FMEA	Failure modes affects and analysis
Galv	Galvanised steel product, produced on Zodiac
HR	Hot rolled material (when referring to steel)
HRP	Hot Rolled Products (Tata Steel hot rolling mill)
HSMD	Horizontal measurement specimen device. Component of the tensile testing equipment at the Laboratory
IGEMS	The software used to draw and programme tool paths for the waterjet
Instron 1	Reference name for the one of the Laboratory automatic tensile testing machines
KPI	Key performance indicator
Met Hold/Held	Material/coil held in processing that requires metallurgical testing, and will not progress to packing and despatch until released by testing
Met Lab	Metallurgical laboratory at Tata Steel
MSA	Measurement systems analysis
Packing	A sacrificial material placed on top and below the sample to be machined, providing protection
RPN	Risk priority number (in FMEA)
SEM	Scanning Electron Microscope
SPC	Statistical process control
SAP	The name of a business management software
Swarf	Removed material as a function of milling in the form of metal chips
SWP	Safe working procedure
UKAS	United Kingdom Accreditation Services. National body for the accreditation of testing, calibration, certification and inspection.
WLI	White light interferometry
Zodiac	Tata Steel galvanizing line

6. Model and Methodology

Extracts from the lean Six Sigma DMAIC approach will be used to assess and improve the current milling process.

The Lean Six Sigma methodology is being applied extensively to tackle quality related issues in many processes of today's industries. It is a tool that builds upon existing processes, provides additional tools and offers a disciplined approach to focus on meeting customer expectations. The DMAIC method that is traditionally adopted in the implementation of Lean Six Sigma has proven to yield cost saving results in most cases (University of Central Florida, 2008).

(George, 2002) outlines two separate cases where DMAIC was applied successfully, one in a company where production and the supply chain struggled to deal with an increase in demand, and another case involving highly specialised technology at a single workspace to reduce scrap, rework, cost and capital expenditure (capex) investment.

The DMAIC approach is commonly applied to existing processes that require improvement, often with some examination of the cost of poor quality (University of Central Florida, 2008).

DMAIC is an acronym for;

Define

Measure

Analyse

Improve

Control

This is an appropriate model that can provide a systematic and logical approach to this project, involving utilisation of many tools and techniques to collect, analyse and present data.

The control segment from this methodology will not be included in this project. Detailed recommendations requiring investment will be presented, and should any be approved by Tata Steel the control stage should be addressed.

7. Introduction

Tata Steel Strip Products UK supplies heavily into the automotive sector making this market crucial to Tata in terms of customer satisfaction and product quality.

Tata Steel produces a catalogue of differing grades of steel satisfying a range of purposes and applications. The automotive industry interests lie primarily with cold rolled steels, which are often high value grades with special treatments and superior properties.

The steelmaking process is a lengthy one, and average production time of a steel coil is six weeks from raw materials to finished product. Many factors affect the finished product such as raw material blend, ladle additions to liquid steel, and processing conditions through many units such as the blast furnace, basic oxygen steelmaking plant (BOS), and the rolling mills. Any variation in any processing can be magnified in effect to the final physical or mechanical properties of product. Each ordered grade of steel must meet specification, satisfying a large range of attributes required to meet the target grade.

Tata Steel at Port Talbot employs a metallurgical testing laboratory to test each coil for mechanical properties to ensure, and often certify, that the product has met specification.

This laboratory performs a range of tests to determine properties and characteristics, the most regular of which is a tensile test. Roughly two hundred tensile tests are performed per day at Port Talbot. A testing standard, BS EN ISO 6892-1:2009, governs how the tensile test must be prepared and executed, by which the laboratory must abide to remain compliant.

Prompt testing of coils is imperative, as coils held for metallurgical testing remain stationary and cannot progress for finishing or for delivery to the customer until testing requirements are satisfied. One of the key performance indicators (KPI) for the laboratory monitors the number of coils held for metallurgical testing. This creates a high pressure, high throughput working laboratory, which values efficiency of processes (considering time constraints), but is also highly driven by quality.

The customer expects a product that is of the correct specification, delivered on time. The characteristics that are critical to quality (CTQ's) include width, gauge, surface, coating weight, and mechanical properties. The metallurgical laboratory influences the former.

Often, automotive customers employ their own testing facilities to check the materials properties. It is important that the test results obtained are within the same range as the tested properties that Tata Steel have supplied and certified with the product sold. It is vital that Tata's metallurgical laboratory has confidence in the testing capability and test results.

8. Define

The define stage will include;

- Problem Statement
- Process Mapping
- Literature Review
- Preliminary Investigation
- Hypothesis

Problem Statement

Over recent years the metallurgical laboratory has experienced several batches of failed tests that do not align with the processing conditions of the products in question. Decreased confidence in testing capability has been expressed within Tata Steel. Product specialists have voiced some concern over the preparation of tensile test specimens after analysing mechanical property results in conjunction with the steel processing conditions. It has been suggested that insufficient preparation, in terms of quality, of tensile test specimens may be a contributory factor.

Upon inspection of the broken test piece ends of random samples, some of the specimens displayed visual evidence of sub-standard milling quality. It is unclear whether the poor milling quality has contributed to the failure of the material, or whether the failures were genuine material failures. Without confidence in the test results due to varied milled quality, this is difficult to determine. It is crucial that the Metallurgical Laboratory explore whether poor milling quality could cause premature fracture of test specimens, and determine how significant a problem this is.

The purpose of this project is to evaluate the effects of poor milling on the surface roughness of tensile specimens, and whether deteriorating surface roughness has an effect on the tested mechanical properties. Lastly, the aim is to design solutions, that are within the scope and control of the metallurgical laboratory and testing standard, for the consideration of Tata Steel.

Problem Statement;

Does the edge quality of milled specimens prepared for tensile testing have an effect on the tested mechanical properties?

Process Mapping

SIPOC is an acronym that stands for suppliers, inputs, process, outputs and customers. In process improvement a SIPOC process map is used to define the inputs or outputs of a process

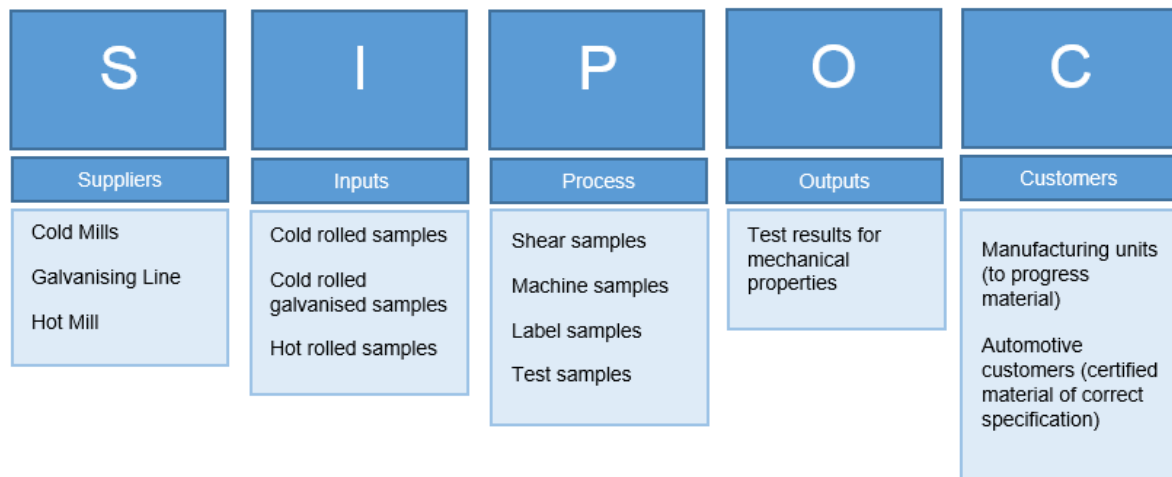


FIGURE 3 SIPOC PROCESS MAP FOR TENSILE TESTING AT TATA STEEL PORT TALBOT.

With reference to figure 3, the scope of this project concentrates on cold rolled and galvanised products supplied by the Cold Mill and galvanising line. Hot rolled samples supplied from the hot mill are outside of the scope of this project.

This project will focus on the process of machining of samples, the other processes listed in figure 3 are not within the scope of this project.

Literature Review

Milling Overview

There are various machining processes that produce finished parts with a high degree of accuracy and surface finish by removing unwanted material from the original workpiece (El-Hofy, 2007). Machining is one of the most widely used metal removal processes in industry for obtaining a finished piece of the desired shape and size with a good surface finish.

Metal cutting machining involves the use of cutting tools that are of a harder material than the workpiece. The cutting tool is usually situated above the workpiece, and this workpiece is held on a machine bed that controls the motion of the workpiece around the cutting tool. The tool is penetrated into the workpiece as far as the depth of cut, which mechanically removes material by rotation of the sharp cutting edges into the material. The predominant cutting action in machining involves shear deformation of the workpiece material to form a chip, and as the chip is removed, a new surface is exposed (Groover, 2002).

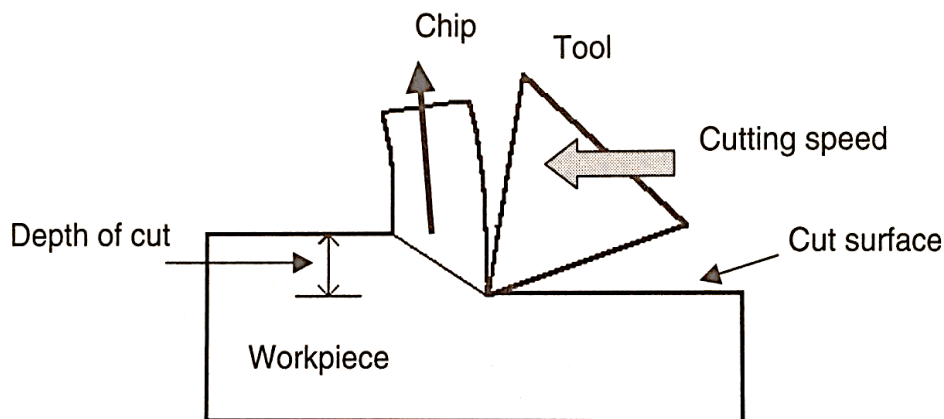


FIGURE 4 SCHEMATIC REPRESENTATION OF MACHINING BY CUTTING (EL-HOFY, 2007).

The machine tool is responsible for application of the cutting power, and for controlling the cutting variables such as the cutting speed, depth of cut and feed rate.

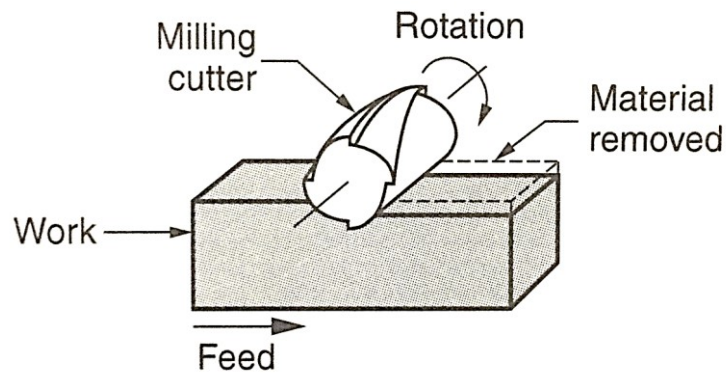


FIGURE 5 SCHEMATIC REPRESENTATION OF PERIPHERAL MILLING, IN WHICH A WORKPIECE IS FED PAST A ROTATING CUTTER WITH MULTIPLE EDGES (GROOVER, 2002).



FIGURE 6 THE FINISHING TOOL FOR MACHINING TENSILE SPECIMENS AT THE METALLURGICAL LABORATORY SHOWING PERIPHERAL MILLING.

Figure 5 and 6 show that the cutting method at the laboratory uses the method of peripheral milling.

The machine tool must have high wear resistance to preserve its geometry, which is important in maintaining dimensional accuracy in the finished piece and to produce a good surface finish. This is also important in ensuring a long tool life that gives value in terms of tool cost. Using suitable tooling can produce dimensions to close tolerances, some as accurate as $\pm 0.025\text{mm}$, and smooth surface finishes of roughness values less than 0.4 microns (Groover, 2002).

Groover 2002 states that “the common feature (of machining) is the use of a cutting tool to form a chip that is removed from the work part. To perform the operation, relative motion is required between the tool and work. This relative motion is achieved in most machining operations by means of a primary motion, called the speed (v), and a secondary motion called the feed (f). The shape of the tool and its penetration into the work surface, combined with these motions, produces the desired shape of the resulting work surface.” The workpiece is fed perpendicular to the tool axis of rotation. Thus feed motion is provided by motion of the workpiece, which meets perpendicular to the speed motion provided by the rotating cutting tool. The cutting edges separate the chip from the parent work material, as in figure 4.

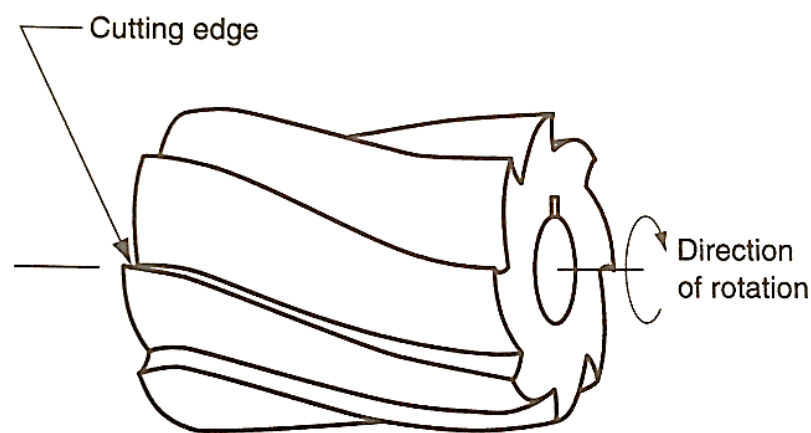


FIGURE 7 A HELICAL MILLING CUTTER, REPRESENTATIVE OF TOOLS WITH MULTIPLE CUTTING EDGES
(GROOVER, 2002).

Machining operations are usually split into two categories; roughing cuts and finishing cuts. Roughing cuts are designed to quickly cut away the majority of the material in large amounts to produce a shape close to the final required dimensions, using a high feed rate and depth. The subsequent finishing cut removes much smaller amounts of material with higher precision to produce a quality surface finish and accurate dimensions, using low feed rates and depth. Cutting speeds are lower during the roughing cut than the finishing cut. For this investigation, optimisation of the finishing cut will be considered, as the final cut influences the final surface quality of the specimen.

Surface quality and accurate dimensions are of major importance when milling. Factors affecting these are shear angle, cutting forces, feed rate, speed rate, vibration, tool temperature and wear (Groover, 2002).

Tool wear occurs during milling due to the high friction coefficient between the tool and the chip. This friction causes considerable temperature increases when cutting mild steel (Beddoes & Bibby, 2003). Beddoes & Bibby explain how temperature affects the cutting action;

1. Altering the properties of the machined surface.
2. Causing dimensional changes to the workpiece and chip, thereby decreasing dimensional accuracy.
3. Adversely affecting the strength, hardness and wear resistance of the cutting tool.

The decrease in hardness and wear resistance of the tool with increasing temperature is the major factor that controls useful tool life (Beddoes & Bibby, 2003). It is important that the milling parameters are set up correctly to minimize the temperatures reached during milling.

Tool wear results in degradation of the tool profile, and the cutting geometry is severely altered as the tool profile changes.

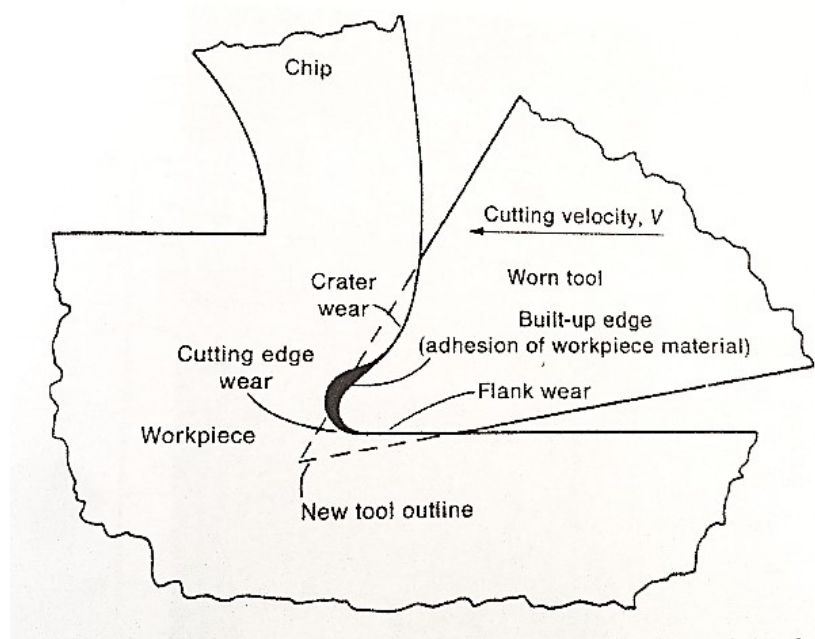


FIGURE 8 DIAGRAM OF CHANGES IN TOOL SHAPE DUE TO WEAR DURING MILLING (BEDDOES & BIBBY, 2003).

Crater wear causes a change to shear angle, while flank wear causes excessive contact between the newly created workpiece surface and the tool, degrading the quality of the machined surface (illustrated in figure 8).

Milling Requirement at the Metallurgical laboratory

Milling is the method employed by the metallurgical laboratory to produce a tensile piece that meets the specification stated in the BS EN testing standard for tensile testing – BS EN ISO 6892-1:2009.

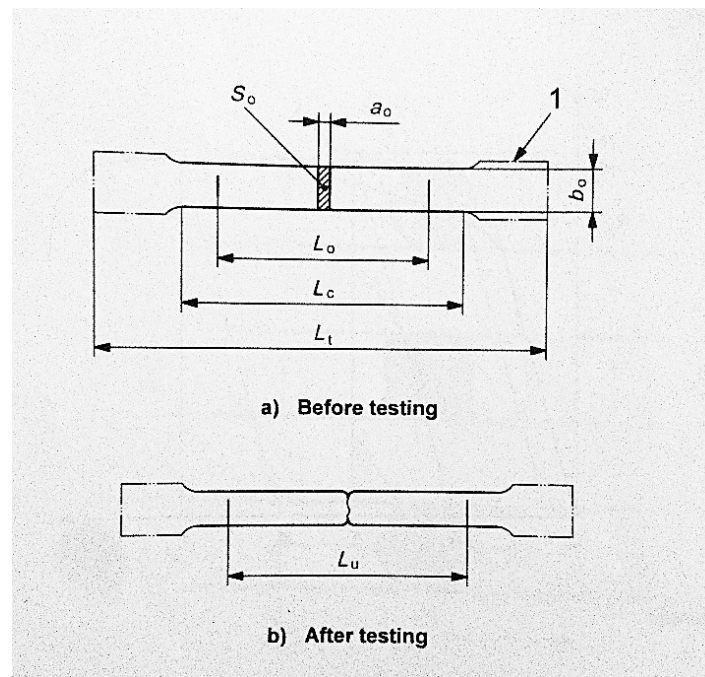


FIGURE 9 EXTRACT FROM TESTING STANDARD PROVIDING GUIDELINES FOR THE TEST PIECE SHAPE THAT SHOULD BE OBTAINED FROM METALLIC SHEET (BSI BRITISH STANDARDS, 2009).

This standard states that “the test piece is usually obtained by machining the sample from the product or a pressed blank”, under section 6.1 “Shape and Dimensions”. The standard goes on to state that “machined test pieces shall incorporate a transition radius between the gripped ends and the parallel length”. It also states under section 8.3 ‘Preparation of Test Pieces’ that “the test pieces shall be prepared so as not to affect the properties of the sample. Any areas which have been hardened by shearing or pressing shall be removed by machining. These test pieces are predominantly prepared from sheet or strip. If possible, the as-rolled surfaces should not be removed....The preparation of these test pieces by punching can result in significant changes to the material properties... (due to work hardening). Materials which exhibit high work hardening should generally be prepared by milling, grinding etc. For very thin materials, it is recommended that strips of identical widths should be cut and assembled into a bundle ...[and] assembled with a thicker strip on each side, before machining to the final dimensions of the test piece” (BSI British standards, 2009).

Machining tolerances are also provided by the standard. The laboratory milling machines are verified monthly by means of a physical inspection of machined specimens using a calibrated micrometer, vernier and radius gauge. Measurements are taken, recorded and documented in a quality management system called SAP.

The current testing methods and preparation practices at the laboratory have been determined by reference to the testing standards.

Krahmer et al, in a paper comparing methods of material removal to produce tensile test specimens, states the factors in the use of milling in compliance with the test standard for preparation of tensile specimens are;

- It demands the construction of a special tooling for holding in place each type of specimen with different shape and dimensions. In fact, clamping of thin sheets is not easy in milling.
- It requires the use of a milling tool with the same diameter as the test piece fillet radii.
- The specimens must be contoured several times to obtain the desired shape.
- As specimens are machined into stacks (several layers) to shorten processing times, the maximum thickness of the stack is determined by the useful length of tool flutes. Thus, tool slenderness is also a factor to consider.

(Krahmer, et al., 2016)

These factors also limit the freedom of using alternate tool geometries and certain machine set ups in the laboratory when considering surface finish achieved.

Machining processes are wasteful of material. Material must be removed from the original mass to create the finished article, which is waste and therefore cost. Managing the waste through recycling can help improve the overall efficiency of the process. The laboratory already recycles milling waste as scrap charge to the BOS plant, thus this will not be considered for a cost saving potential during this project.

Surface Roughness Overview

Surface Roughness is a component of surface texture. The study of surface texture can be compared to describing geology (topography) –the highest peaks and the lowest troughs, the distance between these, and the total number of peaks.

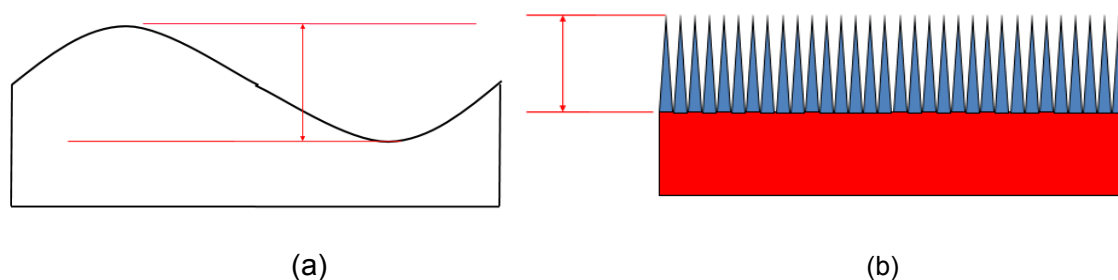


FIGURE 10 REPRESENTATION OF SURFACE ROUGHNESS PROFILES, SHOWING THE HEIGHT BETWEEN THE PEAKS AND TROUGHS. (A) A LOW PEAK COUNT, AND (B) A HIGH PEAK COUNT.

Surface roughness is an important measure of the quality of a finished part. Poor surface finish can lead to premature failure in service, therefore causing difficulties in various applications. Commonly a low roughness, or smooth finish is most desirable. The mechanism which determines the formation of surface roughness is dynamic and complicated, and is dependent on process (Y.H. Tsai, 1999). Thus machinists often use a trial and error approach to improve surface, identifying the most significant milling parameters. For manufacture of precision parts surface finish is often measured as a vital quality parameter, and improved finish can enhance the components performance.

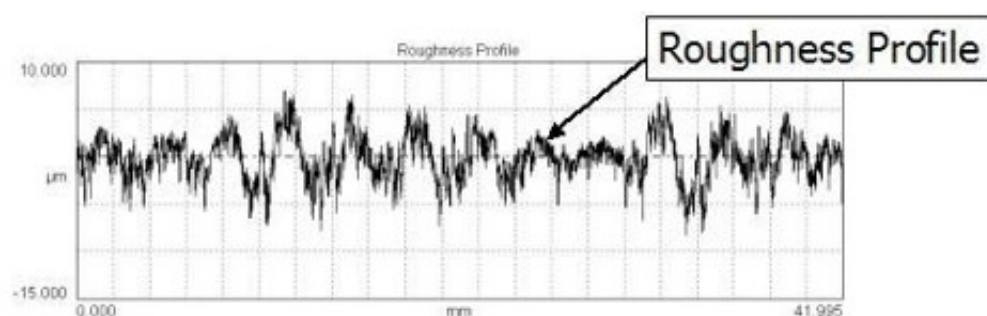


FIGURE 11 AN EXAMPLE OF A TYPICAL SURFACE ROUGHNESS PROFILE (HOLDEN).

Some applications require more surface texture to act as a key, promoting good adhesion for application of a paint or coating.

Roughness average (R_a) is defined as the arithmetical average of the departure of the profile above and below the reference line (centre mean line) throughout the sampling length. The talesurf method is the most common means of analysing surface finish, which involves a stylus travelling a prescribed distance over a selected profile (line) of a sample.

Figure 12 illustrates how roughness average may be calculated.

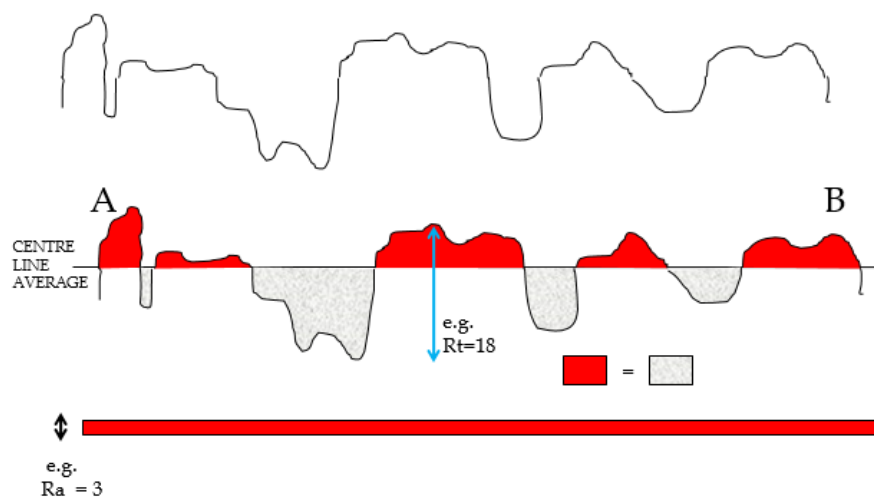


FIGURE 12 SURFACE ROUGHNESS PARAMETER R_a (ROUGHNESS AVERAGE) AND HOW IT MAY BE CALCULATED (HOLDEN).

Surface Roughness Local Testing Apparatus

The surface roughness devices used at Tata Steel (as shown in figure 13) have a probe designed to measure a relatively big surface in relation to the size of the probe tip, such as the top or bottom surface of a steel sample. The samples for this project are less than 1mm thick, of which this stylus is incapable of measuring.

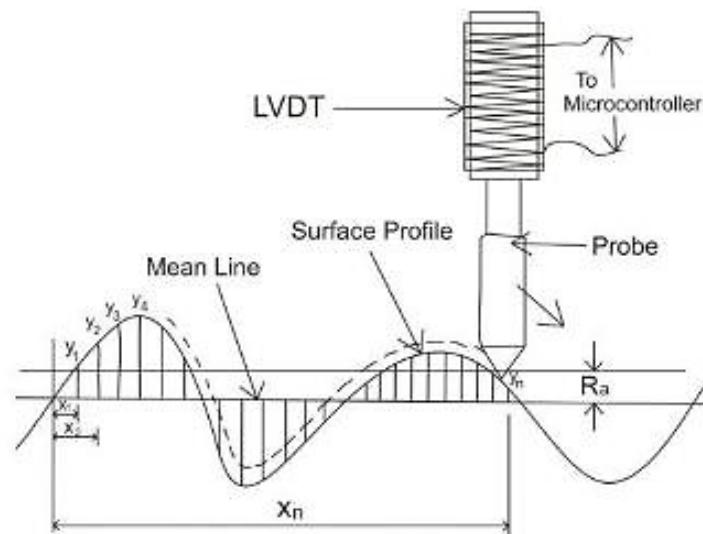


FIGURE 13 DIAGRAMMATIC REPRESENTATION OF THE OPERATION OF A SURFACE ROUGHNESS PROBE (HOLDEN).

The same talesurf type stylus is used at the University of Wales Trinity Saint David (UWTSD) laboratory. Here, a bespoke jig has been designed to hold and align the specimen beneath the stylus in order to measure thinner gauges of material. Although this method seems plausible for gauges ranging from approximately 1-3mm, reliability of measurements for samples below 1mm would be compromised. Due to the nature of the test there would be difficulty ensuring the stylus remains in contact with the thin edge for the prescribed travel.

There was difficulty in finding an alternative method of surface roughness testing for thin gauges of material.

Microscopy was considered a possible method for examining surface finish. However, consultation with numerous sources suggested such methods as unquantifiable and subjective. An appropriate method was eventually discovered through discussion of the project with a past University student, suggesting the use of white light interferometry (WLI).

White Light Interferometry

Vertically scanning white light interferometry is a non-contact optical method for surface height measurement on 3-D structures with surface profiles varying between a few micrometres to a few centimetres (Polytec). A broadband white-light source is used to illuminate the test and reference surfaces. A special lens and beam splitter separates the light into reference and measurement beams. The returning beams are relayed to an image sensor to form an interference pattern of the test topography. Typical equipment is illustrated in figure 14.

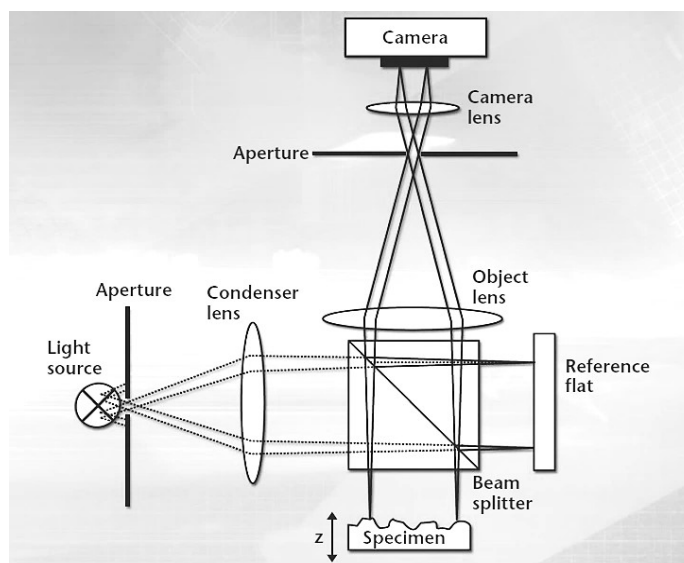


FIGURE 14 OPTICAL SET UP OF A WHITE LIGHT INTERFEROMETER WITH IMAGE SENSOR (POLYTEC).

The most important parameters of the light source are wavelength and coherence length. Interferometry makes use of the wave superposition principle to combine waves in a way that will cause the result of their combination to extract information from those instantaneous wave fronts. This works when two waves combine, resulting in a pattern determined by the phase difference between the two waves. Waves that are in phase will undergo constructive interference while waves that are out of phase will undergo destructive interference. White light interferometry is considered a very powerful measurement tool, using a long coherence length of laser light that produces a more successful measurement than if using a light source with short coherence length (Wyant).

Waterjet Cutting

Investigation of alternative material removal technology may result in improved surface finish of tensile test specimens. As identified in the testing standard, it is important no heat affected zone be introduced into the test piece, resulting in altered its properties.. Waterjet cutting is an increasingly popular method of commercial cutting that does not involve heat transfer.

Waterjet cutting has the advantage of being a cold cut process, thereby enabling a broader range of materials (for which a heat affected zone would be a problem) to be cut. The addition of an abrasive further expands the range of materials to include, for example, glass (Doolan, 2014)

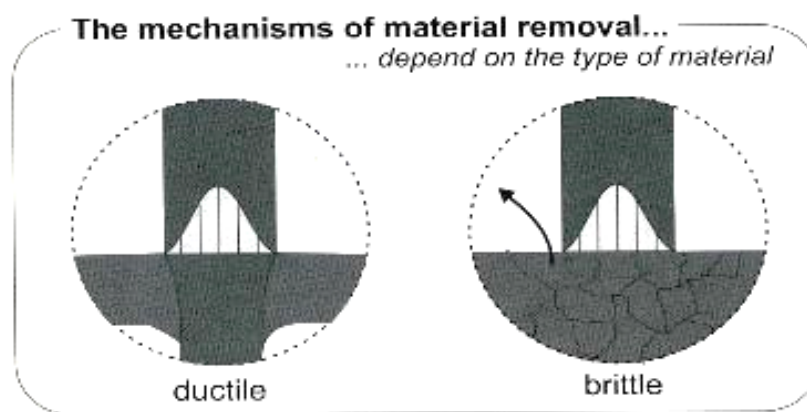


FIGURE 15 MECHANISMS OF MATERIAL REMOVAL BY WATER JET CUTTING (DOOLAN, 2014).

Figure 15 illustrates how ductile materials are cut by displacing or eroding material, whilst brittle materials, such as carbon fibre, use the mechanism of pressurising micro cracks to propagate a network of cracks along the cut line, with material disintegrating and washed away in the water (Doolan, 2014). Figure 16 represents a typical waterjet nozzle.

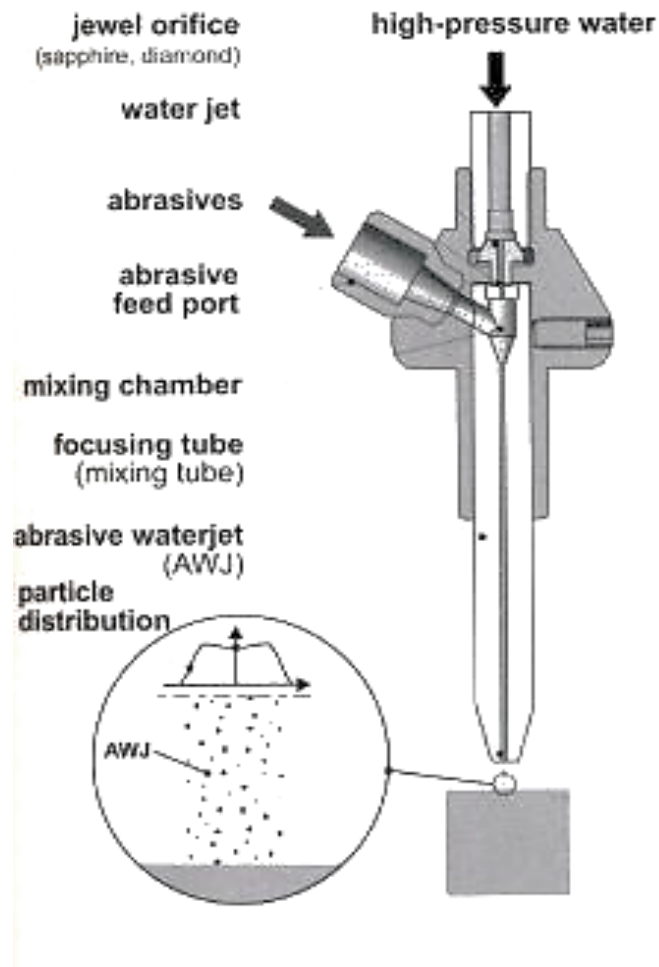


FIGURE 16 ABRASIVE WATER JET CUTTING HEAD (DOOLAN, 2014).

The waterjet formed in the primary orifice is broken down into small drops in the cutting head, transferring energy to the abrasive particles introduced into the mixing tube where the abrasive and water are focussed into an abrasive jet. By volume, the mixture is approximately 4% water 1% abrasive, and the remainder air. The addition of abrasives makes the jet considerably more powerful than a water-only jet.

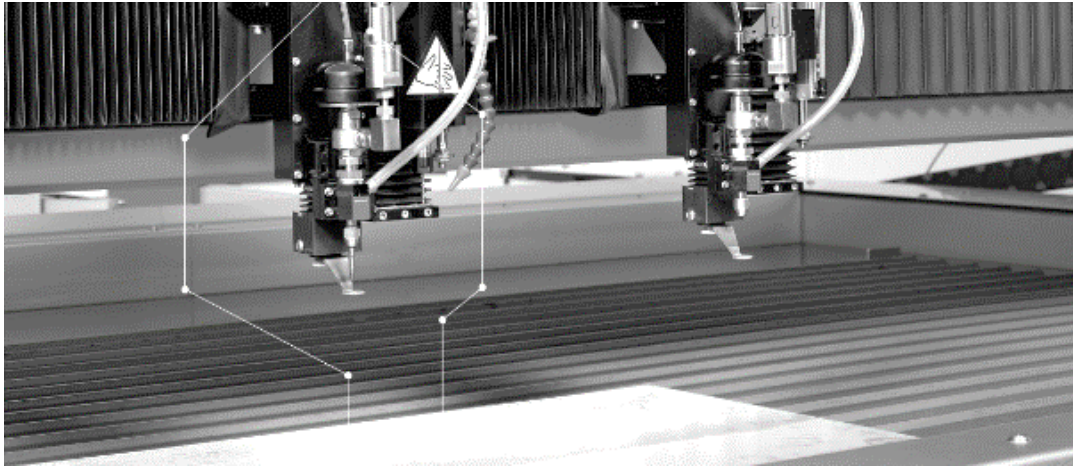


FIGURE 17 WATERJET CUTTING TECHNOLOGY (WATERJET INDUSTRIES, 2017).

The equipment is controlled by a Fanuc operating system, linked to PC software IGEMS. Several physical and programming parameters require set up, dependant on various factors such as the material to be cut and the quality of finish required. These parameters include;

Water Pressure

Two settings are available for the control of the water pressure: a low pressure setting of 11,000 psi and a high pressure setting of 55,000 psi. A method involving 'pressure ramping' may be employed. For example, the increase in pressure for cutting of glass, by adjusting the pressure incrementally within a range.

Material Selection

Different materials, and different thickness of the same material, require different parameter settings. Materials such as foam are easily cut with a water-only jet, whereas the use of abrasive allows the cutting of harder materials such as glass and steel.

Transverse Rate (of Jet)

The speed of which the jet is passed over the material affects the cost and quality of cut. It is possible for adjustments to be made to the speed by using a dial on the controller, permitting adjustments by the operator of 10% increments from 0 to 150% of programmed speed. Alternatively, adjustments can be made in the material settings within IGEMS. These pre-set parameters are intended for operation using an 80 mesh garnet abrasive, therefore adjustments are required when using finer mesh (Doolan, 2014).

Cut Quality and Jet Lag

In contrast to mechanical cutting tools with a fixed geometry, the dynamic nature of the waterjet does not leave a predetermined pattern on the surface of the cut material. During its movement around the cutting path, it is prone to material interaction and the influence of a number of parameters outlined in more detail below.

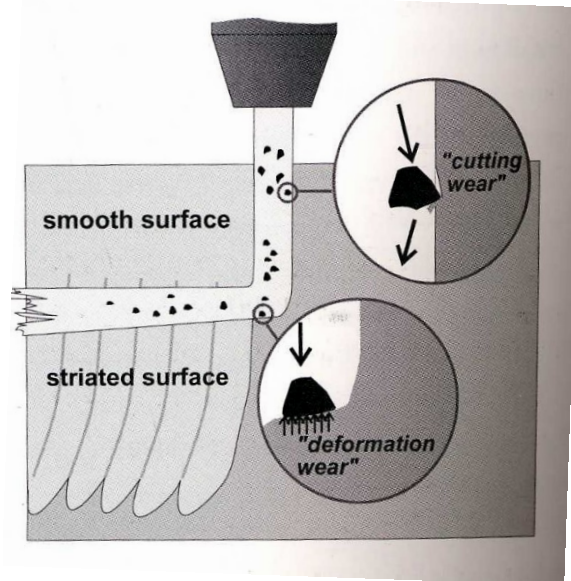


FIGURE 18 ILLUSTRATION OF THE STRIATED SURFACE ASSOCIATED WITH JET-LAG (DOOLAN, 2014).

Figure 18 illustrates how surface quality deteriorates as the depth of the cut gets deeper. This is due to the loss of energy in the jet as the depth of cut increases, as a result of 'jet-material interaction'. The result is a smooth upper region of the cut edge and a rougher striated lower region, referred to subsequently as 'jet lag'. This is a phenomenon that is a common theme in subject literature (Doolan, 2014).

Nozzle Aperture Diameter

The nozzle diameter controls the diameter of the jet. A standard set-up involves a jewel orifice of 0.25mm to focus the water jet, prior to its entry into the mixing tube, and a nozzle exit diameter of 0.76mm.

Abrasive Particle Size

The abrasive particle size is usually referred to as a mesh value. An 80 mesh abrasive is most widely used commercially for most applications, while a 120 mesh is often used for more specialist cutting.

Review of Past Works

A great deal of research exists aiming to optimise machining parameters and improve surface roughness over the past century. This was prompted by (Taylor, 1907) who developed a well-known formula that relates cutting speed to tool life. Some of the main questions that Taylor addressed were what cutting tool, feed rate and speed should be used.

(Yan & Li, 2013) determined that it is the width of the cut that was the most influential parameter when optimising milling in terms of energy consumption, productivity and cutting quality.

However, different conclusions were presented in (Shaw, 1984), (Sandaram & Lambert, 1981), (Boothroyd & Knight, 1989) and (Feng, 2001), who all concluded that cutting speed had a significant effect on surface roughness.

Depth of cut was considered by (Karmaker, 1970) and (Ribeiro Filho, Lauro, Bueno, & Brandão, 2016) also determined that depth of cut and feed rate were the most influential parameters when machining Ti-6Al-4V alloy.

(Suresh Kumar Reddy & Venkateswara Rao, 2005) state that the main considerations for surface roughness when end milling are tool geometry.

The effect of cutting fluid on the finished surface was considered by (Miller, De Vor, & Southerland, 1983). (Mohamad Syahmi Shahrom *, 2006) also studied the effects of coolant levels as well as looking at speed rates, feed rates and depth of cut. (P. Chockalingam) and (Vazquez, Gomar, Ciurana, & Rodríguez, 2014) also studied the effects of coolant on surface finish.

There is an abundance of past research investigating the effects of milling parameters such as feed rate, speed rate, depth of cut and tool geometry. While many previous papers consider the effects of these parameters on tool wear and wear performance, there is limited work available on the effects of worn tools on the surface roughness of the milled sample.

(Rangarajan & Dornfeld, 2004) looks at the effects of back cutting (milling in different directions for two passes), but concludes that it was in fact tool wear that caused nose rounding was the most significant cause of burrs.

(Krahmer, et al., 2016) compared four methods of cutting material specifically for the purpose of tensile testing; milling, abrasive waterjet, punching and electrical discharge machining. While he stated that the milled samples produced the superior surface finish, it was concluded that waterjet cutting was a method that was suitable alternative to milling for tensile test preparation.

Preliminary Investigation

A preliminary investigation was performed at the laboratory to explore milling quality and the milling practices employed at Tata Steel. The aim of the investigation was to identify the areas that require focus during this project, and to concentrate on the most likely factors affecting surface quality.

Although it has been suspected that poor milling of tensile test pieces is the result of some failed results, there is a lack of historical recording of data to support. This is believed to occur as a result of investigations into the preparation of samples by product and technical Specialists, which has been limited to analysis of processing conditions and their misalignment to the tensile test results achieved, leading to the presumption of poor test piece preparation as the cause. Elongation was the primary failure in these cases. This will require further investigation to provide data to support or disprove this theory.

Furthermore, the root cause of poor surface quality of milled surfaces must be reviewed.

Initial literature research presented conflicting data amongst some trials, however the majority of investigations into the effect of milling parameters on surface finish revealed that the greatest influences were depth of cut, speed rate, feed rate, and tool geometry. However, these parameters are not influenced by the laboratory, as a tensile test program has been pre-set into the machines, which is repeatedly run to produce a test piece of the same shape and dimensions. The parameters are not calculated or altered by the operator before each cut, and the operators are not skilled machinists. These operators are required only to load the material, ensure it is secured and adequately packed with sacrificial material, check the tool condition and start the machine.

Therefore there is little knowledge or understanding of milling set up and parameters; the reliance is on advice, information and guidance provided by external milling specialists. Sandvik Coromant Ltd deal with manufacturing tools and machining solutions, and are responsible for the set-up of the milling machine parameters at the laboratory. Contacting Sandvik confirmed that the speed rate, feed rate, depth of cut and most appropriate tooling had already been selected for the required purpose in terms of surface finish of steel samples (Wilkes, 2016). A further visit by Sandvik for re-evaluation confirmed this in November 2016. A BT40 tool holder is employed in the machines which has a run out of 4 microns (Sandvik Coromant Ltd, 2016), and is considered the most accurate of the tool holders, confirmed in their product catalogue. This provides the minimum possible concentricity of the tool during rotation.

A random inspection of used tools from the laboratory confirmed a good concentricity, indicated by a uniform wear across the three cutting flutes. It would be expected that poor concentricity may result in uneven tool wear. This tool wear was observed using an eye glass and whilst acknowledging the limitations of this method of inspection, being subjective and open to inaccuracy, it was used in this instance for illustrative purposes only.

As for the tool itself, Sandvik grade 1670, this is one of the most wear resistant tools offered, which is confirmed against the catalogue's tooling specifications.

An investigation in 2016 into alternative tooling suppliers also revealed that the current tools provided from Sandvik performed the best when compared to other vendors (Clark, 2016).

As a result of these investigations, extensive investigation and trials into these parameters would be of little value, as the outcome would not bear any improvements to current machining processes.

Given this outcome, other factors must be considered that may influence surface finish, to explain why poor milling quality is a problem despite a good machine set up with optimized parameters.

With a poor machine set up, it may be expected that milling defects would occur consistently. However, these milling issues appear more random, therefore operator influenced factors may be the likely cause.

The investigation showed a possible link to issues with milling quality arising from two factors; the use of tools that display excessive signs of wear, and the use of insufficient packing material when clamping specimens. Again, there is a lack of robust recorded data to support this theory to date, although such observations have been made.

Coolant levels and concentration are also under the control of the Laboratory technicians. However, a four week trial during September, where coolant levels and concentrations were inspected daily, showed no deviations from the coolant levels or concentrations set, thus making it difficult to attribute the fluctuations in milled quality to management of coolant. This suggests there would be greater value in investigating more likely factors.

Back cutting was also highlighted during the literature review. However, the milling machines are set up to climb mill on both cuts (front and back) as opposed to conventional milling, and this has been observed as true by visual inspection during the preliminary investigation.

Depth of cut is difficult to reduce in this case as milling throughput is of high importance and volume capability cannot be compromised. Any changes that alter cycle time would be unlikely to be implemented by Tata, as this would affect the amount of material that can be stacked and milled together. Hence, cutting in increments or reducing tool length cannot be

considered. Furthermore, it is difficult to attribute a problem in the machine set up or programming to inconsistent milling quality, and would be a more likely factor resulting in continuous and consistent milling defects.

Discussions were held with various technicians employed at the laboratory. Their understanding of tool wear and judgement of when the tool should be replaced varied. There is no clear procedure detailing what constitutes a worn or usable tool, or clear instruction on when tools should be replaced. The same exists for packing material, and current practices instruct use of scrap obtained from recently tested material, irrelevant of gauge. The testing standard notes that thicker material than the material to be milled should be used, although no clear specifications are detailed. The current process is open to variation.

Therefore, the preliminary investigation directs focus towards operator influenced factors; tool wear and packing.

A review of the Failure Mode and Effects Analysis (FMEA) is currently being undertaken, and team input in these sessions to date has highlighted the main risks for preparation and machining, which have a higher Risk Priority Number (RPN) score. Step number "TH03" in figure 19 highlights the risks involved with machining.

Key Contact/Phone				Core Team							
Robert Perkins ext 4360				Robert Perkins, Terry-Louise Betambeau, Andrew Jones-Angove, Geoff Stanford Bryan Thorn, Tom Lewis, Nathan Fox-Smith, Aaron Trolley, Keiran Parsons, Terry Hughes, Haydn Cale							
Process Flow Step No.	Process Function / Requirement	Potential Failure Mode	Potential Effect(s) of Failure	SEV	CLASS	Potential Cause(s) / Mechanism(s) of Failure	OCCUR	Current Process Controls Prevention	Current Process Controls Detection	DETECT	RPN
TH03	Specimen Cutting Machining and Additional Specimen Preparation	Poor Preparation	Failed or unrepresentative test results	3		Taper on Gauge Length causing early fracture	2	CNC Milling dimension check	Test piece measured and process audit on CNC program	5	30
				3		Incorrect width of test piece	2	CNC Milling dimension check	Test piece measured and process audit on CNC program	5	30
				3		Milled edge burr on test piece causing early fracture	3	Air gun to fully tighten vices	Visual /physical check	5	45
							5	Procedure to pack material	Visual /physical check	5	75
							5	Change worn tools	Visual check of tools	5	75
							4	Deburring Tool	Visual check of sample	5	60
				3		Poor surface finish of machined surface causing early fracture	4	Deburring Tool	Visual check of sample	5	60
							2	Review of machine set up and tools	Annual specialist visit	5	30

FIGURE 19 EXTRACT FROM 2016/2017 FMEA REVIEW DOCUMENT FOR THE METALLURGICAL LABORATORY.

The preliminary investigation and the subjects of highest RPN scores in the FMEA identify the same milling factors as a priority, which validate the correct factors are to be investigated.

The summary outcome of the preliminary investigation is shown in table 2.

TABLE 2 SUMMARY OF FINDINGS FROM PRELIMINARY INVESTIGATION

Factor	Operator Influenced?	Findings	Likely Cause?
Feed Rate	No	Optimised by specialist Inconsistent quality issues do not support	No
Speed rate	No	Optimised by specialist Inconsistent quality issues do not support	No
Depth of cut	No	Optimised by specialist Inconsistent quality issues do not support	No
Tool geometry	No	Optimised by specialist Inconsistent quality issues do not support	No
Tool concentricity	No	Most accurate and precision equipment selected Set up by specialist Uniform wear of cutting faces on used tools Confirmed by product catalogue	No
Tool specification	No	Most wear resistant grade Selected by specialist Confirmed by product catalogue	No
Alternative tool supplier	No	Trial completed in 2016 – best tools by current supplier	No
Coolant type	No	Best selected by specialist	No
Coolant level	Yes	4 week trial showed no variation. Does not support failures	No
Coolant concentration	Yes	4 week trial showed no variation. Does not support failures	No
Back cutting	No	Climb mill confirmed on all cuts	No
Tool wear	Yes	Wear and replacement of tool based on operator judgment Acceptable tool wear and when to replace tool not defined in procedure	Yes
Packing material	Yes	Selected based on operator judgment No details of packing type defined in procedure	Yes

Crack Propagation

An understanding of why poor surface quality might affect a tensile test is crucial for this investigation.

Flaws and inherent weaknesses exist within, and on the surfaces of all materials, be it due to the crystal structure or through manufacture, processing or machining operations. Not all flaws are unstable in serviceable conditions, and most are accepted as part of the materials structure and characteristics and will not affect the mechanical performance. However some flaws can cause a crack to propagate, resulting in early fracture or failure. An area of stress concentration develops where there is a point of weakness, which can develop into a crack, which then continues to propagate, especially when stresses are applied.

“...the physics of stress and strain behavior of materials, in particular the theories of elasticity and plasticity, to the microscopic crystallographic defects found in real materials in order to predict the macroscopic mechanical behavior of those bodies... to understand the causes of failures and also verify the theoretical failure predictions with real life failures.” (Fenix.tecnico)

As certain materials behave differently under stresses and have very different mechanical properties, the theory of fracture is clearly split into different areas – brittle fracture and ductile fracture. In brittle fracture, no apparent plastic deformation takes place, and the material will withstand a certain level of stress before breaking suddenly. However, in ductile fracture, extensive plastic deformation takes place before fracture occurs.

There are two defined fracture modes in the theory of fracture mechanics, which cover fracture under tensile stresses (Mode I fracture) and fracture under shear stress (Mode II fracture). Due to the nature of tensile testing, understanding the mechanics of Mode I fracture is important, where tensile stresses are applied to induce fracture.

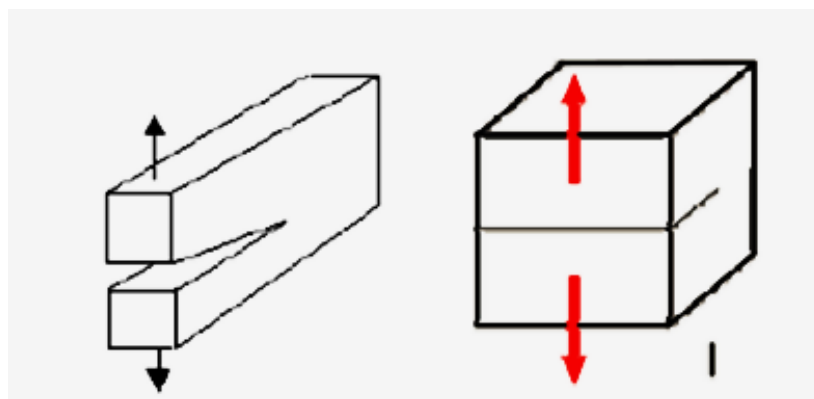


FIGURE 20 FRACTURE REPRESENTATION, WHERE TENSILE STRESSES ARE APPLIED CREATING A CRACK BY “OPENING” (MIANNAY, 1997).

Fracture strength is the stress at which a material fails due to fracture. A tensile test is the most common method of determining the fracture strength (as well as other properties), which plots a stress strain curve to represent performance. Figure 21 shows an example curve.

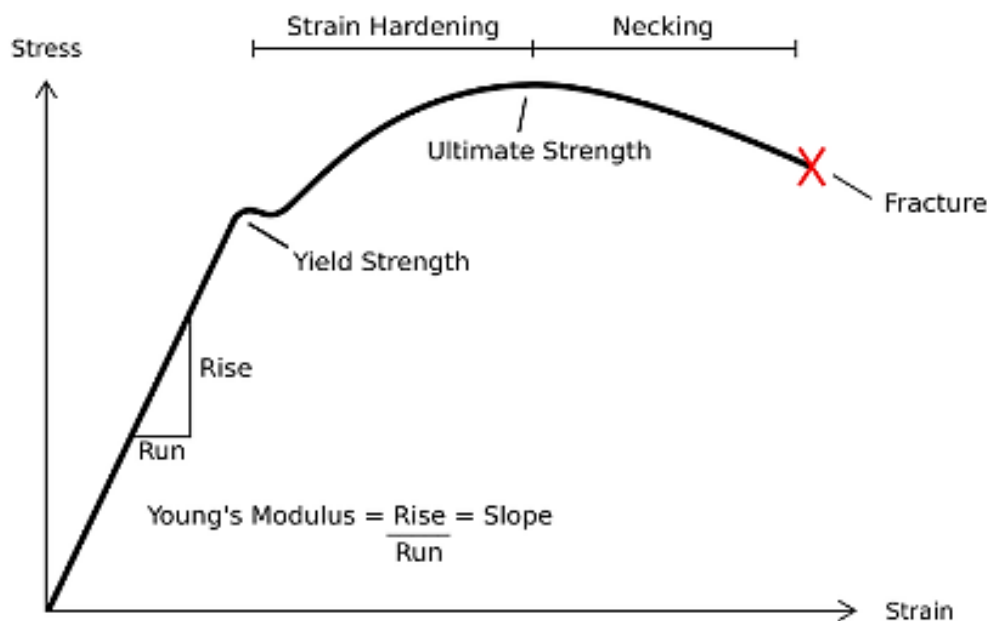


FIGURE 21 A TYPICAL STRESS STRAIN CURVE INCLUDING ITS MAIN FEATURES (AUTODESK INC., 2015).

Ductile materials, such as steel, have a fracture strength that is lower than that of the ultimate tensile strength (UTS). Brittle materials' UTS and fracture strength are equal. In a load controlled test, ductile materials continue to deform with no additional stress applied after reaching the UTS, until rupture.

Ductile materials can absorb a large amount of energy while being pulled apart in the plastic region, where there is slow propagation and "necking". Necking describes the decrease in local cross sectional area of a material under tensile stresses and is illustrated in figure 22. Where any flaws or areas of additional weakness are present outside of those that are normal for the material, the fracture can occur early with less plastic deformation being observed. The fracture behavior of brittle materials can be predicted and described in Gibbs theory of crack propagation, but as ductile fracture involves a high degree of plastic deformation, the behavior of propagation changes fundamentally. Some of the energy from stress concentrations at the crack tips is dissipated by plastic deformation ahead of the crack as it propagates.

FIGURE 22 ILLUSTRATIVE REPRESENTATION OF THE STAGES OF FRACTURE IN DUCTILE MATERIALS WHEN SUBJECT TO TENSILE OR AXIAL FORCES (MY AMIE PREPARATION, 2011).

It is important to understand fracture mechanics of materials during design to anticipate and predict how a material may perform under certain conditions and stress in service and assess its damage tolerance.

With regard to tensile testing, with the theory of fracture and crack propagation in mind, it can be anticipated that any out of the ordinary flaws in the surface of the material may lead to early fracture and reduce the true elongation performance of the material. In terms of testing, this material may fail to meet expected properties, where the un-flawed same material does meet specification.

Where flaws exist in the surface, an area of stress concentration is introduced. The theory of fracture mechanics can demonstrate the effect of cracks on a component and relates the stress magnitude and distribution in the crack tip to the nominal stress applied, to the size, shape and orientation of the crack and to material properties. According to Fatemi, cracks can form;

- due to fatigue
- as a consequence of manufacturing processes (i.e. machining marks or voids in welds)
- metallurgical discontinuities (i.e. inclusions)

(Fatemi, 2011)

Trial 1 – Crack Propagation

A preliminary investigation was performed comparing the elongation achieved by specimens that had varying depth notches along one edge of the parallel length. The trial aimed to demonstrate whether or not notches of varying sizes would affect elongation, and whether fracture would occur at the notch. Five specimens of DP800 material were used to perform the trial, taken from adjacent locations from the same sample. One of the specimens was left un-notched, to provide a base line for results. The other four were notched with increasing depths using a notching tool while the specimens were clamped in a vice.

The specimens were examined under a microscope to measure the notch depth into the parallel length. The results are displayed in figure 23.

FIGURE 23 METALLOGRAPHY REPORT INDICATING MEASURED NOTCH DEPTH FOR TRIAL SPECIMENS
(JOHNSTON, 2017).

Markers were made before at the notch location before tensile testing, so that their location could be identified after the specimens had broken. The broken ends were kept for inspection.



FIGURE 24 BROKEN SPECIMENS MARKING TEST FRACTURE AT THE POINT OF EACH NOTCH.

Figure 24 shows a visible decrease in elongation achieved by each specimen before breaking when the specimens were lined up in order. The trail has been successful in demonstrating that edge defects can cause premature breaking during tensile testing, even though somewhat exaggerated here. There is a considerable visible difference in elongation between the unnotched sample and the sample with the smallest notch of 0.15mm. This would suggest that there may be a range of notch sizes from 0mm to 0.15mm that may affect mechanical properties, and that even the smallest nicks or edge defects may result in early fracture. This sets a good scene for the basis of this project.

A view of the mechanical properties in the table 3 shows decreasing elongation results with increasing notch size, while UTS also appears to have suffered. The clearly affected properties are graphically depicted in figure 25 and 26.

TABLE 3 TABLE OF MECHANICAL PROPERTIES FOR NOTCHED SPECIMENS FOLLOWING TENSILE TESTING.

Coil ID	Dir	Gauge	Width	Rp0.2	UTS	A	r10
TLBC26	L	0.895	20.157	486.5	816.2	18.36	0.673
TLBC27	L	0.891	20.146	484.3	815.1	17.25	0.663
TLBC23B	L	0.889	20.172	487.4	824	14.98	0.683
TLBC23A	L	0.898	20.209	487.1	821.5	11.23	0
TLBC25	L	0.895	20.169	490	794.6	7.36	0
TLBC24	L	0.896	20.219	488.1	746.4	5.11	0

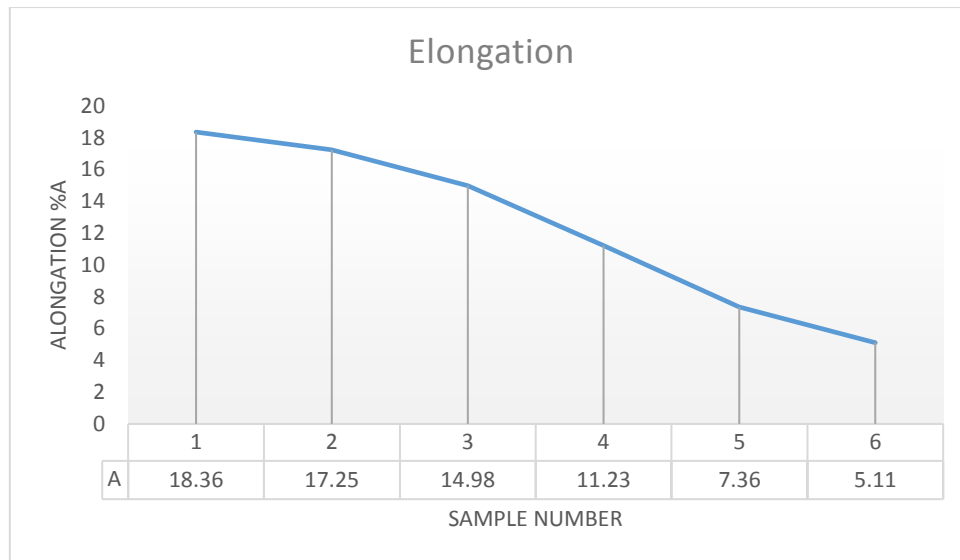


FIGURE 25 PLOTTED ELONGATION FOR RESULTS FROM TABLE 3 SHOWING A TREND DECREASING ELONGATION WITH INCREASING NOTCH DEPTH.

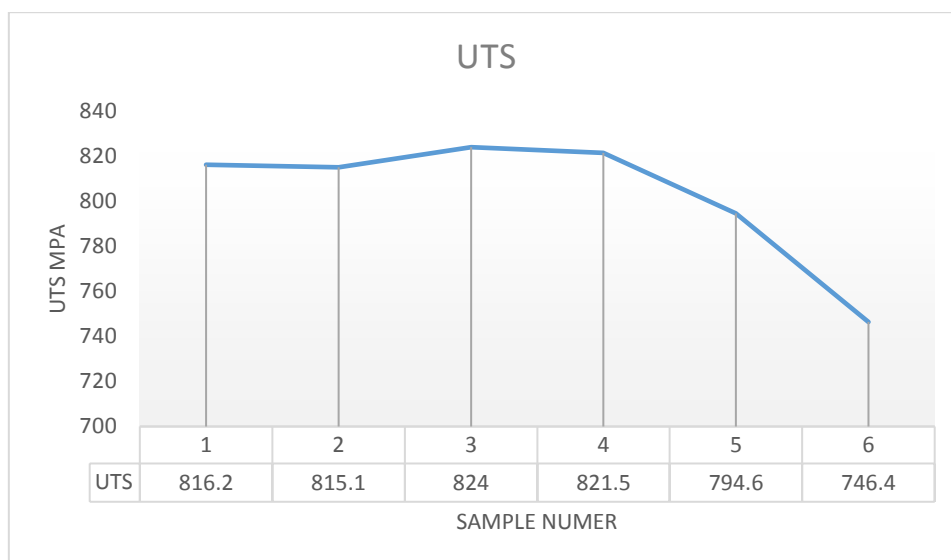


FIGURE 26 PLOTTED UTS FOR RESULTS FROM TABLE 3 SHOWING A DECLINE IN UTS FOR THE SEVERELY NOTCHED SPECIMENS.

This trial indicates that even a small edge defect creating a stress concentration may initiate crack propagation, early failure, and reduced elongation. There is a decline in UTS for severely notched specimens, although it is unlikely that milling defects would produce indents of such magnitude during standard operating times. R value is affected similarly, remaining consistent for the first tests, although a dramatic decline is noted for notches of less severity compared to UTS. A full range of data analysis was not completed for this trial, as this investigation is for indicative purposes only.

Elongation

Sheet metals are often high in strength relative to their cross section area, which is desirable for some industries they serve. However, formability and ductility are also crucial.

Elongation is an indicator of ductility, where materials with higher elongations are more ductile and formable. These materials perform well during deep drawing or pressing operations. Materials with lower elongation have a smaller plastic region before fracture, thus will have little or no deformation under load before fracture, as is the case in brittle materials. Higher elongations will allow materials to deform before they fracture. This may be useful for production of car bodies which require sheet steel to be formed into shape and hold its formed shape, deforming plastically, and not fracture or split during forming.

Elongation is “determined by a tension test. It is the increase in the gauge-length of a test specimen after fracture divided by its original gauge-length” (Instron Ltd, 2016).

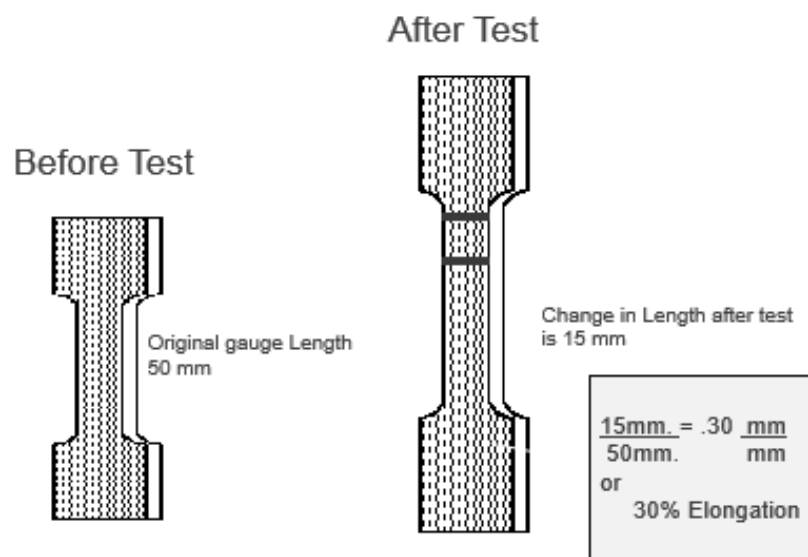


FIGURE 27 DIAGRAM ILLUSTRATING ELONGATION OF A TENSILE TESTED SPECIMEN (ZWICK ROELL LTD, 2013).

Elongation can be calculated using the formula;

$$\begin{aligned}\text{Percent elongation} &= \frac{\text{final gage length} - \text{initial gage length}}{\text{initial gage length}} \\ &= \frac{L_x - L_o}{L_o} = \text{inches per inch} \times 100\end{aligned}$$

R-Value

R-value or plastic strain ratio is a measure of the ability of a sheet metal to resist thinning or thickening when subject to tensile or compressive forces. It is typically advantageous if the material reduces in area a minimal amount when subject to this force, therefore a good drawing material will have a high R-value. Once the material is taken beyond its elastic limit, it has plastically deformed. If this flows easily in the plane of the sheet it will result in a high R-value. Alternatively, if it flows from the materials thickness it will thin during drawing, which may result in weakness. To determine this ratio, assuming constant volume, both the axial and transverse strain needs to be obtained during a uni-axial tensile test (Instron, 2016).

Elongation and R-value properties are particularly important to automotive customers, indicated by their tight test requirements. Internal product specialists pay particular attention to DP800 material, reporting higher quantities of elongation failures which are difficult to explain.

Hypothesis

Research material and trial work suggests that the mechanical properties most likely to be most affected by poor surface finish are elongation and R-value. Despite limited effect in the preliminary trial, it is anticipated that R-value may still be affected by edge defects



FIGURE 28 ATTEMPTED TENSILE SPECIMEN PRODUCED BY MILLING WITH NO PACKING MATERIALS AND A TOOL WORN TO ABOVE 5MM OF WEAR.

Figure 28 shows an exaggerated example of a poorly milled specimen. The width of the gauge length is severely compromised by the serrated edges and sections of unremoved material, and although such extreme examples would not be seen in practice, this does illustrate the possibility that the sensitive R-value monitors may detect surface defects of much less magnitude.

Due to the increase in waterjet cutting commercially, it predicted that the results of waterjet (Chiles, Black, Lissaman, & Martin, 1996) (Momber & Kovacevic, 2012) cut samples will be similar to, or better than milled samples, and that a recommendation for this alternative method of cutting be evaluated during this project.

9. Measure

The measure phase will include;

- Cost savings
- Material selection
- Trial Design
- Methods of data capture

Cost Analysis of Affected Material

The procedure for dealing with failed material is quite complex. The laboratory procedure for test failure is illustrated with a process flow chart in figure 29.

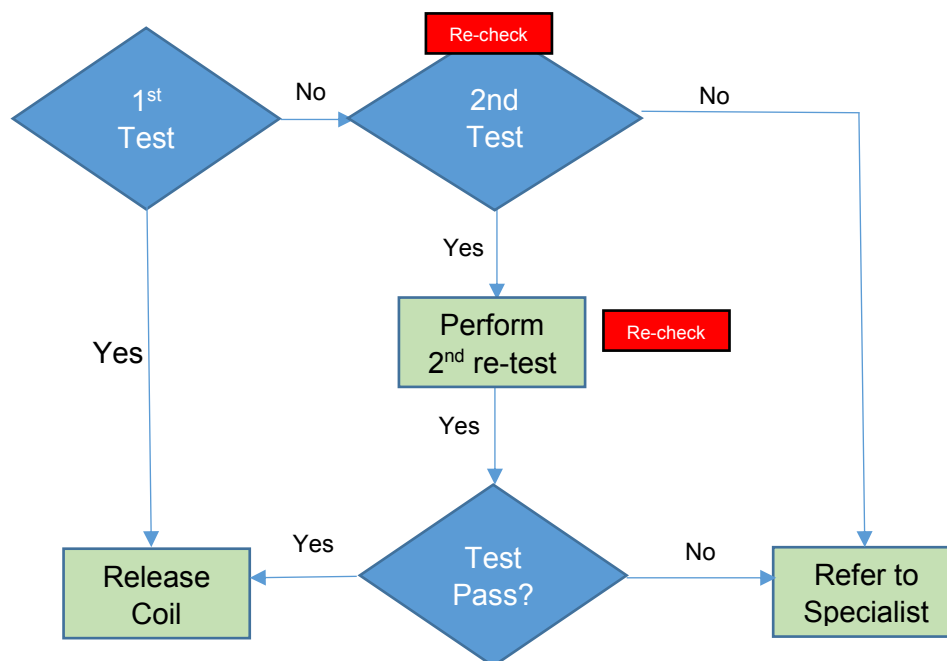


FIGURE 29 PROCESS FLOW CHART FOR TESTING AND RELEASE OF MATERIAL.

When a coil of steel is referred to the specialist there are numerous possible resulting actions. Due to an array of variables, and each coil case being unique, it is difficult to accurately forecast a cost of failed tests and referred material. However, a representative assessment of costs can be formed with a snap shot of data.

Referral

When a test fails after a re-check has been performed, it is referred to the production area Specialist to decide how to best proceed with the coil. Coils are dealt with by the following actions;

1. Discard – generally 50m (one end of coil suspected of not meeting specification).
2. Re-work (whole coil suspected of not meeting specification).
3. Re-sample (processing appears normal, possible testing or preparation issue, damaged sample etc.).
4. Sold via screen sales (not met specification. 60% non-prime, 40% prime (Haines, 2017)).
5. Sold via customer concession (just short of specification, but accepted at a lower price).

Elongation and R-Value Failures

Data was taken from October and November 2016, from the referral database, and Aurora. A total of 8,680 tests were performed for Cold rolled (CR) and galvanised (Galv) products. From these, the elongation and R-Value referral totals are shown in table 4.

TABLE 4 TABLES COMPILING QUANTITIES OF REFERRED MATERIAL FOR ELONGATION AND R-VALUE FAILURES, INCLUDING RESULTING ACTIONS FOR OCTOBER AND NOVEMBER 2016,

Elongation	Referral Action	CR	GALV	TOTAL
	Concession	3	2	5
	Re-Work	2	2	4
	Re-Sample	25	30	55
	Discard	15	20	35
	Screen Sales	2	4	6
Total		47	58	105

R-value	Referral Action	CR	GALV	TOTAL
	Concession	2	2	4
	Re-Work	1	1	2
	Re-Sample	11	10	21
	Discard	19	16	35
	Screen Sales	1	2	3
Total		34	31	65

The cost of the referral actions has been obtained from data provided by the Mills Finance Manager and Area Specialists, and represents a general average derived from data obtained over a six month period. Continuous past and future fluctuations in both costs and price of material in the market make it difficult to obtain a precise cost.

Discard

- 50m discard.
- Average coil width - 900mm.
- CR gauges range from 1mm to 3mm (2mm mean).
- Based on these figures, using a steel weight calculator (Metal Weight Calculator, n.d.), the weight of steel discarded is 706Kg per discard (per coil).
- The discard value must be attributed in the unit of one coil, not tonnes. Coil weights generally vary from 8-28 tonnes.
- Discard material is recycled to the BOS Plant as scrap charge. However, the cost retrieved is negligible against the loss of manufactured material (Richards, 2017).
- Average cost per tonne – CR £350, Galv £500.

Rework

Coils with elongation issues are often routed for re-work through the temper rolling units in attempt to rectify the issues, and costs on average £30 per tonne (Richards, 2017).

Re-Sample

Coils are taken to the rewind or inspection line to have a new sample cut costing £15 per tonne. (Morris, 2017).

Concession

The Finance Manager was unable to release any information on the cost of concessions as the costs are often hidden and difficult to trace (Richards, 2017).

Screen Sales

"In terms of prices an average rejection will cost £64.60/t" (Richards, 2017).

Re-Check

The cost of re-check can be quantified in terms of time and tool cost.

A re-check involves the operator locating a spare, cutting a blank using mechanical shears, milling the specimen, labelling and testing. During week 42, a total of 54 re-checks were required, which took the technician and testing machine four hours and twelve minutes to complete (using two simultaneous testing machines). The testing machines are capable of testing 17 tests per hour each (if at 100% availability), thus costing approximately 3 hours of machine time, and approximately 1.25 man hours.

A cost can also be attributed to tool wear, through additional preparation of test pieces for further testing.

Trial 2. Cost of Tooling

This trial is aimed at attribute a tool cost to milling of one tensile test by monitoring tool wear against the number of tensile specimens produced. The trial covered the same three 12-hour shifts (October 31st – November 2nd). A new end mill was provided at the start, and the number of specimens milled was counted until the end mill was replaced, by judgement of wear by the Technician. Three end mills were provided in total, milling 335, 368 and 385 samples respectively during this period. A range of varying strengths of steel were milled, including hot and cold rolled material, thus theoretically tool wear may vary between cycles. However, as over each 12-hour period roughly the same quantities of each material are milled (based on a relatively consistent production of each material), the wear should offset, and a representative value of tool wear can be attributed to each sample milled, as an estimate.

Cost of tool =	£100.10
Cost of three tools=	£300.30
Number of specimens milled with three tools =	1088
Tool cost per specimen milled =	28p

Trial 3. Number of Milling Defect Re-Checks

This trial aimed to quantify the amount of material that fails due to milling defects. This was done by visually inspecting the broken ends of failed test pieces for evidence of burrs with the human eye. The same three 12-hour shift period as trial 2. A total of 623 CR tests were performed. A total of 31 failed (4.98%), of which 7 showed visual signs of milling defects or burrs (an example is shown in figure 30). A total of 9 tests passed the re-check. Other milling defects could have been present that could not be detected by the human eye.

This trial concludes that the possible amount of material affected by milling defects is this percentage of failures that passed after a the re-check (29%). A re-check pass, after an initial failed test, could indicate that there is no issue with the material itself, and that the test fail was likely to have been caused by external factors, such as preparation by milling. This should be regarded as an indicative figure only, to quantify the possible amount of failures that may be caused by milling defects. Without extensive investigation, a precise figure is very difficult to obtain, and it cannot be said reliably that all failures that pass a re-check are due to surface quality defects.

FIGURE 30 COIL ID 3873601 AN ORIGINAL TEST WITH VISIBLE POOR EDGE FINISH THAT FAILED FOR ELONGATION, AND A RE-CHECK WITH NO VISIBLY GOOD EDGE FINISH WHICH PASSED.

Using the results from trial 2 and 3, some further conclusions can be drawn. The monthly cost of re-checks can be calculated in relation to tool cost

Number of re-checks in three days =	9
Number of re-checks in thirty days (month) =	90
Tool cost for monthly re-checks =	£25.20

The total annual cost of end mills, based on the number of end mills purchased in 2016 of 268, was £29,507.

Table of costs

Using the values from table 4, estimated costs can be calculated for failures for October and November 2016.

Elongation Failures

TABLE 5 TABLE OF COSTINGS FOR ELONGATION FAILURES FOR OCTOBER AND NOVEMBER 2016

MATERIAL	REFERRAL ACTION	NUMBER OF COILS	TONNES (T)	COST (£)	RE-CHECK
CR	Concession	3	x	X	X
	Re-Work	2	41.36	1,240	2
	Re-Sample	25	426.28	6,394	25
	Discard	15	10.59	3,707	15
	Screen Sales	2	29.92	1,933	X
GALV	Concession	2			X
	Re-Work	2	29.26	878	2
	Re-Sample	30	479.57	7,194	30
	Discard	20	14.12	7,060	20
	Screen Sales	4	71.11	4,594	X
TOTALS				<u>£33,000</u>	
					<u>£26.32</u>
				<u>£33,026</u>	

R-Value Failures

TABLE 6 TABLE OF COSTINGS FOR R-VALUE FAILURES FOR OCTOBER AND NOVEMBER 2016

MATERIAL	REFERRAL ACTION	NUMBER OF COILS	TONNES (T)	COST (£)	RE-CHECK
CR	Concession	2	x	x	x
	Re-Work	1	16.52	496	1
	Re-Sample	11	154.33	2,315	11
	Discard	19	13.41	4,695	19
	Screen Sales	1	13	840	x
GALV	Concession	2	x	x	x
	Re-Work	1	11.96	359	1
	Re-Sample	10	166.37	2,496	10
	Discard	16	11.3	5,650	16
	Screen Sales	2	25.83	1,669	x
TOTALS				<u>£18,520</u>	
					<u>£16.24</u>
				<u>£18,536</u>	

Annually, this equates to;

Annual cost of Elongation failures =	£198,156
Annual cost of R-Value Failures =	£110,136

This method of valuation is limited to an estimation based on a snapshot of data. Due to considerable fluctuations, accurate costings could only be obtained on a coil by coil basis, which would not accurately represent future costings due to said fluctuations. Furthermore, the calculations have assumed only one re-check is performed per coil, as there is difficulty in determining if coils were subject to multiple re-checks. This is acceptable for these estimations, as little benefit would be yielded in obtaining precise figures, due to the difficulty of data extraction and the low value of the re-test in relative terms..

The cost of concession has been omitted due to the difficulty in obtaining figures, although the impact of this is suspected to be low due to the relative infrequency of concessions.

The costings calculated in tables 5 and 6 represent the cost of all elongation and R-Value failures, of which only a portion may be the cause of milling defects. This portion can be estimated by applying data acquired from “trail 3”. This trial concluded that approximately 29% of these failures occurred as a result of milling. Therefore the annual cost of milling quality is represented in table 7.

TABLE 7 TABLE OF ANNUAL COST FOR FAILURES DUE TO MILLING DEFECTS

Milling Quality Induced Failure Category	Annual Cost of Milling Quality
Elongation	£57,465
R Value	£31,939

There is also an unseen cost that is difficult to quantify, and that is the cost of reputation. Prolonged or frequent quality issues that are externally visible to the customer may result in their withdrawal of purchasing steel from Tata Steel. The cost of this, at worst case, could result in the closure of Tata Steel Port Talbot.

Material Selection

For the purposes of this investigation, high profile grades have been selected that appear to be most problematic. Resolution of the cause of material failures of these grades are likely to return the maximum benefit. Sourcing samples is challenging and can take several weeks. This timescale has been accounted for in the project plan (figure 1) and all samples were received by December 2016. The grades chosen represent a harder and a softer type of steel. It is expected that the results from this project on these grades may enable predictions to be made on similar grades across the product range.

DX57 IF Steel

DX57 samples have been obtained to represent Interstitial free (IF) steel in this study. There are several grades that fit this category. Examples are 3013 and XSESG, which are typical specifications supplied to Jaguar/Landover. DX57 is a mild IF steel, with ultra-low carbon content of around 50ppm. Additions are kept low such as Manganese, Phosphorus, Sulphur (0.008% max), and Nitrogen (0.004% max). The carbon is stabilised by additions of Titanium, and an excess of Titanium is desirable (0.03%) as it is found to improve the R-value, in tandem with high soak temperatures during annealing. High temperatures are required to achieve a formable product, but not too high as to cause coarse austenitic grains. High soak times increase nucleation during annealing for a fine grain structure.

DX57 grades are most suitable for car panels, as it is a soft, highly formable product with good elongation, R-values and n values (for drawing and stretching respectively). A new DX57 product has recently been developed promising 0.2 minimum n values.

DX57-GI Hyperform steel has excellent deep drawing and stretching properties, enabling automotive engineers to design more complex parts for vehicle exteriors and interiors. As a result they will be able to design vehicles that are more aesthetically pleasing to their customers, as well as having better functionality' (Tata Steel Europe, 2014)

Tight specification, chemistry and processing conditions are producing DX57 grades up to the specification limits. Therefore, good preparation and confidence in results is vital, as poor sample preparation could be the difference between a material pass or fail.

DP800 Dual Phase Steel

Dual phase steels are known primarily for being materials of high strength. DP800 offers a product that possesses a UTS in the region of 800MPa, appealing to automotive customers as higher strength can be obtained through a lighter component. Dual Phase steel offers the benefit of possessing a unique mix of properties. Ductility and strength are often opposing properties, where a gain in one often result in a decline of the other. Benefits of both properties are realised by producing a product that has a structure containing parts of two phases; a ferritic and a martensitic phase. Ferrite offers ductility, while martensite formation offers strength, usually existing as around 5-10% martensite in a ferritic matrix.

Typical vehicle applications are rails, car seat panels and sills; parts that can be shaped and formed, but offer high strength.

Kate Watts from the Product Development department at Tata Steel offers that current issues faced by the DP800 grades during testing are that tensile tests are seen to be breaking on or outside of gauge length (Watts, 2016). It is possible that a poor edge finish of the test piece could cause a break outside of gauge length, invalidating the test and producing lower elongations, and to fully understand product capability the metallurgical laboratory must be confident in testing and preparation methods.

Product Specifications

The specifications and tolerances for these products are outlined in table 8.

TABLE 8 PRODUCT SPECIFICATIONS FOR DX57 AND DP800

Product	Yield	UTS	Elongation	R-value
DX57	120-170	260-350	>41	>2.1
DP800	470-560	>780	>14	>0.18

Sample Preparation

Tata Steel procedures state that samples prepared for tensile testing should be taken from the W4 position of the full width sheet.

The W4 position refers to a section that is one quarter the width of strip from any mill edge.

Tata procedures for preparing samples illustrate the three directions of testing;

- 'L' Longitudinal – Taken in the rolling direction.
- 'T' Transverse – Taken perpendicular to the rolling direction.
- 'X' 45° Degree – Taken at a 45° angle to the rolling angle.

FIGURE 31 DIAGRAM FROM TATA STEEL PROCEDURE TO SHOW HOW SAMPLES ARE TO BE TAKEN FROM THE ROLLING DIRECTIONS L, X AND T FROM A FULL WIDTH STRIP OF STEEL, ALSO IDENTIFYING THE W4 LOCATION (TATA STEEL TECHNOLOGY SWP & RA DATABASE, 2016)

The structure, and therefore properties, can vary in each direction due to the elongated rolling grain structure produced by rolling, as shown in figure 32. Thus the tensile performance and strength of the material may be greater when subject to tensile stress in one direction than another; in the flow of the grains, or against.

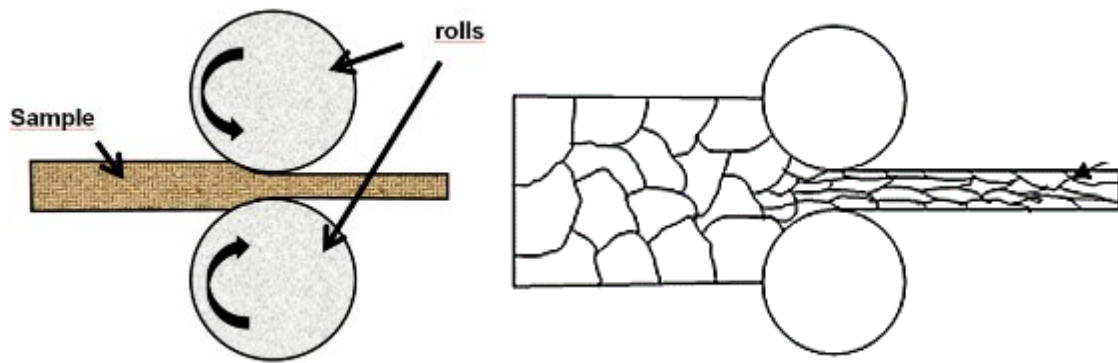


FIGURE 32 ILLUSTRATIVE REPRESENTATIONS OF MATERIAL AS IT IS COLD ROLLED AND THE RESULTING ELONGATED GRAIN STRUCTURE (PANDEY, 2015)

The test direction for each product is determined at the point of order by the customer. The test direction cannot deviate from this during testing with an aim to achieve improved test properties. This variable cannot be controlled by the laboratory, and the customer stated test direction must be honoured.

The samples for this project will be tested in the standard test directions typically ordered for the chosen products;

- DP800 – L direction
- DX57 – T direction

This also ensures that the data gathered is relevant and meaningful when compared with past and future data for these products.

Full width sheets of DP800 and DX57 of approximately 1450mm were obtained and prepared in accordance with the typical test direction and standard procedure for cutting samples. What is different is that where usually one to three samples are cut from a full width sheet to complete testing of each coil, the maximum amount of samples will be cut from the W4 position in this trial, to obtain the highest amount of comparable material.

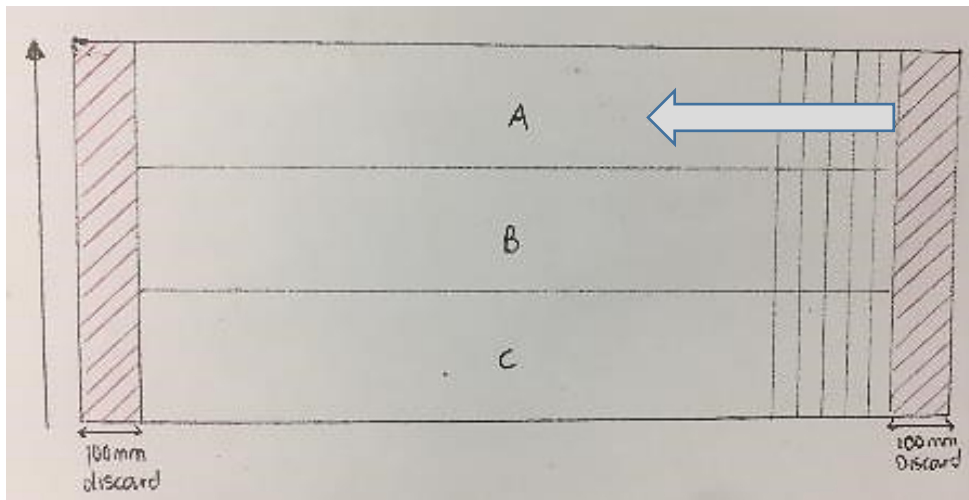


FIGURE 33 DP800 SAMPLE PREPARATION OF A FULL WIDTH SHEET

Figure 33 shows how DP800 samples were obtained in the L direction. Firstly, 100mm of material is discarded from the mill edge. Using a mechanical shears, the full width strip is cut into three full strips, A, B and C, with a 250mm set backstop. The strips are then rotated to take perpendicular cuts set at 38mm backstop, which leave sample strips in the direction of rolling. Eight strips from A, B and C were taken in the W4 position. The next sequential full width sheet was cut using the same method, taking eight strips from section A and B resulting in a total of 40 available specimens. Eight further samples from C were taken as spares. The material was labelled DP01-DP40 in the order it was cut. (left to right).

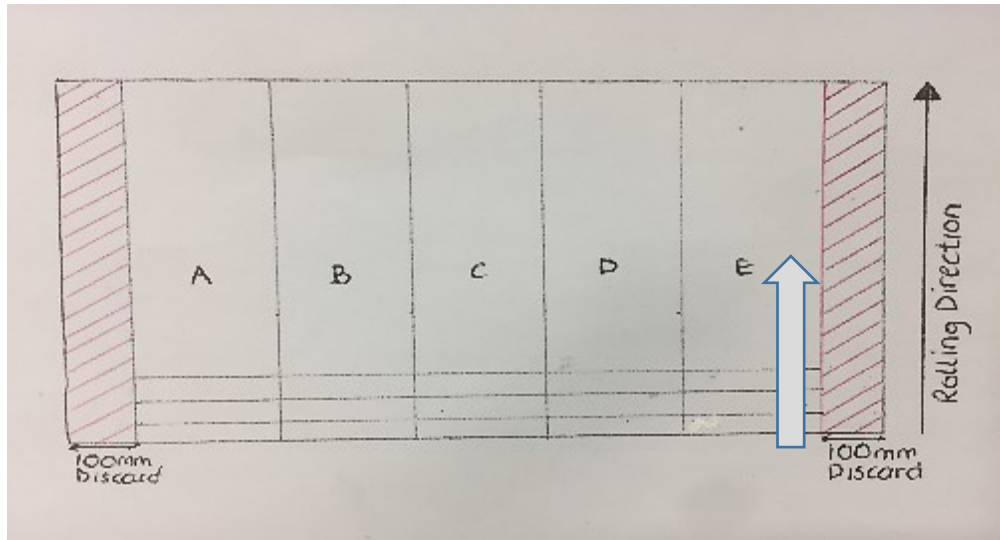


FIGURE 34 DX57 SAMPLE PREPARATION OF A FULL WIDTH SHEET

Figure 34 illustrates how DX57 samples were obtained in the T direction. Again, 100mm of material was discarded from each mill edge before 250mm cuts are made in the rolling direction in accordance with the illustration to obtain sections A-E. From section A, within the W4 position, thirty strips at 38mm cuts were taken from two sequential full width sheets, providing sixty comparable samples, including spares. The material was labelled DX01-DX60 in order it was cut. (bottom to top).

Due to the destructive nature of the tensile test, Quality Specialists in conjunction with the United Kingdom Accreditation Service (UKAS) have deemed this method for obtaining samples for comparison the most appropriate for data analysis in measurement system analysis (MSA) studies, therefore the method is reliable in this instance.

Trial Design

This project initially appeared to suit adoption of the experimental design method of testing, where a trial and error type design incorporates combinations of variables to determine the “ideal” combination. This method has been utilised in many papers with the subject of optimisation of milling conditions and parameters. However, through information gathered to date supported by preliminary trial work, an investigation into multiple parameters is unnecessary. Most value lies in investigation of two parameters; tool wear and clamping or packing of material.

It was later thought that it may not be prudent to fully rely on the evaluation and feedback of the current milling set up provided by Sandvik Ltd, due to their vested interest given they are the approved supplier of milling consumables. A further site visit was organised from an independent company to further validate milling set up, particularly feed and speed rates, tooling and depth of cut. Blu Thomas, manager at Brother Engineering Ltd, used computer software to simulate current milling practices on site. Figure 35 shows the drawing of the milling program. The result of this evaluation matched the one of Sandvik Ltd, giving confidence that the correct variables are being considered for this trial - operator influenced factors.

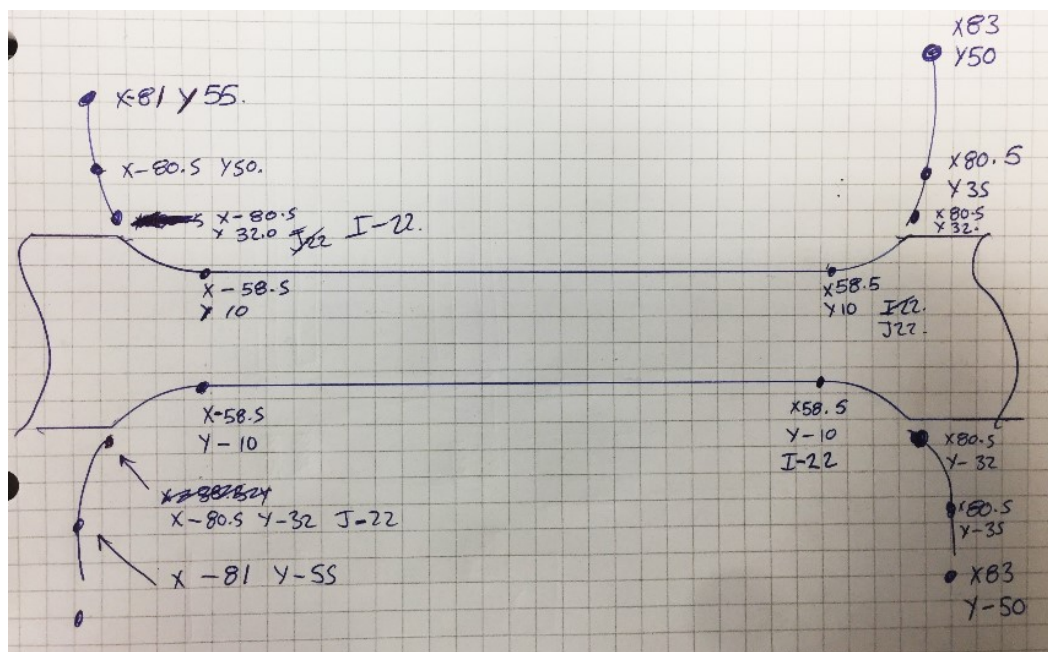


FIGURE 35 A DRAWING FOR THE PROGRAMMING OF THE TENSILE MILLING PROGRAM AT THE METALLURGICAL LABORATORY, DRAWN BY BROTHER ENGINEERING (BROTHER ENGINEERING LTD, 2017)

There are three trials that will be performed;

1. Tool wear is the primary variable to be investigated, with a view to determine the optimum time to replace a tool based on wear. Advice from tool manufacturers indicates that excessive tool wear is typically considered as 0.3mm of wear and above. By inspecting used tools at the laboratory, tool wear varies from 0.1 - 0.5mm. A trial testing at tool wear increments of 0.15mm would be appropriate.
2. Packing is the second variable that this project will explore. Packing material is always used at the laboratory, although the thickness of packing material does vary considerably. Two packing gauges will be compared – 2mm and 5mm (figure 36 shows examples of these).
3. Waterjet cutting of tensile test specimens will also be compared to the current method of milling.



FIGURE 36 EXAMPLE OF THICK PACKING OF 5MM GAUGE AND THIN PACKING OF 2MM GAUGE.

The surface finish will be assessed at each interval samples are taken against each variable, and corresponding tensile tests performed to evaluate the effect, if any, on mechanical properties.

Two types of material will be included in the testing of this trial – DP800 and DX57.

Five samples will be produced for testing of each parameter, and spare samples are available if necessary. No more than five samples are to be used to test each parameter, so that the minimum number of full width sheets of material were used to obtain the total number of samples required for the trials, ensuring the material remains comparable.

A more extensive range of increments will be explored for tool wear, being the primary focus for investigation, whereas secondary trials for waterjet cutting and packing will be of a simplified design comprising of a comparison of two opposing variables. The results of these additional trials will determine if further research worthwhile at a later date.

The schedules of testing are shown in tables 9,10 and 11.

Deteriorating Tool Wear

TABLE 9 SCHEDULE OF TESTING FOR SAMPLES PREPARED WITH VARYING LEVELS OF TOOL WEAR

<i>Material</i>	<i>Tool Wear 0</i>	<i>Tool Wear 1</i>	<i>Tool Wear 2</i>	<i>Tool Wear 3</i>
<i>DX57 ID</i>	DX01	DX06	DX11	DX16
	DX02	DX07	DX12	DX17
	DX03	DX08	DX13	DX18
	DX04	DX09	DX14	DX19
	DX05	DX10	DX15	DX20
<i>DP800 ID</i>	DP01	DP06	DP11	DP16
	DP02	DP07	DP12	DP17
	DP03	DP08	DP13	DP18
	DP04	DP09	DP14	DP19
	DP05	DP10	DP15	DP20

- All milling parameters will remain constant bar tool wear;
 - 5mm gauge packing.
 - prepared by the same operator.

Thick Packing Vs Thin Packing

TABLE 10 SCHEDULE OF TESTING FOR SAMPLES PREPARED BY USING 5MM OR 2MM PACKING MATERIAL

<i>Material</i>	<i>Thick Packing</i>	<i>Thin Packing</i>
<i>DX57 ID</i>	DX01	DX21
	DX02	DX22
	DX03	DX23
	DX04	DX24
	DX05	DX25
<i>DP800 ID</i>	DP01	DP21
	DP02	DP22
	DP03	DP23
	DP04	DP24
	DP05	DP25

- All milling parameters will remain constant bar packing material gauge;
 - new tool of 0mm wear.
 - prepared by the same operator.

CNC Milled Vs Water Jet Cut

TABLE 11 SCHEDULE OF TESTING FOR SAMPLES PREPARED BY MILLING OR WATER JET CUTTING

<i>Material</i>	<i>CNC Milled</i>	<i>Water Jet Cut</i>
<i>DX57 ID</i>	DX01	WJ01
	DX02	WJ02
	DX03	WJ03
	DX04	WJ04
	DX05	WJ05
<i>DP800 ID</i>	DP01	WJ11
	DP02	WJ12
	DP03	WJ13
	DP04	WJ14
	DP05	WJ15

- CNC Milled specimens will be prepared under optimum milling conditions;
 - 5mm gauge packing.
 - new tool with 0mm wear.
 - prepared by the same operator.
- Waterjet cut samples will be prepared under optimum conditions, which will be determined on the day of cutting by the waterjet representative and will be consistently prepared by one person.

Some of the specimen numbers are duplicated in the trial design. This can occur as the preparation conditions are identical for some sections of each of the three trials. For example, the milled samples required in the waterjet comparison trial require the same preparation conditions as the samples required in the tool wear trial at 0mm wear, and so forth.

Tool wear will be measured using an eye glass with a rule set at 0.1mm increments. The limitations are acknowledged for this method of measurement, being subjective, but alternative methods of tool wear measurement require an investment, which at this point is unsubstantiated. Although a subjective method of measurement, all measurements will be taken by one operator to remove any variability caused by differing interpretation.

The packing gauges will be measured using a standard calibrated micrometer. The same micrometer of identification TH001 will be used to obtain all measurements.

For surface roughness measurement, the closest facility with WLI equipment is Swansea University, which can only be accessed by staff and students of the university. A quotation of £1,200 was obtained for the testing of fifty samples to support this project. Authorisation to proceed was not granted due to insufficient evidence of tangible benefits or payback period at this stage of the project, and could therefore not be justified. A contingency plan was developed in the event that WLI testing would not be available, also methods in the contingency may not have given the same levels of scientific or quantitative analysis. A form of microscopy in which samples are magnified and photographs of the surfaces assessed appeared to be an alternative possible method available, although not ideal due to its subjective nature.

However, a Tata Steel representative expressed an interest in the project and was able to provide support for WLI testing at Swansea university, through an Engineering Doctorate student, on the terms that any findings were shared. The student was able to schedule testing for thirty-eight samples, although testing would be limited to this number. Due to this limited availability, only a portion of the total trial specimens can be examined. However, this is sufficient, as all of the samples will be tensile tested which is the true measurement of performance. The aim of the project is to determine whether increasing tool wear (and other variables) affect tensile test results, therefore an appropriate measure of performance is to relate a scale of tool wear increments to mechanical property. Surface evaluation will help to understand the surface finish to make a link between the parameter (tool wear etc.) and mechanical property results.

Although surface roughness is reduced and is recognised as a potential issue due to missing information, 60% of tests would have WLI testing performed, providing a representative

evaluation. The limited availability of surface roughness also had an influence in the design of the schedule of testing, for a smaller sample size selection of the trials.

Table 12 shows the schedule of testing for WLI.

TABLE 12 SCHEDULE OF TESTING IDENTIFYING SAMPLES TO BE TESTED FOR ROUGHNESS AVERAGE

<i>Parameter</i>	<i>DP800</i>	<i>DX57</i>
<i>Water jet cut</i>	WJ01, WJ02, WJ03	WJ11, WJ12, WJ13
<i>Tool Wear 0*</i>	DP01, DP02, DP03	DX01, DX02, DX03
<i>Tool Wear 1</i>	DP06, DP07, DP08	DX06, DX07, DX08
<i>Tool Wear 2</i>	DP11, DP12, DP13	DX11, DX12, DX13
<i>Tool Wear 3</i>	DP16, DP17, DP18	DX16, DX17, DX18
<i>Thin Packing</i>	DP21, DP22, DP23	DX21, DX22, DX23

*Tool Wear 0 also “Thick Packing” and “CNC milled” (for comparison with waterjet cut)

All tensile tests will be performed on one tensile testing machine only “Instron 1” to ensure consistency. This is an automated tensile testing system (shown in figures 37 and 38) that integrates a horizontal measurement specimen device (HSMD) for taking gauge and width readings (an average of 3 readings), and an ABB robot which handles and transfers specimens through the system.

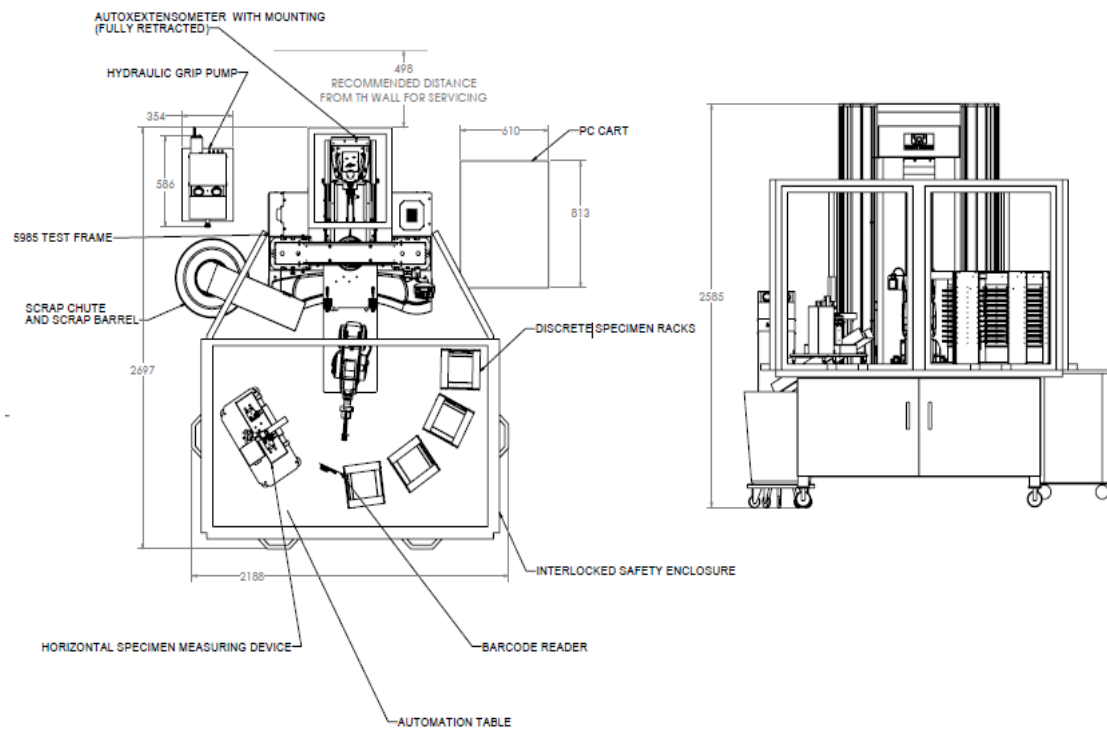


FIGURE 37 SCHEMATIC REPRESENTATION OF AUTOMATIC TENSILE TESTING FRAME AND SYSTEM "INSTRON 1".

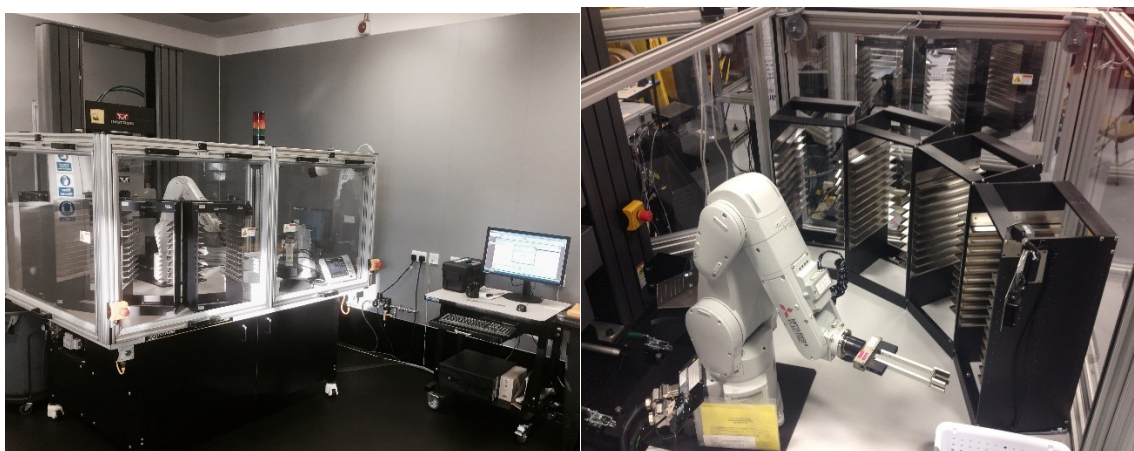


FIGURE 38 IMAGES OF THE AUTOMATED TENSILE TESTING SYSTEM "INSTRON 1".

This machine is verified daily using a standard check tensile and results analysed via statistical process control (SPC). The HSMD is subject to automatic verification checks at intervals of ten tests using a standard calibrated gauge bar. It can be confirmed that during this trial no verification checks failed, verifying the integrity of the machine during this project. The verification checks are electronically logged for the tensile test machine and are date stamped.

A MSA study has been performed for each of the mechanical properties measured by Instron 1 ensuring consistent capability. The MSA study for the measurement of elongation is shown in figure 39. MSA studies for other mechanical properties are documented in the appendices (appendix 3, 4 and 5).

SP-UK	Measurement Capability Procedure 3 (Gauge R&R) No Operator Influence			
Measuring Equipment:		Characteristic:		
Gauge Location:	Test House	Measured Part:		
Gauge Description:	Tensile Test Machine	Drawing No.:		
Gauge Number:		Characteristic:		
Gauge Resolution:	0.01	Nominal value:		
		Total Tolerance:		
		%		
		Unit		
%GRR RESULT IN BLUE IS ONLY CONSIDERED.				
Measurement Procedure				
Result of Procedure 1:				
Record No.:	Sheet:	Date:		
		Cg =		
		Cgk =		
Table values in: % Deviation from: N/A				
Obj. No.	Series 1	Series 2	Mean Xi bar	Range Ri
1	26.430	27.550	26.990	1.120
2	27.670	26.910	27.290	0.760
3	22.800	22.080	22.440	0.720
4	24.600	24.390	24.495	0.210
5	27.430	27.470	27.450	0.040
6	35.110	35.480	35.295	0.370
7	37.830	37.430	37.630	0.400
8	44.310	43.860	44.085	0.450
9	43.980	43.900	43.940	0.080
10	19.830	20.640	20.235	0.810
11	10.030	10.110	10.070	0.080
12	29.030	28.400	28.715	0.630
13	27.870	29.180	28.525	1.310
14	28.760	29.290	29.025	0.530
15	19.460	20.380	19.920	0.920
16	27.270	25.700	26.485	1.570
17	27.280	28.860	28.070	1.580
18	21.880	23.110	22.495	1.230
19	31.390	31.960	31.675	0.570
20	29.470	29.960	29.715	0.490
21	21.280	19.940	20.610	1.340
22	35.900	34.020	34.960	1.880
23	17.540	18.730	18.135	1.190
24	18.860	16.950	17.905	1.910
25	23.257	23.860	23.559	0.603
R _p		34.015		

Plot of the Ranges

The plot shows the range (Ri) for each of the 25 objects. The y-axis ranges from 0.000 to 2.500. The data points are connected by a line, showing fluctuations between approximately 0.04 and 1.91.

Evaluation:

Mean Range R bar = 0.7948 %

Equipment Variation (EV) K₁ = 0.886
EV = R bar * K₁ = 0.7043 %

Part Variation (PV) K₃ = 0.250
PV = R_p * K₃ = 8.5038 %

Repeatability and Reproducibility (GRR)
 $GRR = \sqrt{EV^2}$ = 0.7043

Total Variation (TV)
 $TV = \sqrt{GRR^2 + PV^2}$ = 8.5329

%GRR = 100[GRR/TV] = 8.25 %

%GRR = (EV / TOL) 100 = #VALUE! %

ndc (number of distinct categories) = 17

%GRR ≤ 10 % X

Acceptable

10% < %GRR ≤ 30 %

May be Acceptable

%GRR > 30 %

Measurement System needs Improvement

Remarks:

FIGURE 39 MSA STUDY FOR ELONGATION FOR AUTOMATIC TENSILE TESTING SYSTEM (TATA STEEL PORT TALBOT, 2016)

During the trial samples are to be segregated using standard specimen tape and clearly labelled to ensure samples do not become mixed.

Tool wear will be monitored for the time it takes the tool to wear to a maximum 0.45mm. The batches of stacked samples (boxes) milled will be counted and recorded manually on a log sheet at the set increments of 1.5mm wear. There are limitations in measuring tool wear against number of samples;

- varying gauges and hardness of samples make it difficult to attribute equal tool wear to one sample. However, over a twelve hour period, the flow of testing remains consistent with ranges of material equally mixed throughout the day.
- The number of samples varies per box. The box height allowance is approximately 30mm. This could therefore be filled with either 30 samples of 1mm gauge or 3 samples of 10mm, for example. Due to this the most appropriate method of recording the quantity of material milled against tool wear will be per box milled and not per sample.

Boxes are filled to capacity for each cycle during normal operating times. If insufficient samples are available to mill a full box, they are retained until more samples are ready. The boxes (shown in figure 40) will be filled to capacity for the trial.

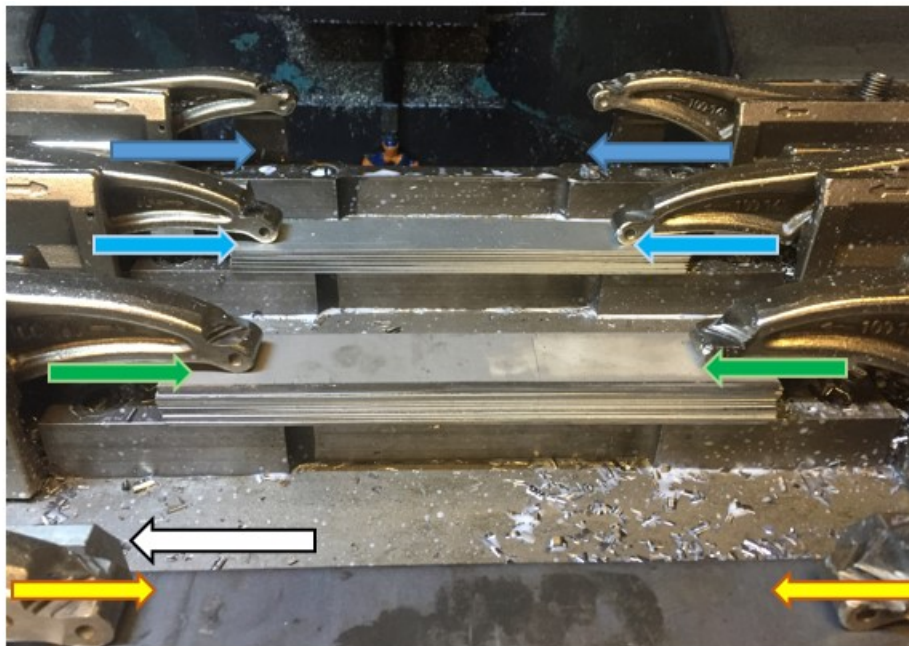


FIGURE 40 THE FOUR MILLING MACHINE VICES IDENTIFIED WITH COLOURS. A BACKSTOP IS HIGHLIGHTED BY WHITE

Each vice has a backstop to which the samples must be flush. The backstop also has an inward lip indicating the maximum number of samples that can be held. The maximum thickness of the stack is determined by the useful length of tool flutes. The protruding lip makes it difficult to overfill a box.

Based on this practice it is possible to record the number of full boxes that wears the tool to 0.15mm, 0.3mm and 0.45mm. It is expected that the number of boxes milled between each tool wear increment will be roughly equal.

Access to the waterjet cutter based at UWTSD was allowed for preparation of material. Daniel Butler, waterjet technician at this facility, would set up and perform the cuts on supplied material accordingly. This waterjet cutter operates using a 120 mesh abrasive, a finer grit than the 80 mesh that is used commercially. Butler commented that the grit, nozzle diameter, jet pressure and other parameters designed to achieve a superior surface finish (Butler, 2017). A drawing of the shape required including dimensions was supplied to Butler (figure 41) which would be replicated in the IGEMS software and the image uploaded to the waterjet cutter Fanuc operating system.

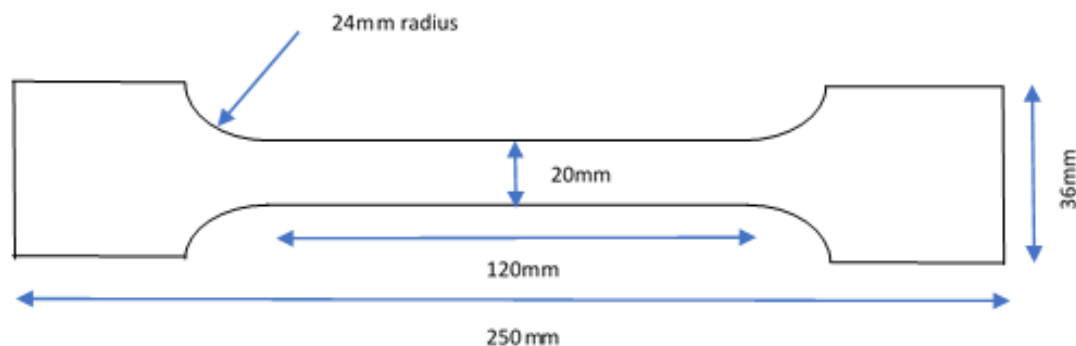


FIGURE 41 DESIGN TEMPLATE SHOWING DIMENSIONS OF SHAPE REQUIRED, SUPPLIED TO THE WATERJET CUTTING FACILITY.

Data Collection Methods

Methods of data collection are summarised in table 13.

TABLE 13 TABLE SUMMARISING DATA COLLECTION METHODS AND MEASUREMENT EQUIPMENT

<i>Data Collection Task</i>	<i>Equipment for Measurement</i>	<i>Method of Data Capture</i>
<i>Measure gauge of packing</i>	Calibrated Standard Micrometer (ID TH001)	Check sheet
<i>Measure tool wear</i>	Eye Glass	Log sheet
<i>Surface finish</i>	White Light Interferometry	Excel file
<i>Mechanical property results</i>	Instron 1 automatic tensile testing system	'Aurora' database
<i>Number of boxes milled for tool wear increments</i>	Manual count	Log sheet
<i>Timing of waterjet cycles</i>	Stopwatch	Written table

10. Analyse

This section will include;

- Analysis
- Conclusion
- Final Time Line

Analysis

Analysis will be divided into three sections of assessment;

- Deteriorating tool wear.
- Thick packing vs thin packing.
- Milling vs waterjet cutting.

The raw data used for analysis can be found in the appendices (appendix 1 and 2).

The three trials will be evaluated by graphically assessing trends in tested mechanical properties. Several mechanical properties will be assessed for any significant effect;

- Ultimate tensile strength (UTS).
- Yield strength (or Proof Stress).
- Elongation (A%).
- R-value.

All processes have a certain amount of variation which frequently occurs during the normal execution of this process. These acceptable levels of variation will be assessed by recording the percentage increase or decrease of the mean result set, where values above 5% will be considered as significant change. This method is adopted by (Krahmer, et al., 2016) and (Instron, 2016).

A “t-test” will be applied where appropriate to statistically prove any significant changes. The t-test is designed to analyse small sample sizes of less than 30. A level of 95% confidence will be applied to these calculations which is widely accepted for the purposes of demonstrating trends.

The surface quality will be assessed by roughness average results and surface images produced by WLI testing. Roughness average results will be subject to a t-test.

Deteriorating Tool Wear

For this trial there were twenty samples each for DP800 and DX57 materials.

Each batch of twenty samples prepared for this trial are allocated proportionally as set out in the schedule of testing.

The amount of samples that required milling to wear the tool down by each 0.15mm was measured by counting the number of boxes. Scrap material was used to wear the tool replicating normal production material, and the test samples required for this trial milled at the set tool wear intervals. As expected, the number of boxes milled remained roughly equal (as shown in table 14), indicating even wear as tool wear progresses.

TABLE 14 TABLE OF TOOL WEAR AND NUMBER OF BOXES OF SAMPLES MILLED AT EACH INTERVAL

Tool Wear (mm)	Boxes Milled
0	11
0.15	21
0.3	33
0.45	44

When viewing the mechanical properties graphs, it is important to note that the results do not represent decreasing tool wear on a sample by sample basis, but should be considered five-sample segments at a time to represent each tool wear category.

DP800 Results

Surface Quality Results

TABLE 15 TABLE SHOWING MEAN ROUGHNESS AVERAGE READINGS FOR DP800 SAMPLES MILLED AT VARYING LEVELS OF TOOL WEAR

Tool Wear (mm)	Average Roughness Ra (μm)
0	1.46
0.15	1.47
0.3	1.59
0.45	3.32

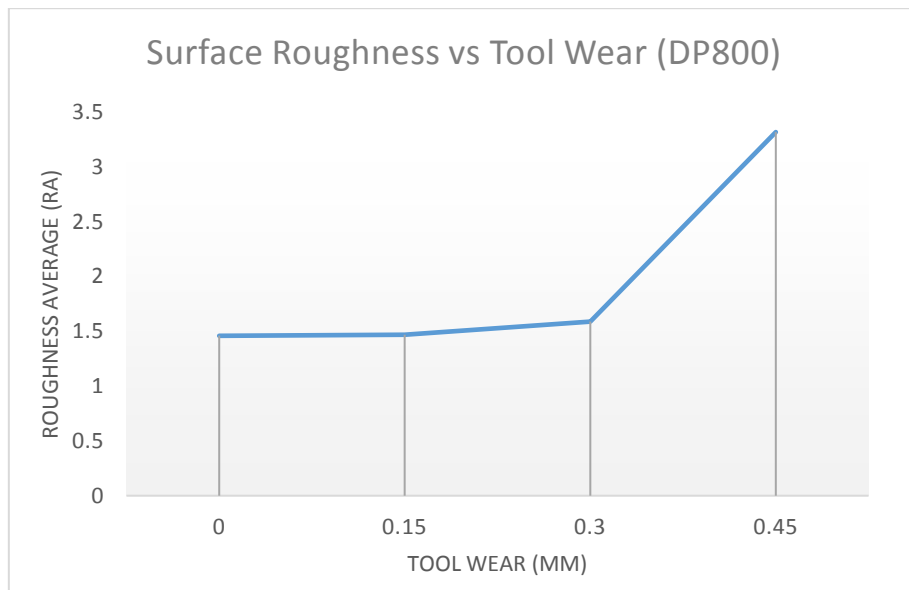


FIGURE 42 GRAPH PLOTTING ROUGHNESS AVERAGE AGAINST INCREASING TOOL WEAR FOR DP800 MATERIAL.

TABLE 16 T-TEST RESULTS DEMONSTRATING THE OCCURRENCE OF ANY SIGNIFICANT CHANGES IN DATA FOR ROUGHNESS DURING THE TOOL WEAR TRIAL FOR DP800 MATERIAL.

Roughness Average Data Set 1	Roughness Average Data Set 2	Trials	Confidence Level	P Value	Statistically Significant Difference?
0mm tool wear	0.15mm tool wear	2	95%	0.989	No
0mm tool wear	0.3mm tool wear	2	95%	0.647	No
0mm tool wear	0.45mm tool wear	2	95%	0.002	Yes

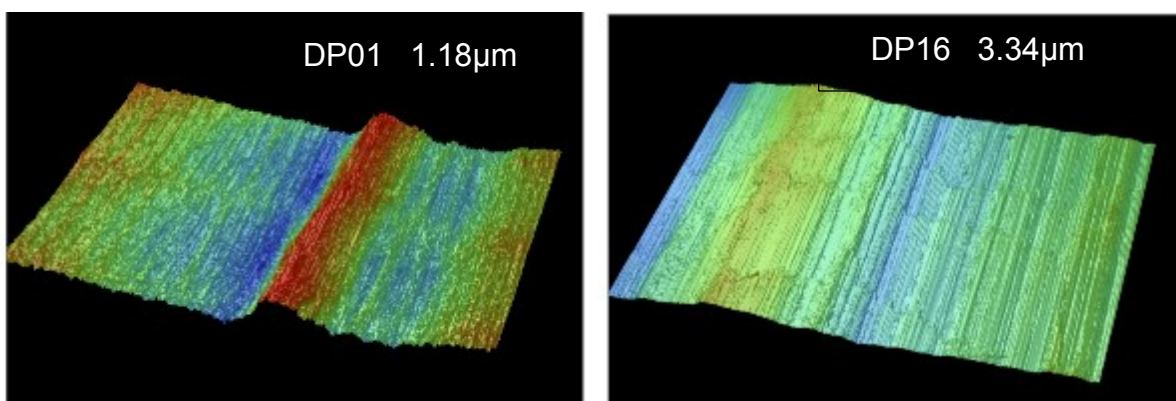


FIGURE 43 SURFACE TOPOGRAPHY IMAGES AND ROUGHNESS AVERAGE RESULT FOR THE EXTREMES OF TOOL WEAR ASSESSED FOR DP800; DP01 0MM WEAR AND DP16 0.45MM WEAR.

Mechanical Properties Results

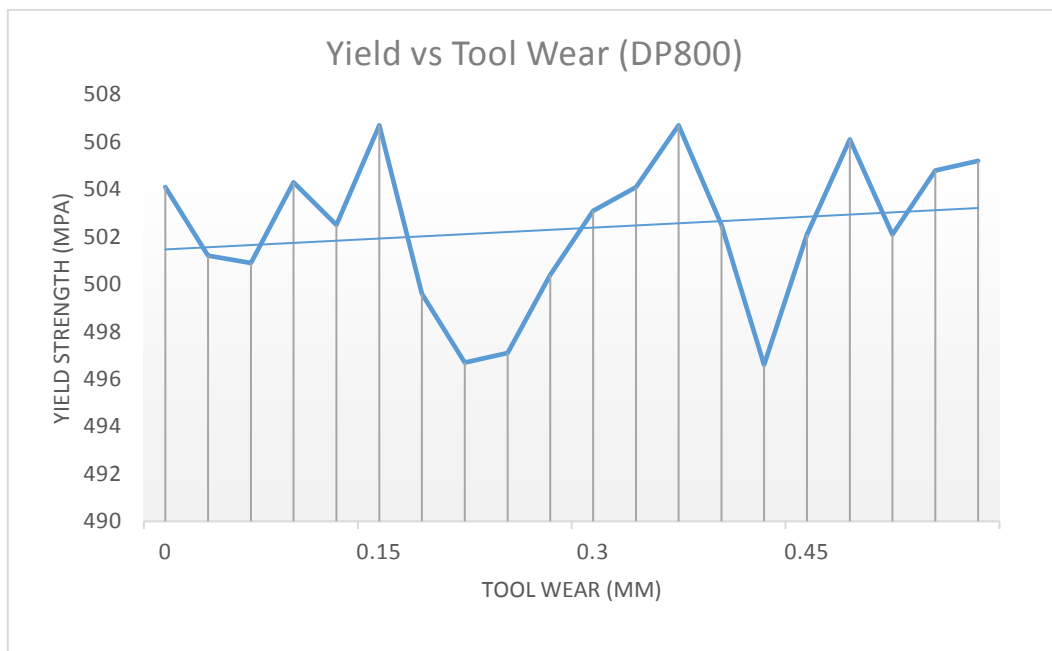


FIGURE 44 GRAPH PLOTTING YIELD AGAINST INCREASING TOOL WEAR FOR DP800 MATERIAL.

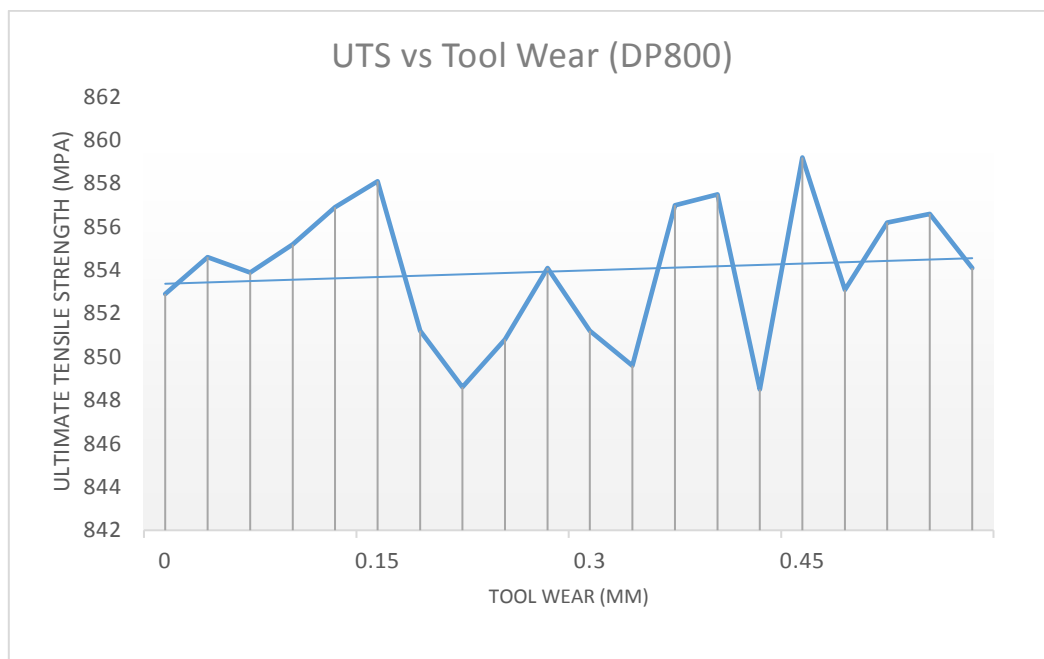


FIGURE 45 GRAPH PLOTTING UTS AGAINST INCREASING TOOL WEAR FOR DP800 MATERIAL.

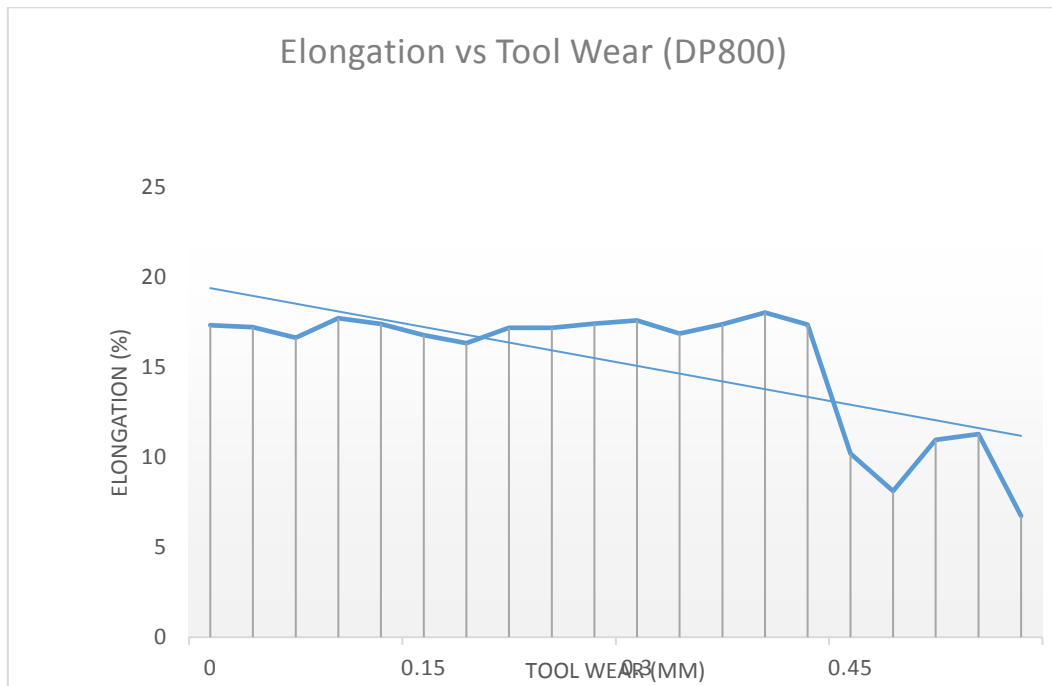


FIGURE 46 GRAPH PLOTTING ELONGATION AGAINST INCREASING TOOL WEAR FOR DP800 MATERIAL

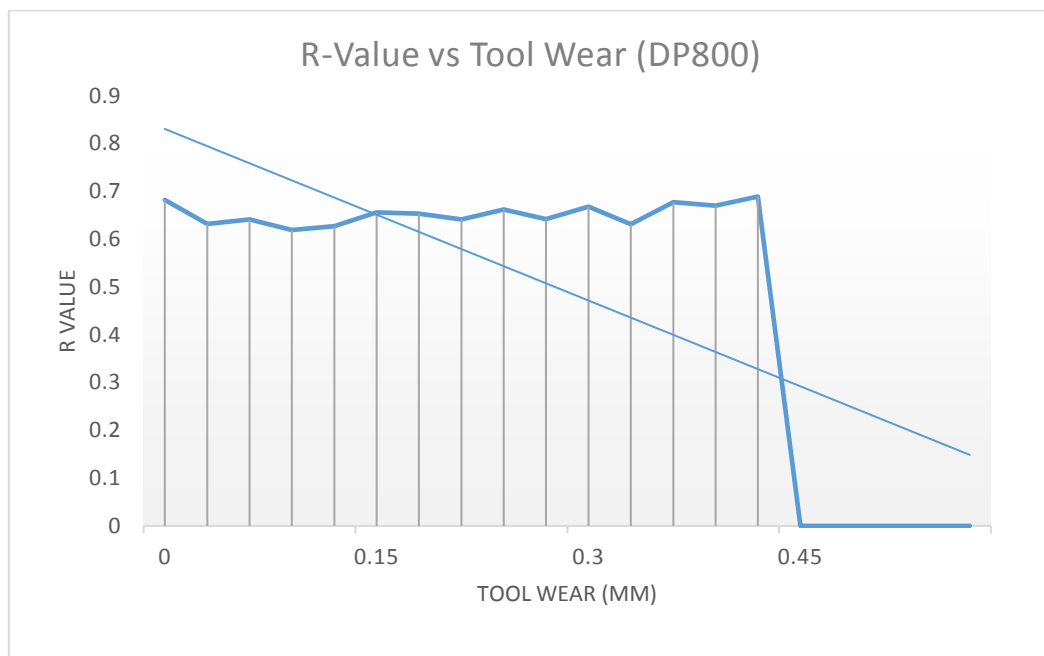


FIGURE 47 GRAPH PLOTTING R-VALUE AGAINST INCREASING TOOL WEAR FOR DP800 MATERIAL.

Variation Results

TABLE 17 TABLE SHOWING PERCENTAGE VARIATION FOR MECHANICAL PROPERTIES FOR DP800, FOR INCREASING LEVELS OF TOOL WEAR WHEN COMPARED TO 0MM TOOL WEAR, BASED ON MEAN RESULTS, RED INDICATING A DECREASE, GREEN INDICATING AN INCREASE

Tool Wear (mm)	+/- Yield	+/- UTS	+/- A	+/- R-value
Tool Wear 0.15mm	0.5%	0.25%	1.6%	0.66%
Tool Wear 0.3mm	0%	0.23%	1.01%	4.18%
Tool Wear 0.45mm	0.29%	0.13%	45.2%	100%

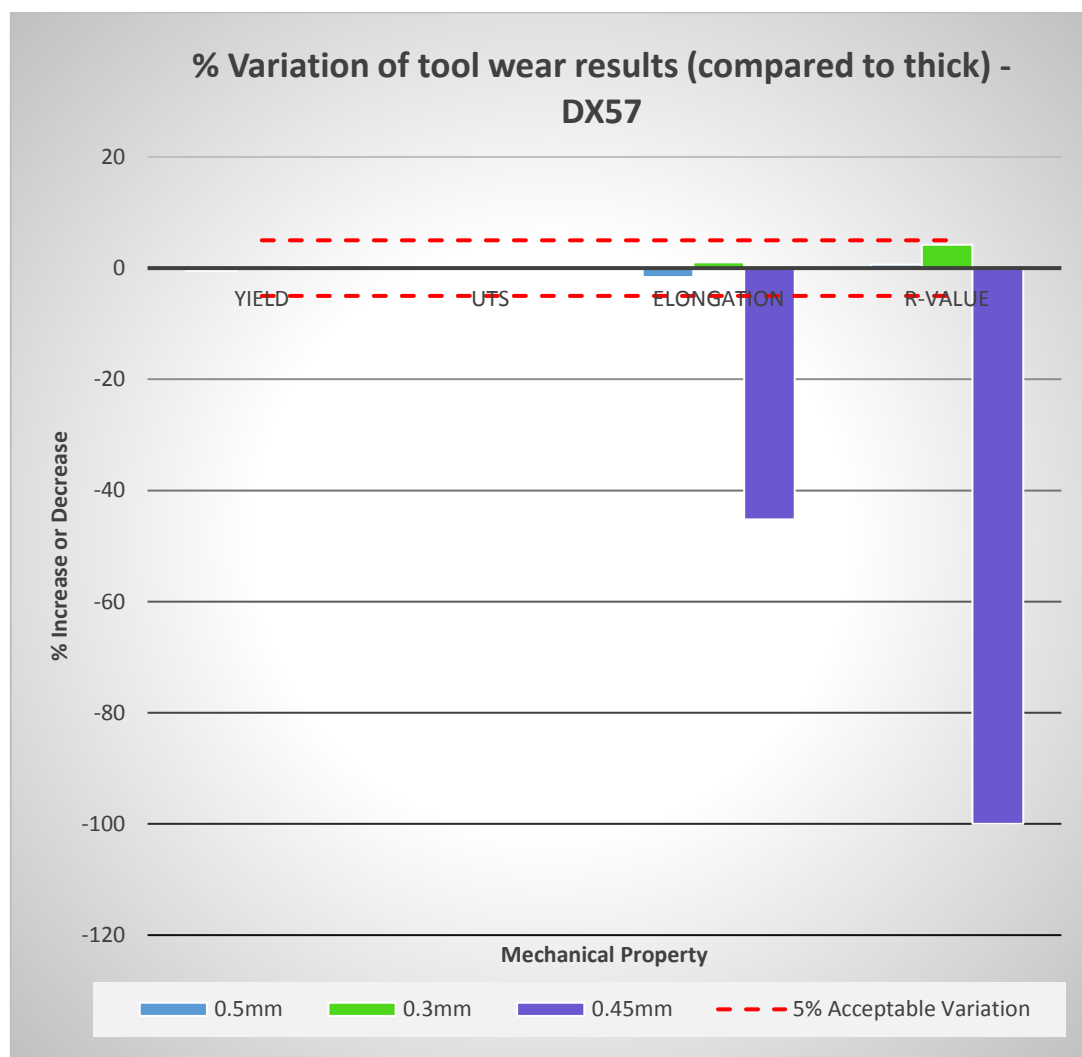


FIGURE 48 HISTOGRAM SHOWING VARIATION OF MECHANICAL PROPERTIES OF DP800 SAMPLES PREPARED WITH INCREASING TOOL WEAR, COMPARED TO A NEW TOOL, INDICATING THE ACCEPTABLE LEVEL OF VARIATION OF 5%.

T-Test Results

The variation results show that a t-test is appropriate for elongation and R-value.

TABLE 18 T-TEST RESULTS DEMONSTRATING ANY STATISTICALLY SIGNIFICANT CHANGES IN DATA FOR ELONGATION DURING THE TOOL WEAR TRIAL FOR DP800 MATERIAL

Elongation Data Set 1	Elongation Data Set 2	Trials	Confidence Level	P Value	Statistically Significant Difference?
0mm tool wear	0.15mm tool wear	2	95%	0.315	No
0mm tool wear	0.3mm tool wear	2	95%	0.487	No
0mm tool wear	0.45mm tool wear	2	95%	2.305×10^{-5}	Yes

TABLE 19 T-TEST RESULTS DEMONSTRATING ANY STATISTICALLY SIGNIFICANT CHANGES IN DATA FOR R-VALUE DURING THE TOOL WEAR TRIAL FOR DP800 MATERIAL

R-value Data Set 1	R-value Data Set 2	Trials	Confidence Level	P Value	Statistically Significant Difference?
0mm tool wear	0.15mm tool wear	2	95%	0.394	No
0mm tool wear	0.3mm tool wear	2	95%	0.106	No
0mm tool wear	0.45mm tool wear	2	95%	8.7×10^{-12}	Yes

DX57 Results

Surface Quality Results

TABLE 20 TABLE SHOWING MEAN ROUGHNESS AVERAGE READINGS FOR DX57 SAMPLES MILLED AT VARYING LEVELS OF TOOL WEAR

Tool Wear (mm)	Average Roughness Ra (μm)
0	1.42
0.15	1.47
0.3	1.51
0.45	5.31

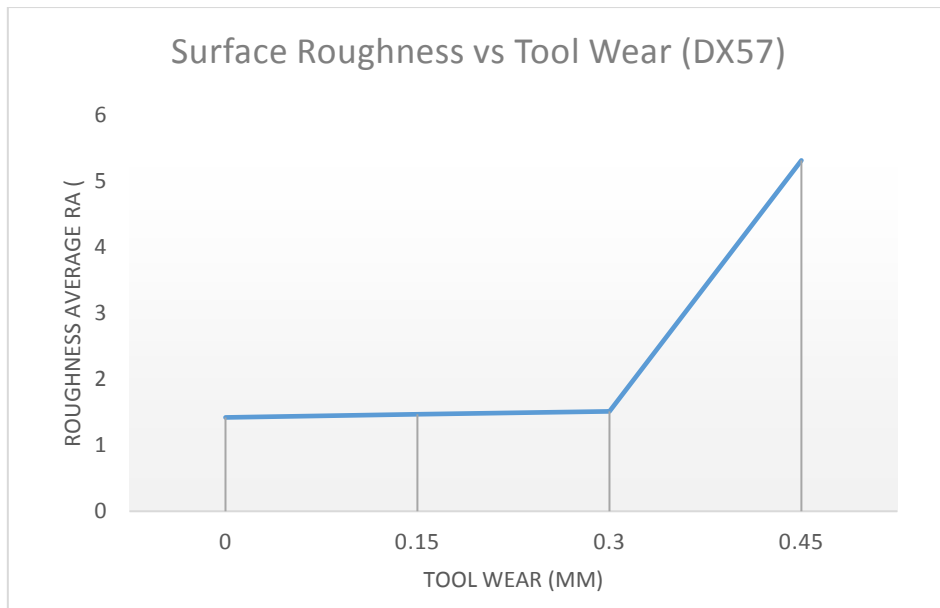


FIGURE 49 GRAPH PLOTTING ROUGHNESS AVERAGE AGAINST INCREASING TOOL WEAR FOR DX57 MATERIAL.

TABLE 21 T-TEST RESULTS DEMONSTRATING THE OCCURRENCE OF ANY SIGNIFICANT CHANGES IN DATA FOR ROUGHNESS AVERAGE DURING THE TOOL WEAR TRIAL FOR DX57 MATERIAL.

Roughness Average Data Set 1	Roughness Average Data Set 2	Trials	Confidence Level	P Value	Statistically Significant Difference?
0mm tool wear	0.15mm tool wear	2	95%	0.981	No
0mm tool wear	0.3mm tool wear	2	95%	0.862	No
0mm tool wear	0.45mm tool wear	2	95%	0.004	Yes

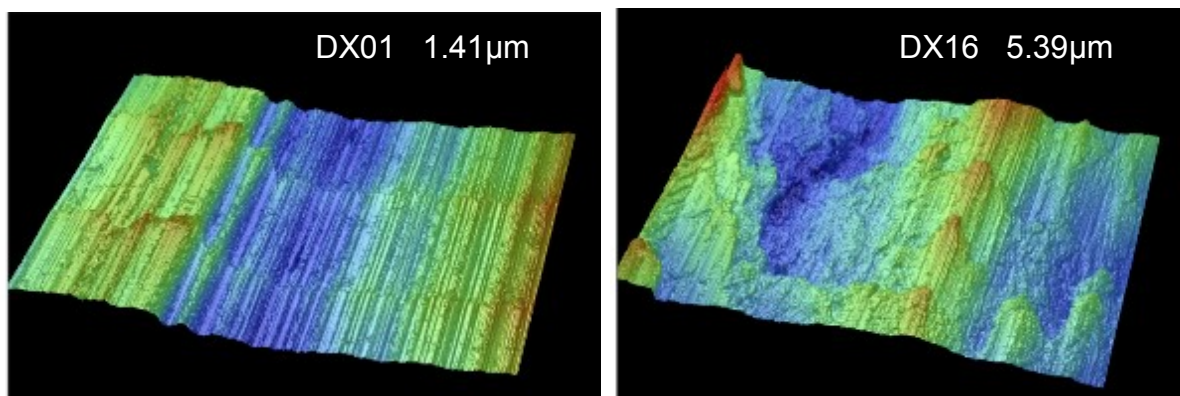


FIGURE 50 SURFACE TOPOGRAPHY IMAGES AND ROUGHNESS AVERAGE RESULT FOR THE EXTREMES OF TOOL WEAR ASSESSED FOR DX57; DX01 0MM WEAR AND DX16 0.45MM WEAR.

Mechanical Property Results

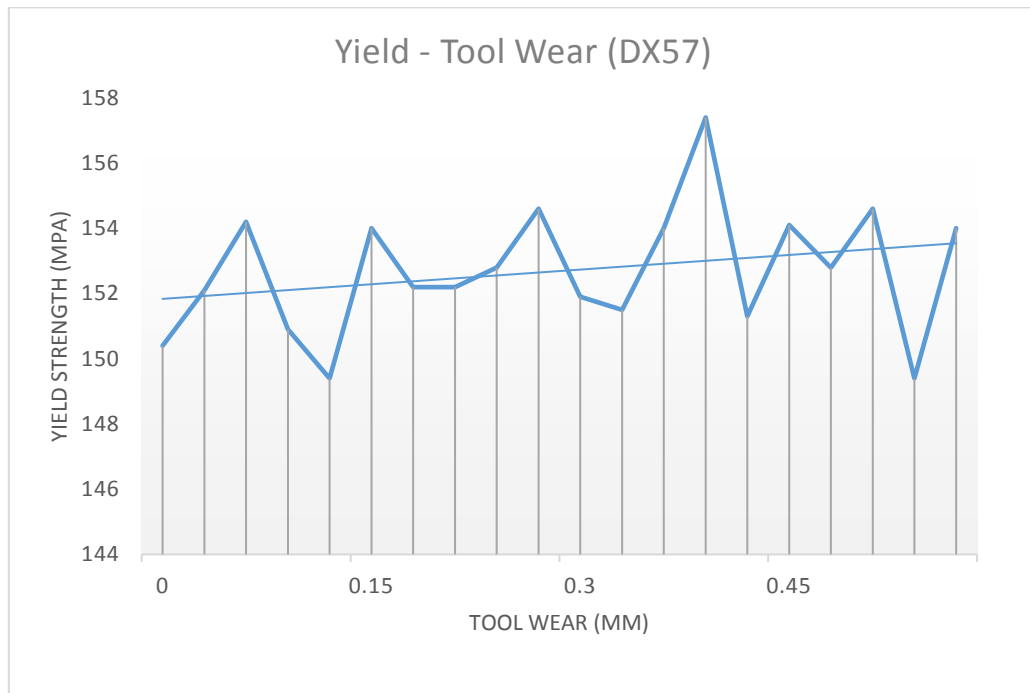


FIGURE 51 GRAPH PLOTTING YIELD AGAINST INCREASING TOOL WEAR FOR DX57 MATERIAL.

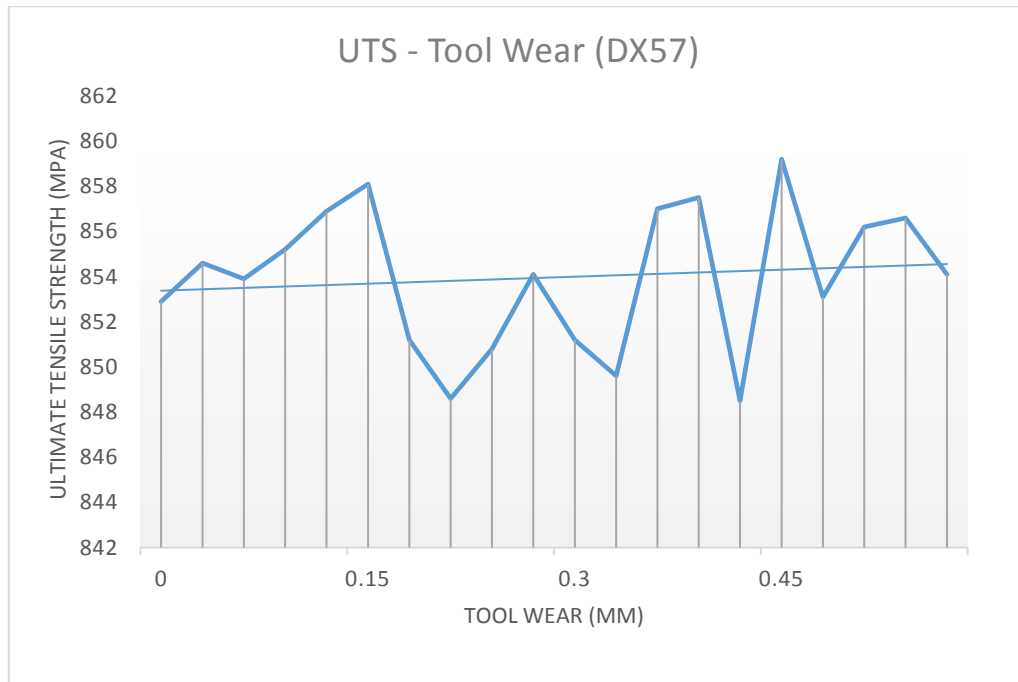


FIGURE 52 GRAPH PLOTTING UTS AGAINST INCREASING TOOL WEAR FOR DX57 MATERIAL.

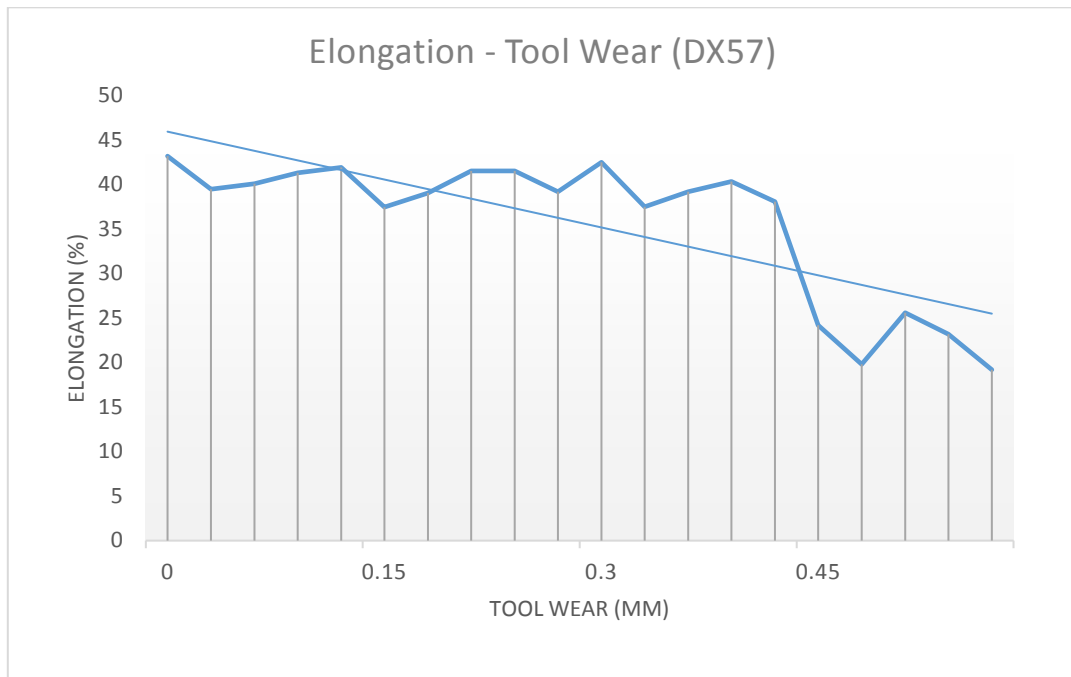


FIGURE 53 GRAPH PLOTTING ELONGATION AGAINST INCREASING TOOL WEAR FOR DX57 MATERIAL.

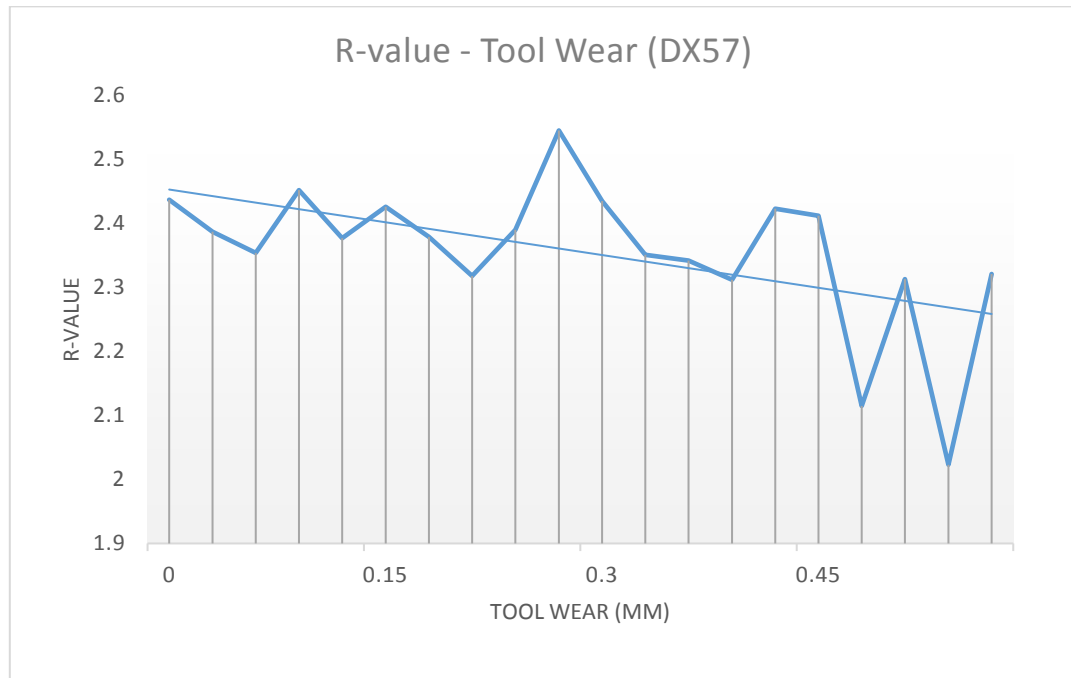


FIGURE 54 GRAPH PLOTTING R-VALUE AGAINST INCREASING TOOL WEAR FOR DX57 MATERIAL.

Variation Results

TABLE 22 TABLE SHOWING PERCENTAGE VARIATION FOR MECHANICAL PROPERTIES FOR DX57, FOR INCREASING LEVELS OF TOOL WEAR WHEN COMPARED TO 0MM TOOL WEAR, BASED ON MEAN RESULTS, RED INDICATING A DECREASE, GREEN INDICATING AN INCREASE

Tool Wear (mm)	+/- Yield	+/- UTS	+/- A	+/- R-value
Tool Wear 0.15mm	1.16%	0.33%	3.49%	0.42%
Tool Wear 0.3mm	1.2%	0.25%	4.09%	1.2%
Tool Wear 0.45mm	1.04%	0.6%	45.65%	6.85%

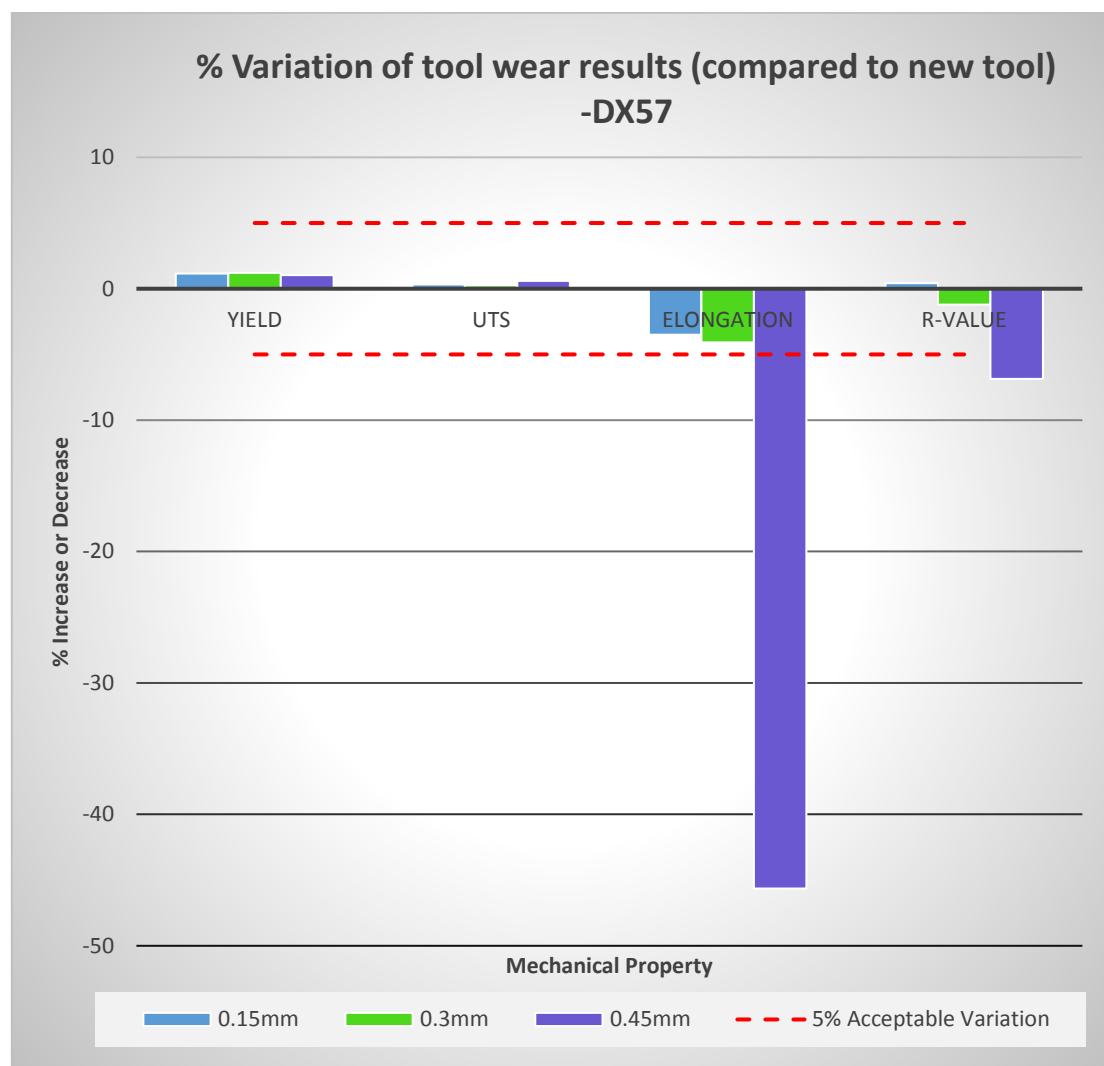


FIGURE 55 HISTOGRAM SHOWING VARIATION OF MECHANICAL PROPERTIES OF DX57 SAMPLES PREPARED WITH INCREASING TOOL WEAR, COMPARED TO A NEW TOOL, INDICATING THE ACCEPTABLE LEVEL OF VARIATION OF 5%.

T-Test Results

The variation results show that a t-test is appropriate for elongation and R-value.

TABLE 23 T-TEST RESULTS DEMONSTRATING ANY STATISTICALLY SIGNIFICANT CHANGES IN DATA FOR ELONGATION DURING THE TOOL WEAR TRIAL FOR DX57 MATERIAL

Elongation Data Set 1	Elongation Data Set 2	Trials	Confidence Level	P Value	Statistically Significant Difference?
0mm tool wear	0.15mm tool wear	2	95%	0.196	No
0mm tool wear	0.3mm tool wear	2	95%	0.166	No
0mm tool wear	0.45mm tool wear	2	95%	9.529×10^{-7}	Yes

TABLE 24 TABLE 25 T-TEST RESULTS DEMONSTRATING ANY STATISTICALLY SIGNIFICANT CHANGES IN DATA FOR R-VALUE DURING THE TOOL WEAR TRIAL FOR DX57 MATERIAL

R-value Data Set 1	R-value Data Set 2	Trials	Confidence Level	P Value	Statistically Significant Difference?
0mm tool wear	0.15mm tool wear	2	95%	0.814	No
0mm tool wear	0.3mm tool wear	2	95%	0.37	No
0mm tool wear	0.45mm tool wear	2	95%	0.043	Yes

Discussion and Further Work

Increasing tool wear did not significantly affect the surface quality until it had surpassed a of 0.3mm, where roughness average increased significantly. The mean roughness averages are shown in tables 15 and 20 for DP800 and DX57 respectively, with the t-tests (tables 16 and 21) demonstrating a significant change of surface quality at 0.45mm of tool wear. The surface of the DX57 materials surface quality was affected more than DP800.

Figures 43 and 50 shows a visible deterioration in surface profile in both materials in support of the roughness average increase, for samples taken at the extremes of 0mm and 0.45mm. The images are illustrative and represent only a section of the edge profile, and the roughness average result represents a bigger portion of the sample length and may feature peaks and troughs of higher magnitude than those displayed in the images. What is interesting is that for both the harder and softer material, the initial surface roughness produced on both samples with a new tool were very similar, producing mean results of 1.46 μ m for DP800 and 1.42 μ m for DX57.

As expected, elongation declines for both materials as the tool wears. However, a gradual and progressive decline had been expected where elongation and surface quality decreased in proportion to increasing tool wear, and the overall trend line does support this (figures 46 and 53). However, upon further assessment of these graphs, elongation is relatively consistent up to a tool wear of 0.3mm, which then significantly declines at 0.45mm. This suggests that tool wear does not have an effect until it reaches a specific level of wear. These results verify the original hypothesis that surface quality issues can prevent the material reaching its true elongation, by inducing premature fracture. This could be a function of an edge defect propagating into a crack, by introduction of a point of weakness.

The yield strength and UTS for both materials show no significant change in results with increasing tool wear, even beyond 0.3mm of wear where the surface quality had worsened considerably. When observing the development of a stress-strain curve, the yield and UTS stress are determined prior to the test piece breaking. Elongation figure is calculated when the test piece fractures. The yield and UTS figure may already be derived before any early fracture can have an effect, thus the strength of the material is not compromised by reduced surface quality at levels produced in this trial.

Similarly to elongation, the R-value for both materials are not significantly affected until 0.45mm of tool wear, while remaining consistent for the tool wear increments below this (tables 19, 24 and figures 48, 54). For DP800 no reading was recorded for R-value at 0.45mm of wear, and while DX57 did produce readings at this level of wear, they had decreased significantly. The graph (figure 54) could be interpreted as having a slight downward trend in

R-values from 0-3mm of tool wear, however the variation table and t-test (tables 22 and 24) determine that there is no significant change to be noted.

DX57 is a softer material which has R-value characteristics approximately four times that of DP800. The lower standard R-value readings of DP800 may account for the sharp decline to zero, whereas DX57 can still produce due a higher starting value.

Although the crack propagation trial had shown no effect on R-value, only one notch had been imposed into an edge that been milled under optimum conditions (new cutting tool and thick packing). Thus the surface along the whole parallel length would have been of good quality (alike the 0mm wear category of this trial). The R-value monitors would have assessed an edge that was, for the majority, of good quality. However, in the tool wear trial, the whole sample would have been affected by the increasingly worn tool, and the R-value probes would detect the reduced quality of surface. Theoretically, edge defects may affect the materials ability to resist thinning under tensile stresses, thus reducing R-values in this case. This may explain these reductions in R-values, although further investigations may be required to determine the cause.

The mechanical properties that were affected (elongation and R-value) correlate with the surface roughness results in trials for both materials, supporting the relationship between tool wear, surface finish and mechanical properties.

Although the method of using an eyeglass to measure tool wear had limitations, the validity of tool wear readings obtained are somewhat validated by the correlation between the increments of tool wear compared to the increments of boxes milled recorded in table 14. The number of samples milled for each 0.15mm of wear are relatively consistent, which would suggests a good interpretation of the eye glass readings.

This results of this trial do align with the tool manufacturers statement that a tool can be worn up to 0.3mm of wear before requiring replacement. The results show that the mechanical properties are affected at a point somewhere between 0.3mm of wear and 0.45mm of wear, therefore the tool loses performance at these wear levels. This cannot be pinpointed more accurately than this during this trial, due to the range of increments investigated of 0.15mm, but it is reasonable to conclude that it is recommended to replace a tool at 0.3mm of wear.

Metallography analysis was performed on the DX57 and DP800 material to investigate the cause of early fracture.

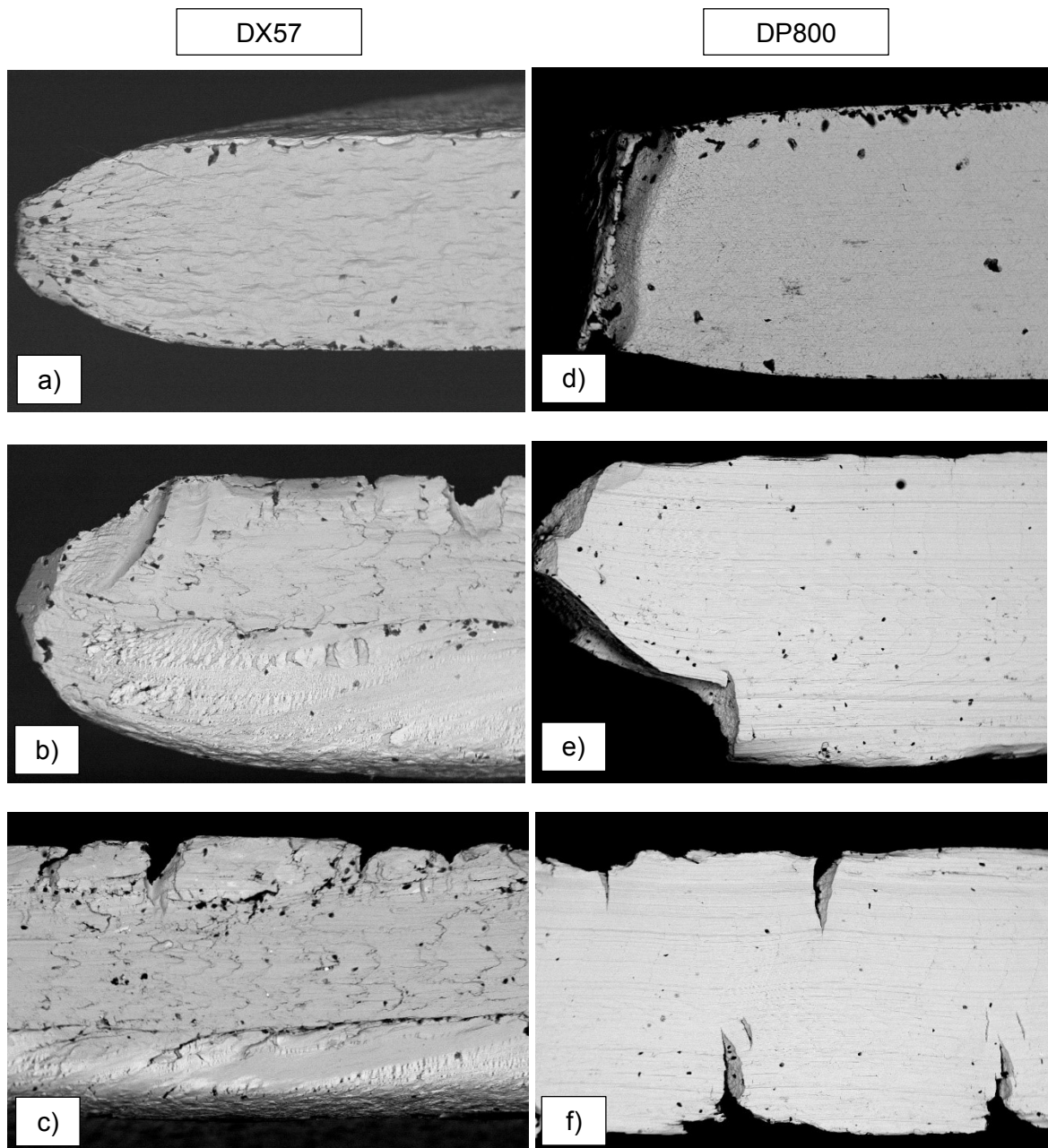


FIGURE 56 METALLOGRAPHY IMAGES FOR A) DX57 PREPARED WITH NEW TOOL B) DX57 MILLED WITH 0.45MM WORN TOOL LOW AT FRACTURE C) DX57 MILLED WITH 0.45MM WORN TOOL AWAY FROM FRACTURE D) DP800 PREPARED WITH NEW TOOL E) DP800 MILLED WITH A 0.45MM WORN TOOL AT FRACTURE F) DP800 MILLED WITH 0.45MM WORN TOOL AWAY FROM FRACTURE.

In both materials the fracture appears to differ in shape at 0.45mm of tool wear. The DP800 sample (figure 56, e) shows a particularly noticeable change in the way the test piece has fractured, with a sharp jagged edge. This appears to have cracked apart rather than torn in a way that might be expected for a ductile material during a tensile test, and appears to have begun from one of the cracks that indent from the bottom surface. Figure 56, c) and f) shows images for both materials along the surface away from fracture, which exhibit numerous edge

cracks, that would introduce weakness to the surface. It is likely that fracture has occurred from the presence of a crack that has propagated from an edge defect. With this additional metallography evidence, it is reasonable to conclude that edge defects that have introduced by milling with a worn tool cause a decline in elongation performance.

When inspecting the tools it is clear that the geometry becomes altered with wear.

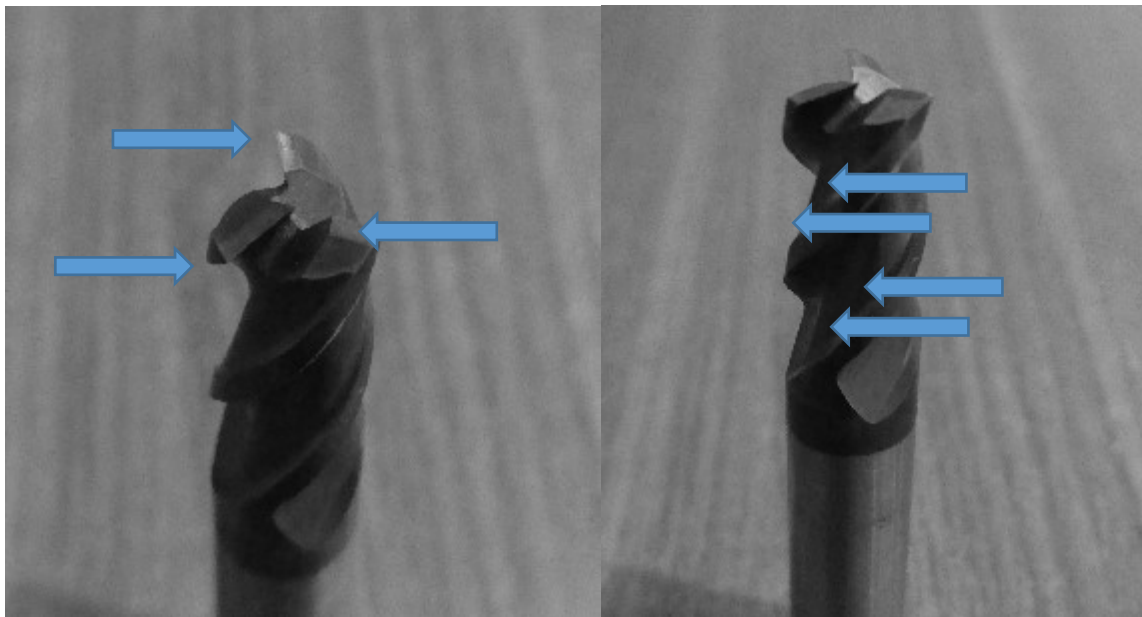


FIGURE 57 IMAGES OF NEW CUTTING TOOL HIGHLIGHTING CUTTING EDGES, CONTINUING DOWN THE FLUTES

As the tool wears the cutting edges of the tool become worn or blunt, indicated by the appearance of the pointed edges flattening off. The drawing in figure 58 illustrates this.

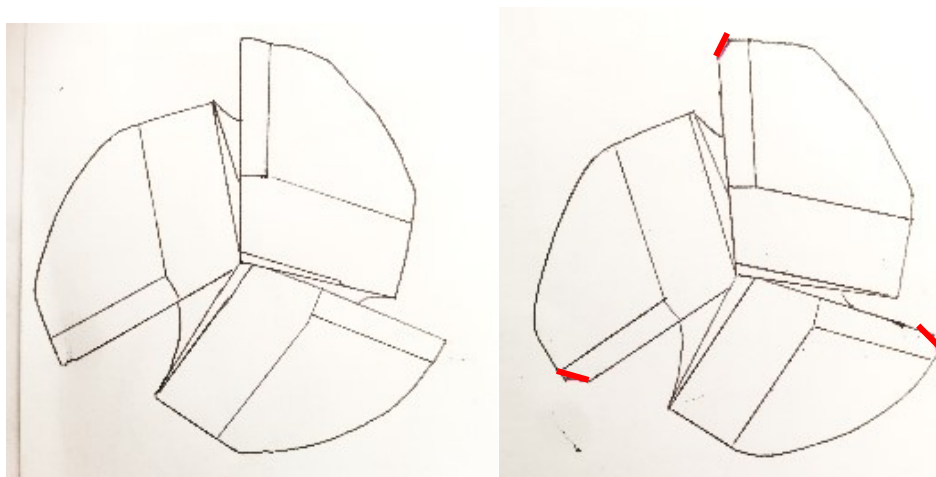


FIGURE 58 ILLUSTRATION OF CUTTING TOOL AS VIEWED FROM ABOVE, (A) HIGHLIGHTING THE SHARP CUTTING EDGES OF THE THREE FLUTES, (B) HIGHLIGHTED THE SHAPE OF THE WORN CUTTING EDGES

The wear continues along the cutting surfaces around the periphery of the tool. As the geometry of the tool declines, it would become more difficult to achieve a good surface finish due to the bluntness of the tool flank.

It is possible that the performance of the tool has worsened after the coating has been removed through significant wear, exposing the tool substrate. The tool manufacturer states that the 2.5µm coating provides a heat and wear barrier, but the carbide substrate can perform acceptably well up to 0.3mm of wear after the coating is removed before resulting in reduced cutting performance.

It is likely to be a combination of loss of coating and some loss of dimensional control, reducing proximity of the tool with the workpiece, that results in this reduced tool performance, and therefore reduced surface quality.

Thick Packing Vs Thin Packing

For this trial ten samples were tested for each material, both DP800 and DX57.

Five samples of each material were used to test each variable as outlined in the schedule of testing.

Roughness average data will not be graphically represented as it was in the tool wear trial, as a variation can be assessed in table form as there are only two data points.

DP800 Results

Surface Quality Results

TABLE 26 TABLE SHOWING MEAN ROUGHNESS AVERAGE READINGS FOR DP800 SAMPLES MILLED WITH DIFFERENT PACKING GAUGES.

Packing Type	Average Roughness Ra (μm)
Thick	1.42
Thin	1.47

TABLE 27 T-TEST RESULTS DEMONSTRATING THE OCCURRENCE OF ANY SIGNIFICANT CHANGES IN DATA FOR ROUGHNESS AVERAGE DURING THE PACKING TRIAL FOR DP800 MATERIAL.

Roughness Average Data Set 1	Roughness Average Data Set 2	Trials	Confidence Level	P Value	Statistically Significant Difference?
Thin Packing	Thick Packing	2	95%	0.960	No

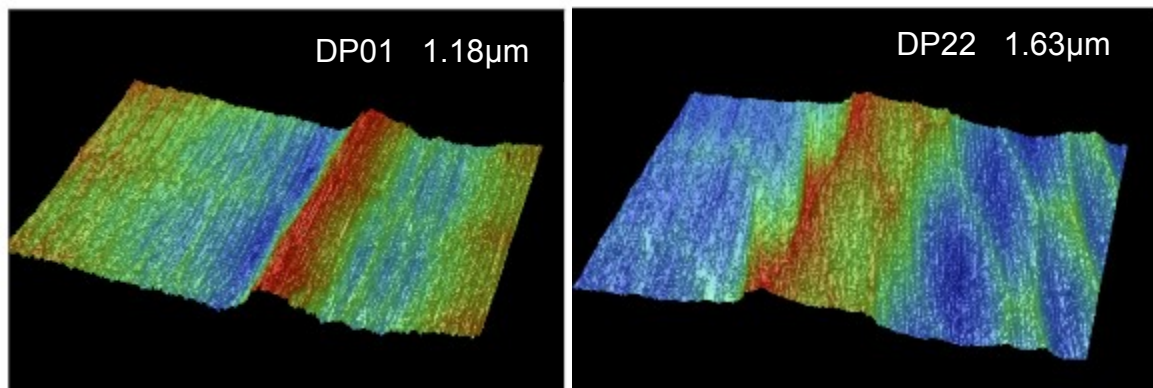


FIGURE 59 SURFACE TOPOGRAPHY IMAGES AND ROUGHNESS AVERAGE RESULT FOR DP800 MATERIAL PREPARED USING THICK AND THIN PACKING MATERIAL, 5MM AND 2MM RESPECTIVELY.

Mechanical Property Results

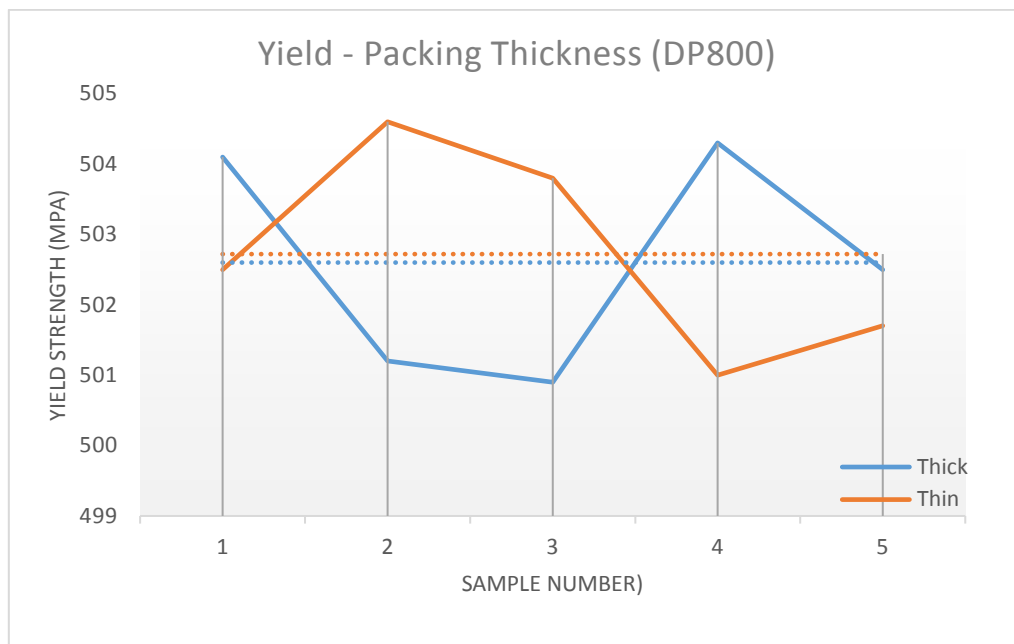


FIGURE 60 GRAPH PLOTTING YIELD FOR MATERIAL MILLED USING THICK OR THIN PACKING, FOR DP800 MATERIAL.

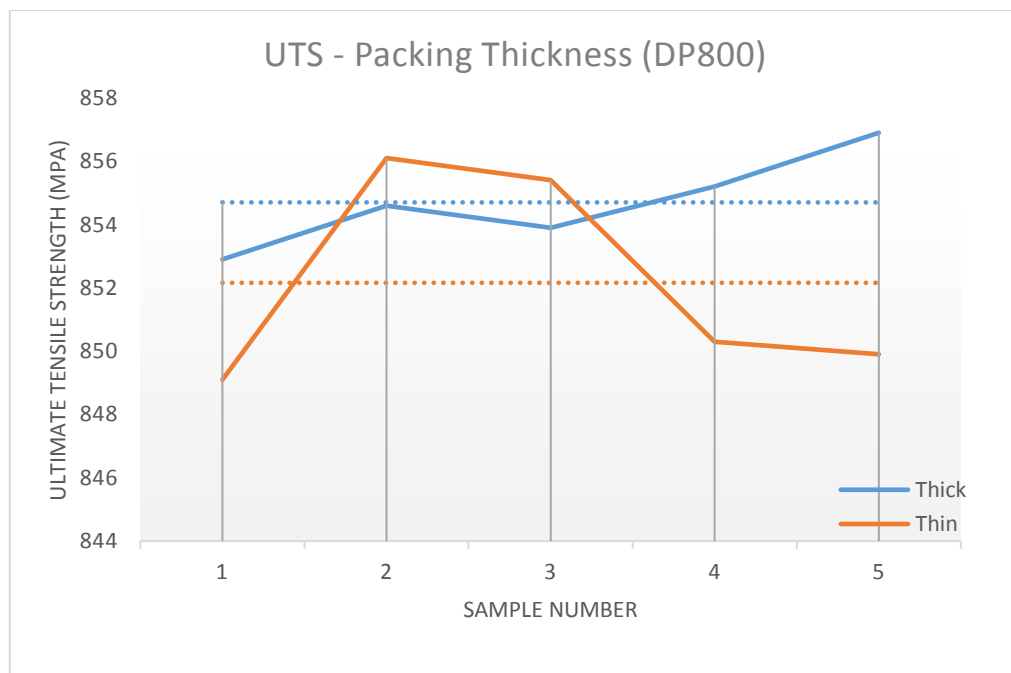


FIGURE 61 GRAPH PLOTTING UTS FOR MATERIAL MILLED USING THICK OR THIN PACKING, FOR DP800 MATERIAL.

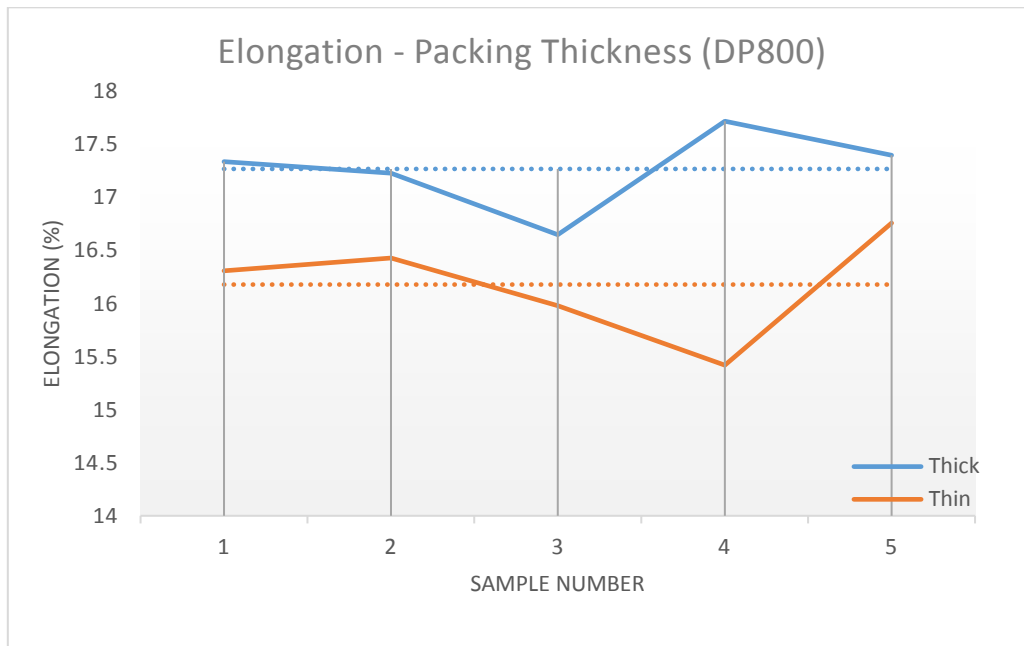


FIGURE 62 GRAPH PLOTTING ELONGATION FOR MATERIAL MILLED USING THICK OR THIN PACKING, FOR DP800 MATERIAL.

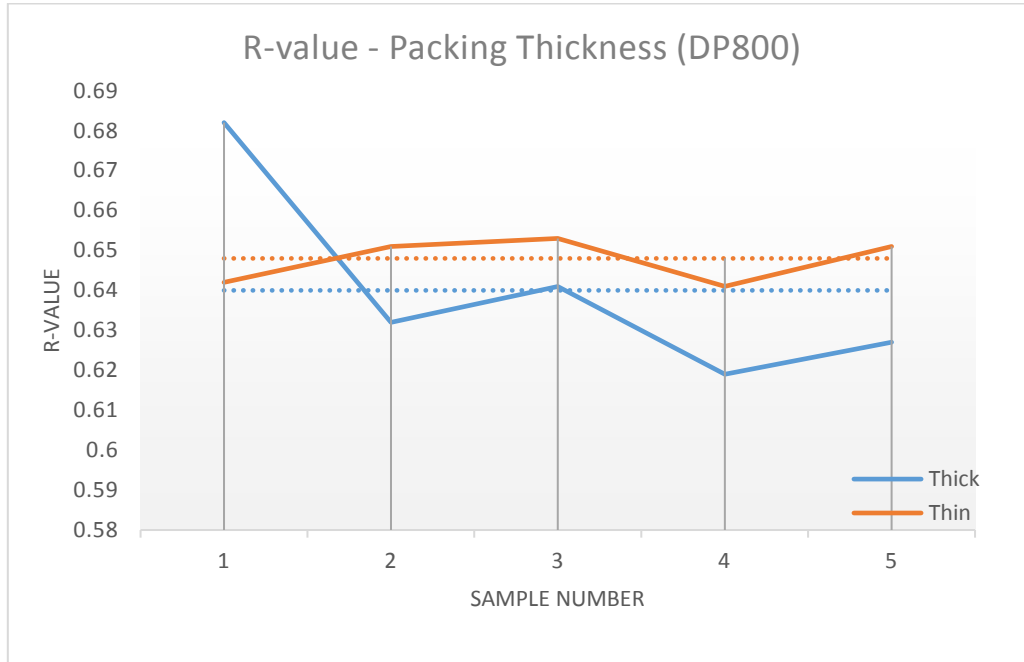


FIGURE 63 GRAPH PLOTTING R-VALUE FOR MATERIAL MILLED USING THICK OR THIN PACKING, FOR DP800 MATERIAL.

Variation Results

TABLE 28 TABLE SHOWING PERCENTAGE VARIATION FOR MECHANICAL PROPERTIES FOR DP800, FOR MILLING USING THIN PACKING WHEN COMPARED TO THICK PACKING, BASED ON MEAN RESULTS, RED INDICATING A DECREASE, GREEN INDICATING AN INCREASE.

Packing Type	+/- Yield	+/- UTS	+/- A	+/- R-value
Thin	0.02%	0.3%	6.31%	1.25%

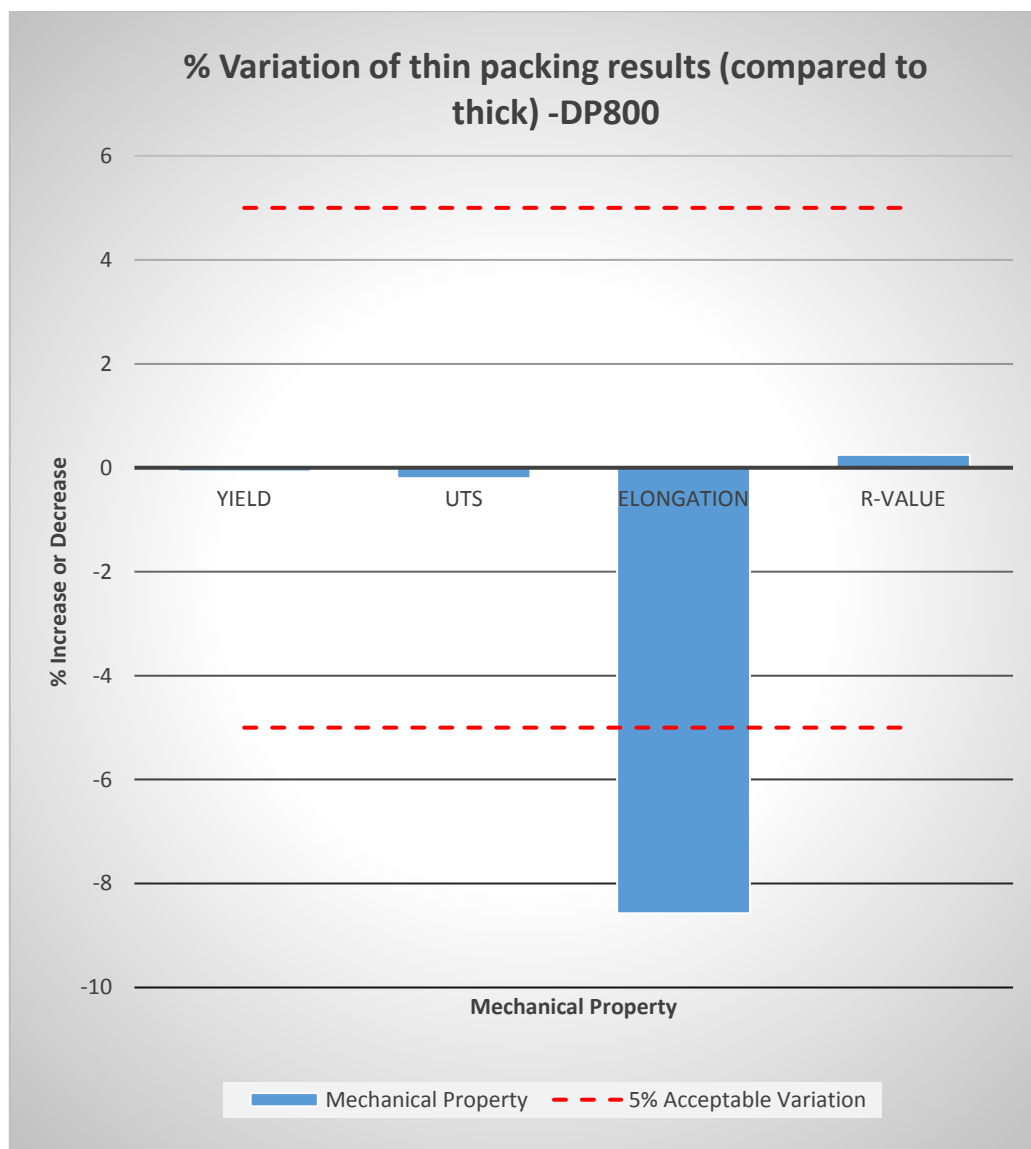


FIGURE 64 HISTOGRAM SHOWING VARIATION OF MECHANICAL PROPERTIES OF DP800 SAMPLES PREPARED WITH THIN PACKING, COMPARED TO THICK PACKING, INDICATING THE ACCEPTABLE LEVEL OF VARIATION OF 5%.

T-Test Results

The variation results show that a t-test is appropriate for elongation.

TABLE 29 T-TEST RESULTS DEMONSTRATING ANY STATISTICALLY SIGNIFICANT CHANGES IN DATA FOR ELONGATION DURING THE PACKING TRIAL FOR DP800 MATERIAL.

Elongation Data Set 1	Elongation Data Set 2	Trials	Confidence Level	P Value	Statistically Significant Difference?
Thin Packing	Thick Packing	2	95%	0.005	Yes

DX57 Results

Surface Quality Results

TABLE 30 TABLE SHOWING MEAN ROUGHNESS AVERAGE READINGS FOR DX57 SAMPLES MILLED WITH DIFFERENT PACKING GAUGES.

Packing Type	Roughness Average Ra (μm)
Thick packing	1.42
Thin packing	1.55

TABLE 31 T-TEST RESULTS DEMONSTRATING THE OCCURRENCE OF ANY SIGNIFICANT CHANGES IN DATA FOR ROUGHNESS AVERAGE DURING THE PACKING TRIAL FOR DX57 MATERIAL.

Roughness Average Data Set 1	Roughness Average Data Set 2	Trials	Confidence Level	P Value	Statistically Significant Difference?
Thin Packing	Thick Packing	2	95%	0.736	No

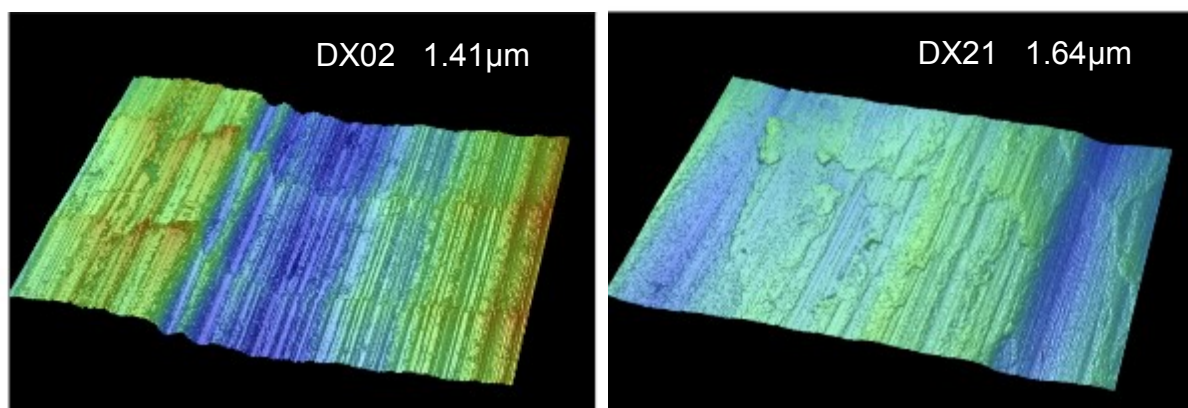


FIGURE 65 SURFACE TOPOGRAPHY IMAGES AND ROUGHNESS AVERAGE RESULT FOR DX57 MATERIAL PREPARED USING THICK AND THIN PACKING MATERIAL, 5MM AND 2MM RESPECTIVELY.

Mechanical Property Results

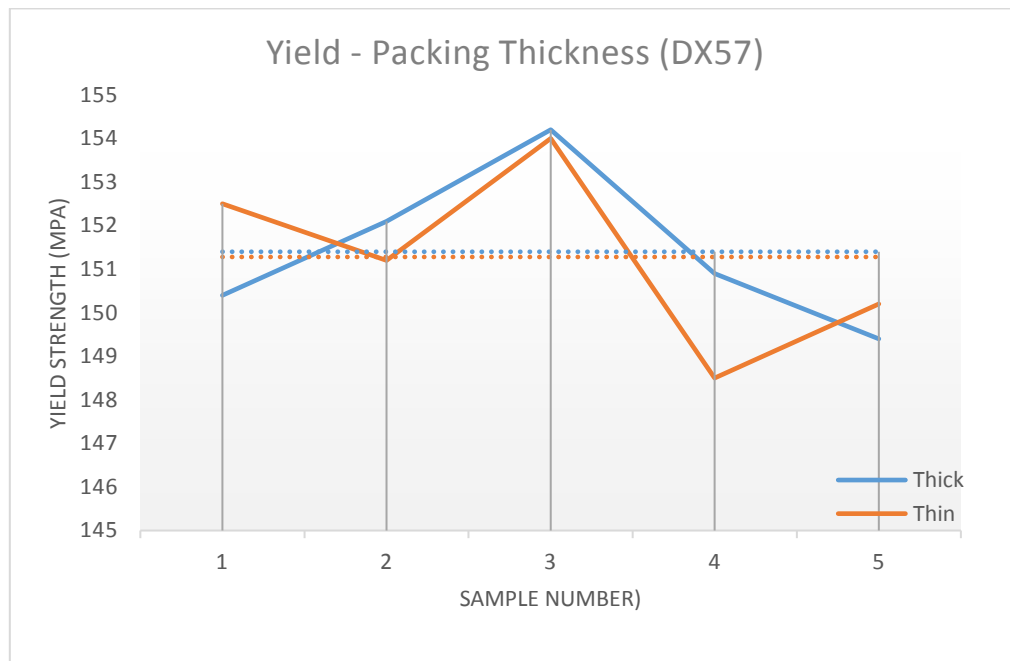


FIGURE 66 GRAPH PLOTTING YIELD FOR MATERIAL MILLED USING THICK OR THIN PACKING, FOR DX57 MATERIAL.

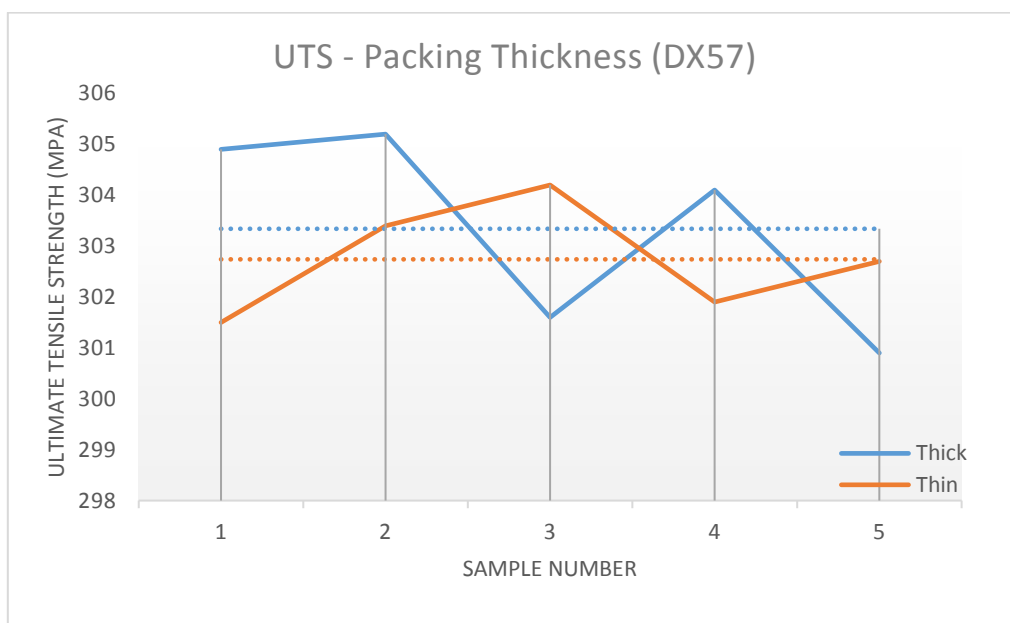


FIGURE 67 GRAPH PLOTTING UTS FOR MATERIAL MILLED USING THICK OR THIN PACKING, FOR DX57 MATERIAL.

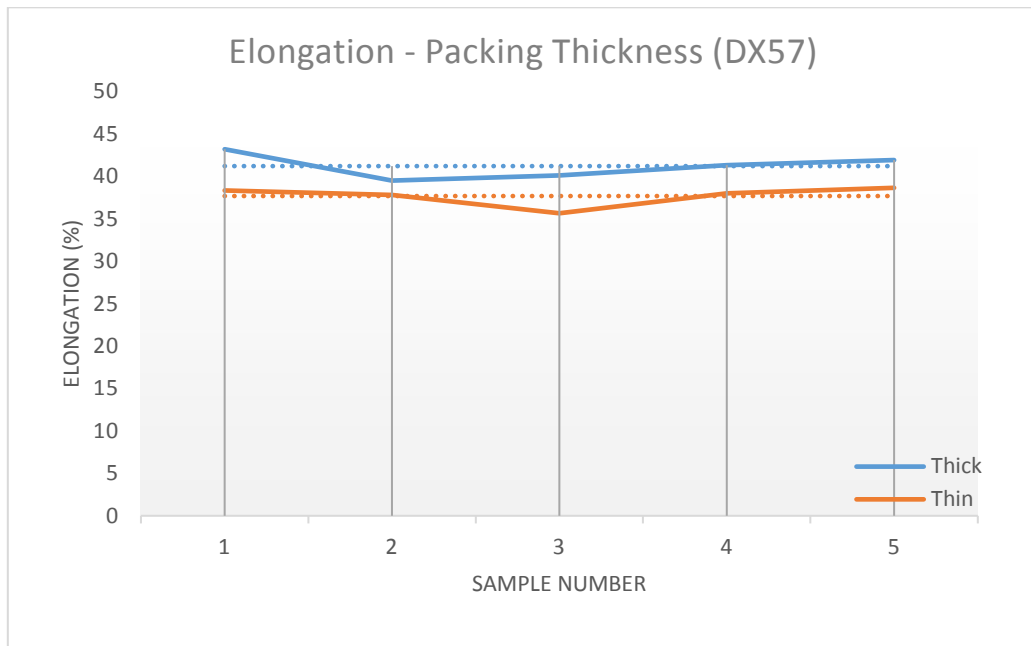


FIGURE 68 GRAPH PLOTTING ELONGATION FOR MATERIAL MILLED USING THICK OR THIN PACKING, FOR DX57 MATERIAL.

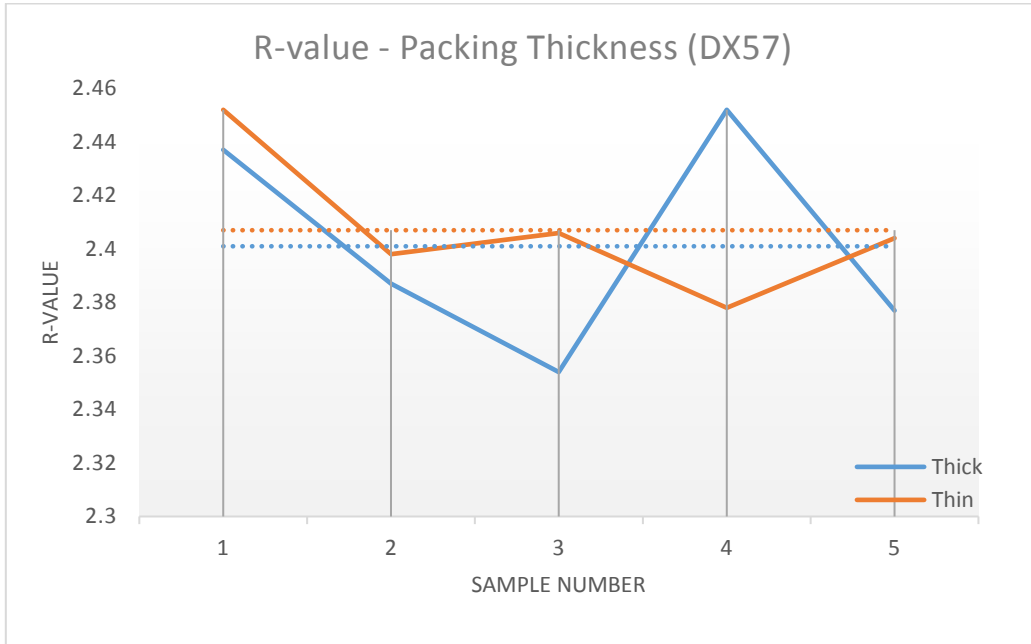


FIGURE 69 GRAPH PLOTTING R-VALUE FOR MATERIAL MILLED USING THICK OR THIN PACKING, FOR DX57 MATERIAL.

Variation Results

TABLE 32 TABLE SHOWING PERCENTAGE VARIATION FOR MECHANICAL PROPERTIES FOR DX57, FOR MILLING USING THIN PACKING WHEN COMPARED TO THICK PACKING, BASED ON MEAN RESULTS, RED INDICATING A DECREASE, GREEN INDICATING AN INCREASE.

Packing Type	+/- Yield	+/- UTS	+/- A	+/- R-value
Thin	0.07%	0.2%	8.57%	0.25%

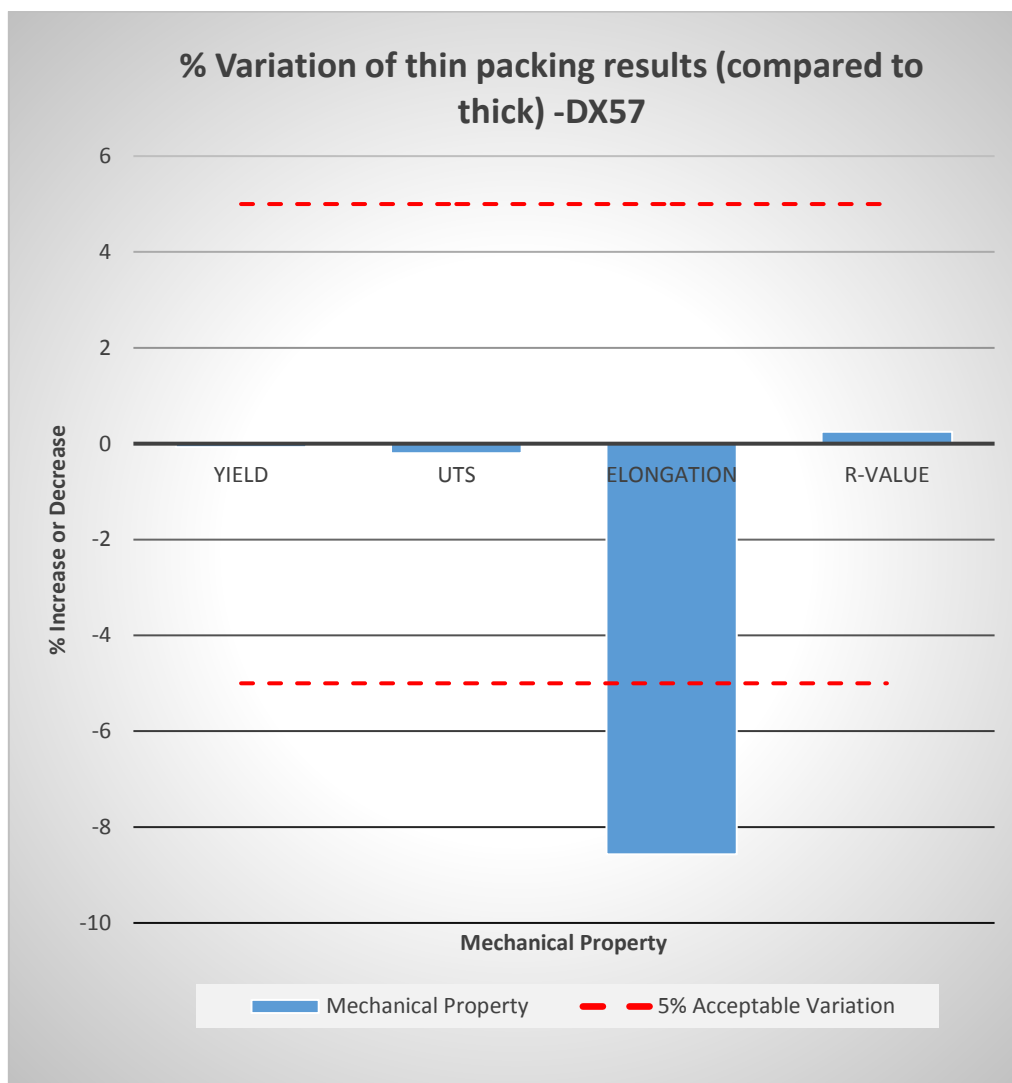


FIGURE 70 71 HISTOGRAM SHOWING VARIATION OF MECHANICAL PROPERTIES OF DX57 SAMPLES PREPARED WITH THIN PACKING, COMPARED TO THICK PACKING, INDICATING THE ACCEPTABLE LEVEL OF VARIATION OF 5%.

T-Test Results

The variation results show that a t-test is appropriate for elongation.

TABLE 33 T-TEST RESULTS DEMONSTRATING ANY STATISTICALLY SIGNIFICANT CHANGES IN DATA FOR ELONGATION DURING THE PACKING TRIAL FOR DX57 MATERIAL.

Elongation Data Set 1	Elongation Data Set 2	Trials	Confidence Level	P Value	Statistically Significant Difference?
Thin Packing	Thick Packing	2	95%	0.003	Yes

Discussion and Further Work

The roughness average results increase with thin packing for both materials, although to a lesser extent than the tool wear trial. The roughness average increases by 9.15% for DP800 5% for DX57, taken from results in tables 26 and 30. Similar to the previous trial, the surface finish produced on both materials using thick packing are the same.

The WLI image for DP800 prepared using thin packing in figure 59 have more red and blue areas, representing the increase in peaks and troughs contributing to the higher roughness average result. This may not always be obvious in some of the images as they represent only a small section of the length of the sample.

As with the tool wear trial, yield strength and UTS show no significant. Although UTS appears reduced on the graph, bearing in mind the scale this equates to under 0.3% reduction in UTS for both materials, and the t-test supports no significant change. R Value in this case shows an increase, where mean trend lines in figures 63 and 69 are above the trend lines for thick packing, although the increase is not significant.

Elongation shows the only significant change, decreasing by 6.31% and 8.57% for DP800 and DX57 respectively, both outside of the acceptable level of variation of 5%.

The packing trial shows a correlation between the surface roughness results and elongation results for both materials, supporting the relationship between the two. This was also the outcome of the tool wear trial. Due to this link between the trials and the limited availability of testing, metallography analysis was not performed on samples from the packing trial, as results were expected to be the same as the tool wear trial, with early fracture resulting from the propagation from defects in the surface.

Further Observations

A phenomenon was observed when machining with thinner packing, where removed material had become dislodged between individual samples within the stack, as seen in figure 72. This suggests inadequate clamping of samples across the centre of the stack as a possible cause, as movement is being allowed.

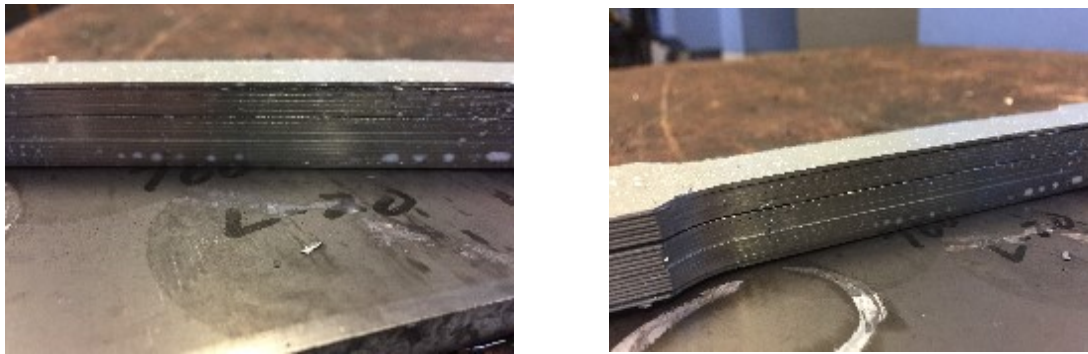


FIGURE 72 A “BOX” OF SAMPLES TAKEN STRAIGHT FROM THE MILLER WITH EVIDENCE OF SEPARATION AND BURRS BETWEEN SOME OF THE SAMPLES.

Visual inspection showed that the actual edge surface quality was not severely compromised by this, as the burrs had been pushed onto the top and bottom surface of the tensile piece, leaving a relatively clean edge. This expected presence of edge burrs led to the original hypothesis that R-value would be affected, and the absence of edge burrs may account for no significant change to R-value being noted.

The results of the trial conclude that the use of thick packing gauge performs better than thin packing, which is not adequate for milling. The more rigid thick material provides more effective clamping across the entire length. Use of thicker sacrificial packing helps reduce the effects of movement or separation of samples while milling, although another factor may contribute to this – ineffective design of the machine bed clamps. The vices secure samples at each end and do not offer security to the centre of the stack, as pictured in figure 73. This clamping system was designed to enable maximum height of material to be milled at any one time. As the stack height is dictated by the tool length, alternative designs may take up space compromising the amount of samples that can be milled. The tool height cannot be reduced without affecting the set up and performance of the machine, as the range of milling parameters are carefully set up in balance.



FIGURE 73 CURRENT CLAMPING SYSTEM FOR MILLING IN THE METALLURGICAL LABORATORY.

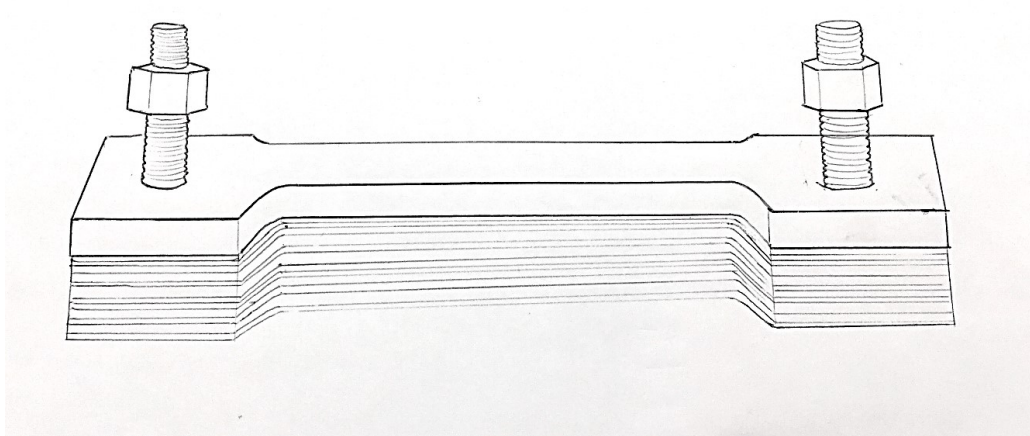


FIGURE 74 DRAWING OF SUGGESTED ALTERNATIVE CLAMPING SYSTEM.

Figure 74 offers an alternative clamping design that provides support across the whole length. The proposed design utilises a hardened steel bar secured at both ends, which would theoretically reduce the amount of vibration allowed across the gauge length. The maximum stack height would not be affected as the clamp would make the use of packing material unnecessary, saving space.

Higher axial forces created by the cutting tool can also contribute to the separation of samples, referred to as the “corkscrew effect”. The helix angle at which the cutting flutes spiral around the body of the tool influence the axial and radial forces that act upon the workpiece during milling. Figure 75 shows examples of tools with differing helix angles.

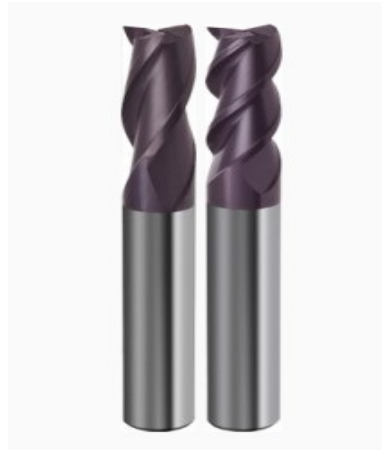


FIGURE 75 EXAMPLES OF END MILLS. (LEFT) A 30° HELIX CUTTER (RIGHT) A 45° HELIX CUTTER (AUSTRALIA, 2015)

During milling, the workpiece is subject to many forces, including axial and radial forces. Axial forces act parallel to the axis of rotation, while radial forces act at right angles to the axis of rotation. Figure 76 illustrates this.

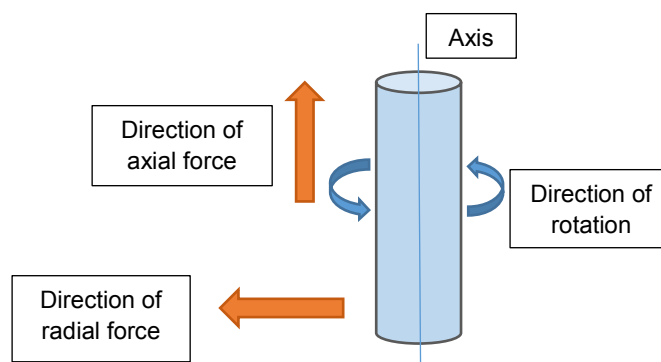


FIGURE 76 SCHEMATIC REPRESENTATION OF A ROTATING BODY SHOWING THE AXIS, THE DIRECTION OF ROTATION, AND THE AXIAL AND RADIAL FORCES ACTING UPON IT

Angled cutting faces that spiral around the shaft can affect the degree of axial and radial forces. A tool which features a more shallow helix of 30° will result in an reduced axial forces, thus avoiding the so called the “corkscrew effect”. The corkscrew effect tends to pull the stack of test pieces in an upward direction away from the machine bed and clamping, much the same as when removing a cork from a bottle. However, where axial forces are reduced the radial forces increase. These increased outward forces can increase the likelihood of chatter and cutter deflection occurring, which in essence is the tool bouncing from the edge of the workpiece, which can also create a poor surface finish.

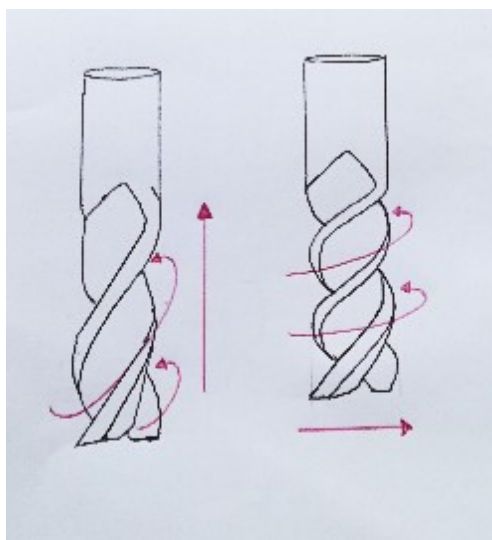


FIGURE 77 AN ILLUSTRATION OF HELIX TOOLS TO REPRESENT (LEFT) 30° CUTTER WITH HIGHER RADIAL FORCES, 45° CUTTER WITH HIGHER AXIAL FORCES AND PULL UP OR CORKSCREW

A tool that creates high axial forces can result in pulling the stacked samples in an upward direction, or in the case of this project, pull the samples apart. A tool of helix angle 45°, as currently employed at the Metallurgical Laboratory, operates with higher axial forces, as more effort is required to draw the removed material upward in the corkscrew effect.

It is important when milling that the two forces are balanced, so that neither an unacceptable level of chatter is encountered nor vibration caused by separation of samples.

Consideration was given to the possibility that milling material in bundles may be contributing to this phenomenon, and whether this would still occur if milling only one sample. However, without adequate clamping force across the length of the workpiece, it would be expected that this would still occur for one sample. Furthermore, milling of one sample as opposed to multiple samples would not be a realistic approach for the laboratory, as milling volume capability is crucial, and this approach would be wasteful on many levels. The testing standard also advises that milling should be performed in bundles, therefore optimisation of this approach is recommended.

Milling Vs Waterjet Cutting

Ten samples from both DP800 and DX57 were used to compare the method of milling with waterjet cutting, for preparation of tensile test specimens, testing five samples for each method according to the testing schedule.

Roughness average data will not be graphically represented as it was in the tool wear trial, as a variation can be assessed in table form as there are only two data points.

DP800 Results

Surface Quality Results

TABLE 34 TABLE SHOWING MEAN ROUGHNESS AVERAGE READINGS FOR DP800 SAMPLES PREPARED BY DIFFERENT METHODS

Cutting Method	Roughness Average Ra (μm)
Milling	1.42
Waterjet	5.56

TABLE 35 T-TEST RESULTS DEMONSTRATING THE OCCURRENCE OF ANY SIGNIFICANT CHANGES IN DATA FOR ROUGHNESS AVERAGE DURING THE WATERJET TRIAL FOR DP800 MATERIAL.

Roughness Average Data Set 1	Roughness Average Data Set 2	Trials	Confidence Level	P Value	Statistically Significant Difference?
Milled	Waterjet	2	95%	0.0008	Yes

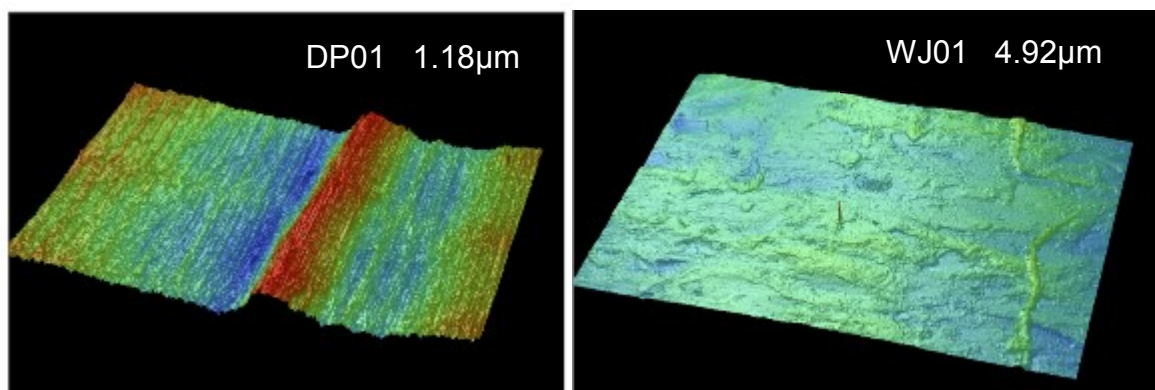


FIGURE 78 SURFACE TOPOGRAPHY IMAGES AND ROUGHNESS AVERAGE RESULT FOR DP800 MATERIAL PREPARED BY MILLING (LEFT) AND WATERJET CUTTING (RIGHT)

Mechanical Properties

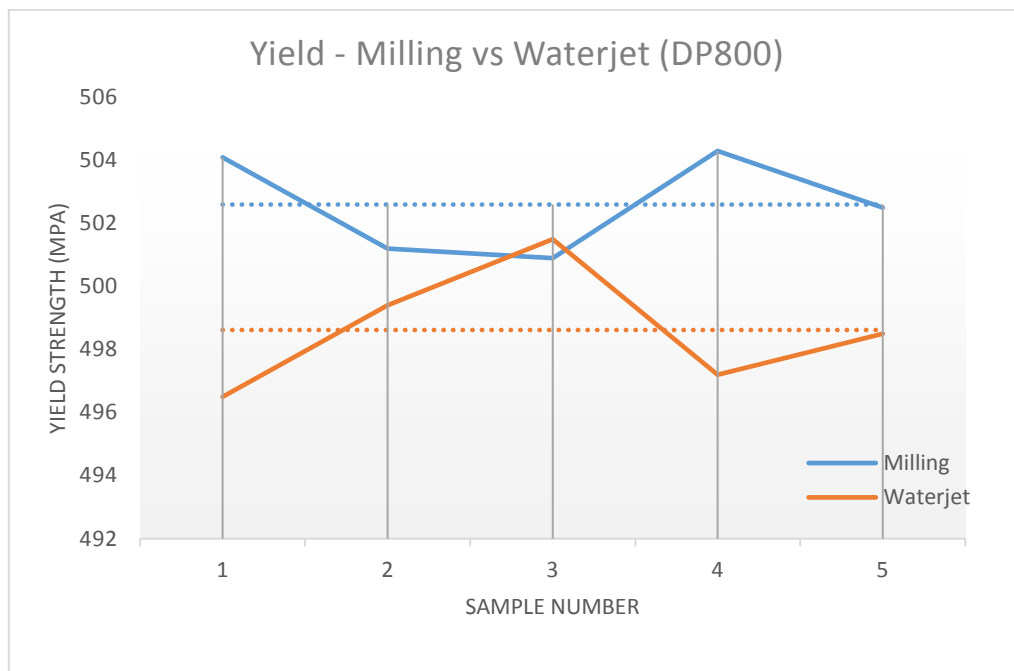


FIGURE 79 GRAPH PLOTTING YIELD FOR MILLED AND WATERJET CUT SAMPLES, FOR DP800 MATERIAL.

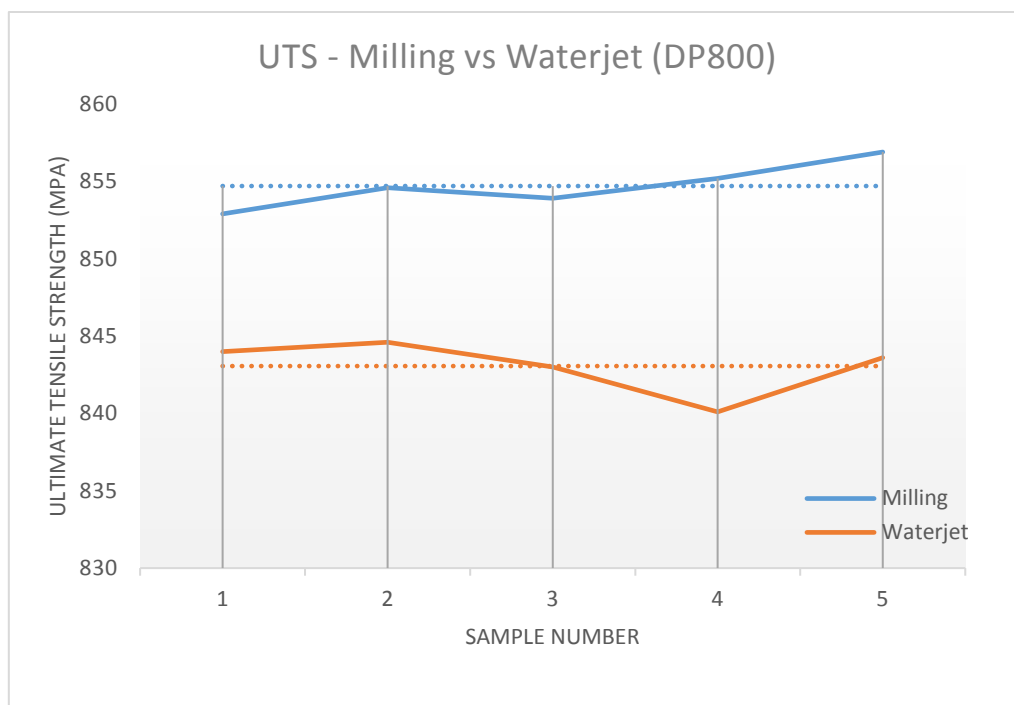


FIGURE 80 GRAPH PLOTTING UTS FOR MILLED AND WATERJET CUT SAMPLES FOR DP800 MATERIAL.

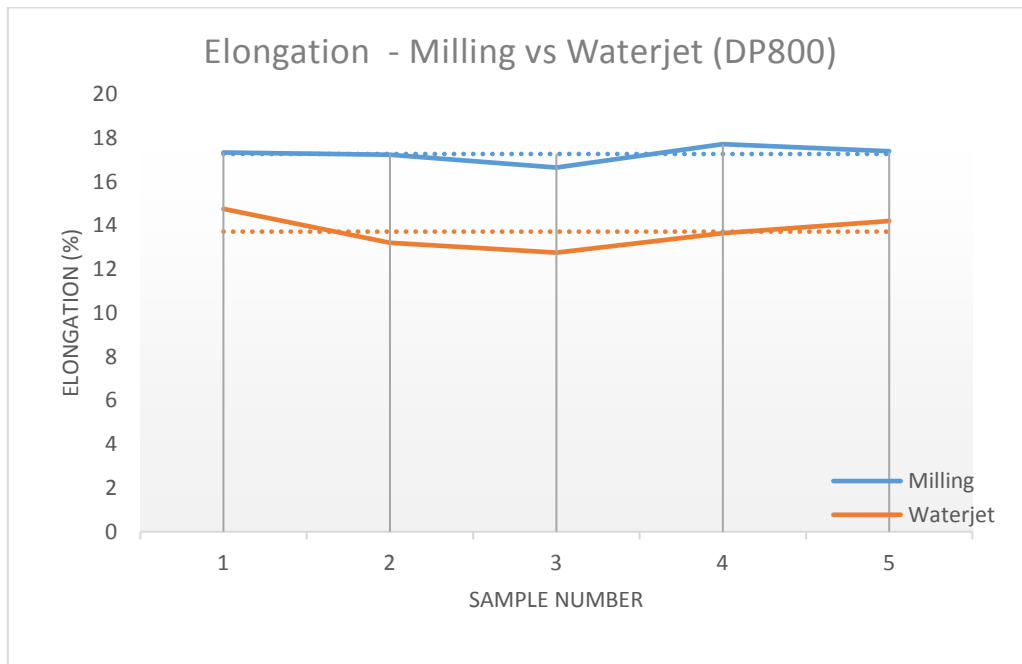


FIGURE 81 GRAPH PLOTTING ELONGATION FOR MILLED AND WATERJET CUT SAMPLES FOR DP800 MATERIAL.

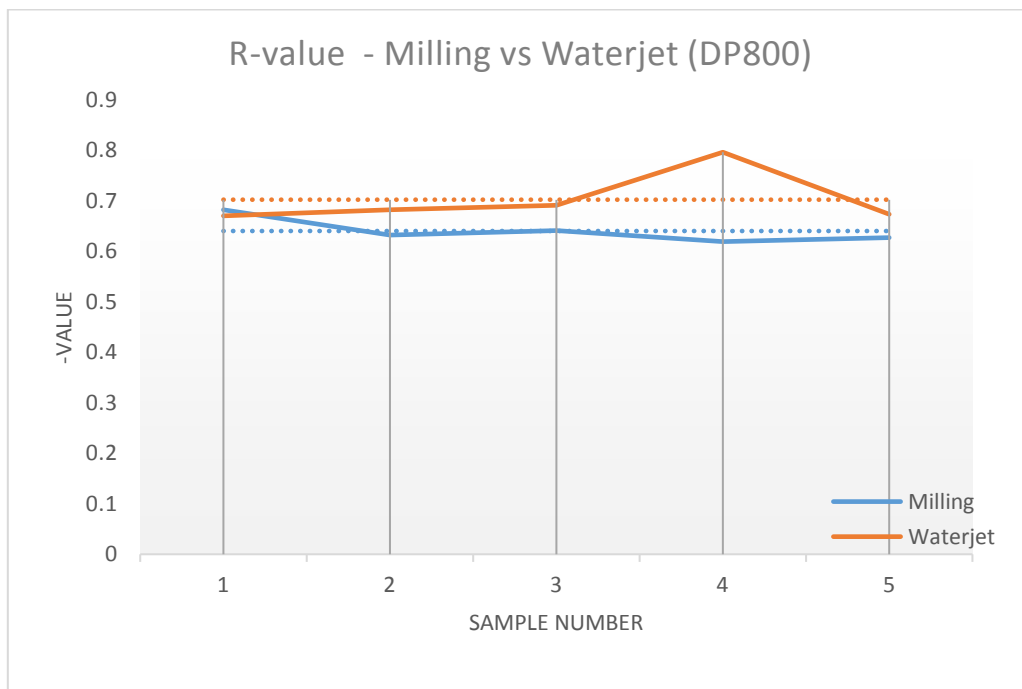


FIGURE 82 GRAPH PLOTTING R-VALUE FOR MILLED AND WATERJET CUT SAMPLES, FOR DP800 MATERIAL.

Variation Results

TABLE 36 TABLE SHOWING PERCENTAGE VARIATION FOR MECHANICAL PROPERTIES FOR DP800, FOR WATERJET CUT SAMPLES COMPARED TO MILLED, BASED ON MEAN RESULTS, RED INDICATING A DECREASE, GREEN INDICATING AN INCREASE.

Method	+/- Yield	+/- UTS	+/- A	+/- R-value
Waterjet	0.79%	1.36%	20.56%	9.69%

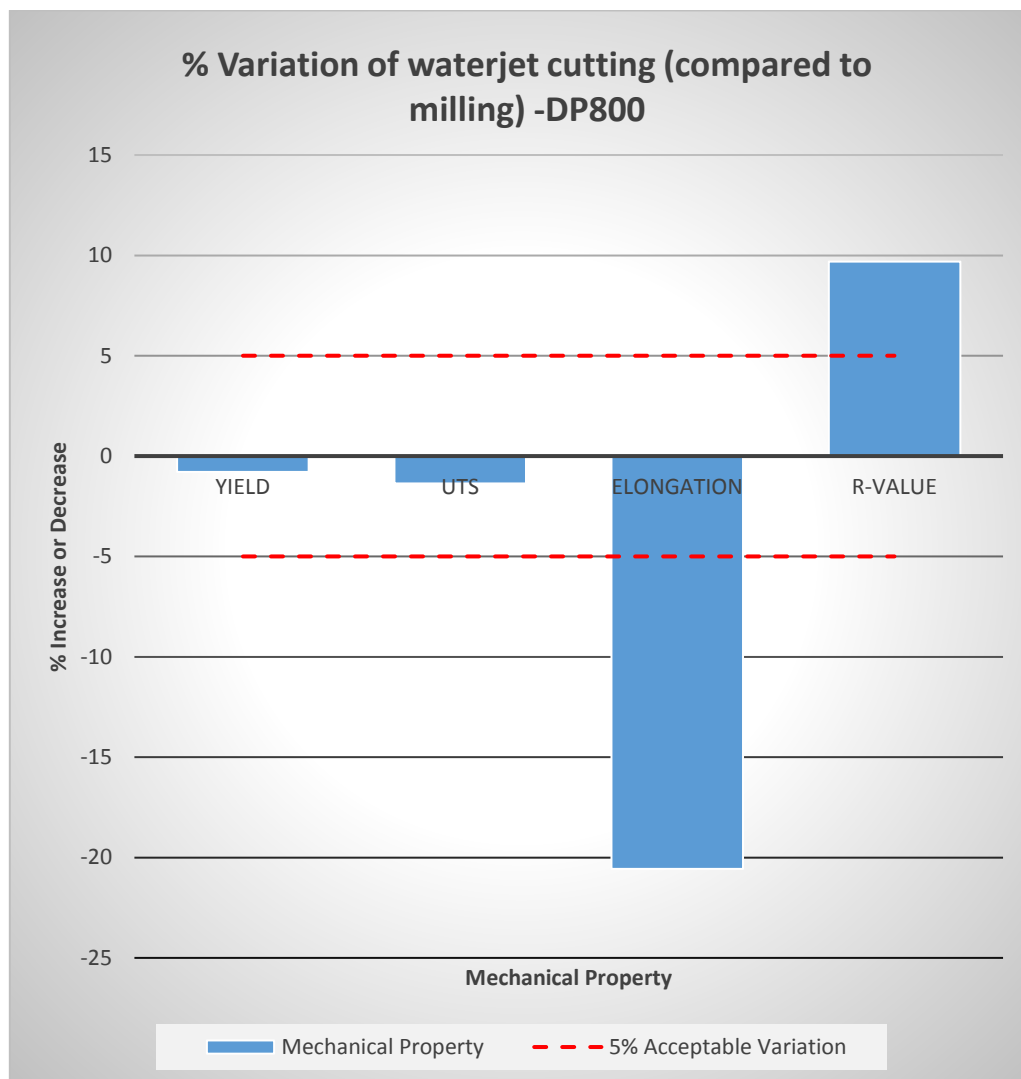


FIGURE 83 HISTOGRAM SHOWING VARIATION OF MECHANICAL PROPERTIES OF DP800 SAMPLES PREPARED BY WATERJET CUTTING, COMPARED TO MILLING, INDICATING THE ACCEPTABLE LEVEL OF VARIATION OF 5%.

T-Test Results

The variation results show that a t-test is appropriate for elongation and R-value.

TABLE 37 T-TEST RESULTS DEMONSTRATING ANY STATISTICALLY SIGNIFICANT CHANGES IN DATA FOR ELONGATION DURING THE WATERJET TRIAL FOR DP800 MATERIAL.

Elongation Data Set 1	Elongation Data Set 2	Trials	Confidence Level	P Value	Statistically Significant Difference?
Milled	Waterjet	2	95%	1.893×10^{-5}	Yes

TABLE 38 T-TEST RESULTS DEMONSTRATING ANY STATISTICALLY SIGNIFICANT CHANGES IN DATA FOR R-VALUE DURING THE WATERJET TRIAL FOR DP800 MATERIAL

R-value Data Set 1	R-value Data Set 2	Trials	Confidence Level	P Value	Statistically Significant Difference?
Milled	Waterjet	2	95%	0.045	Yes

DX57 Results

Surface Quality Results

TABLE 39 TABLE SHOWING MEAN ROUGHNESS AVERAGE READINGS FOR DX57 SAMPLES PREPARED BY DIFFERENT METHODS

Cutting Method	Roughness Average Ra (μm)
Milling	1.42
Waterjet	5.55

TABLE 40 T-TEST RESULTS DEMONSTRATING THE OCCURRENCE OF ANY SIGNIFICANT CHANGES IN DATA FOR ROUGHNESS AVERAGE DURING THE WATERJET TRIAL FOR DX57 MATERIAL.

Roughness Average Data Set 1	Roughness Average Data Set 2	Trials	Confidence Level	P Value	Statistically Significant Difference?
Milled	Waterjet	2	95%	0.0007	Yes

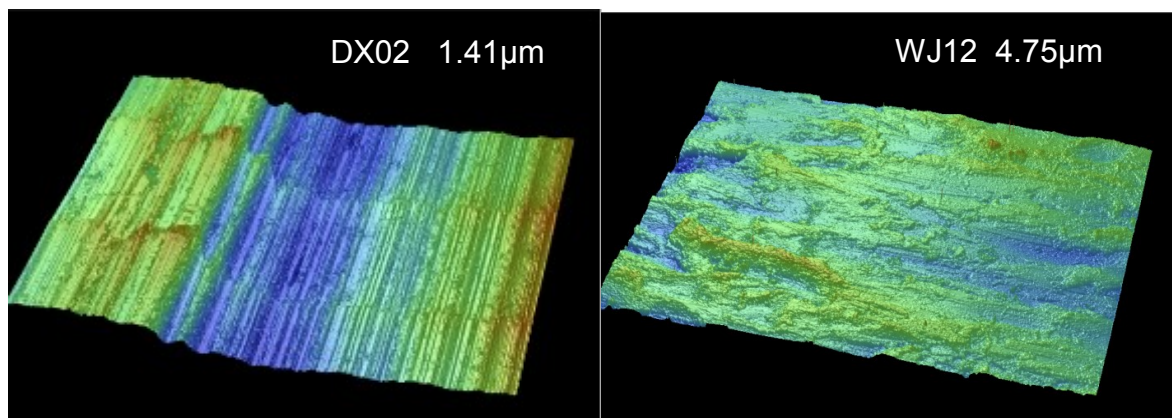


FIGURE 84 SURFACE TOPOGRAPHY IMAGES AND ROUGHNESS AVERAGE RESULT FOR DX57 MATERIAL PREPARED BY MILLING (LEFT) AND WATERJET CUTTING (RIGHT)

Mechanical Properties

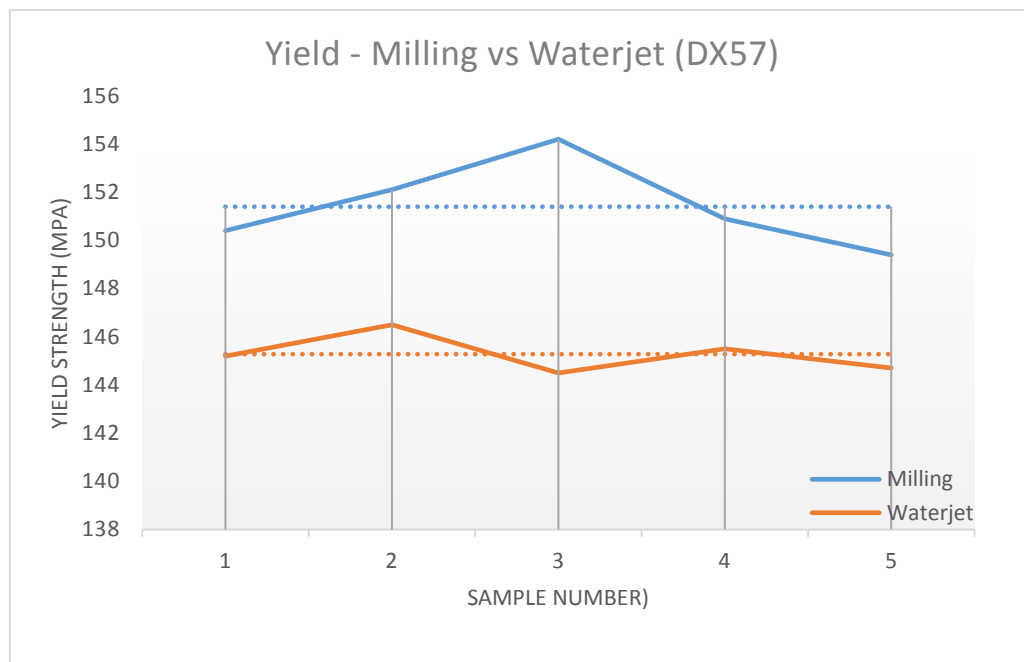


FIGURE 85 GRAPH PLOTTING YIELD FOR MILLED AND WATERJET CUT SAMPLES FOR DX57 MATERIAL.

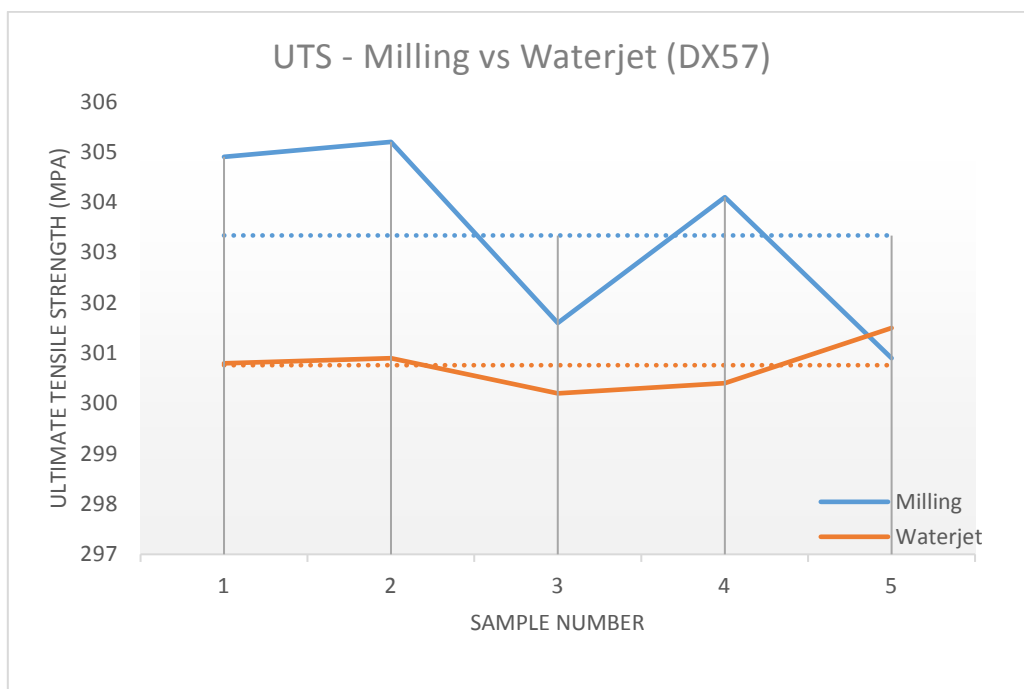


FIGURE 86 GRAPH PLOTTING UTS FOR MILLED AND WATERJET CUT SAMPLES FOR DX57 MATERIAL.

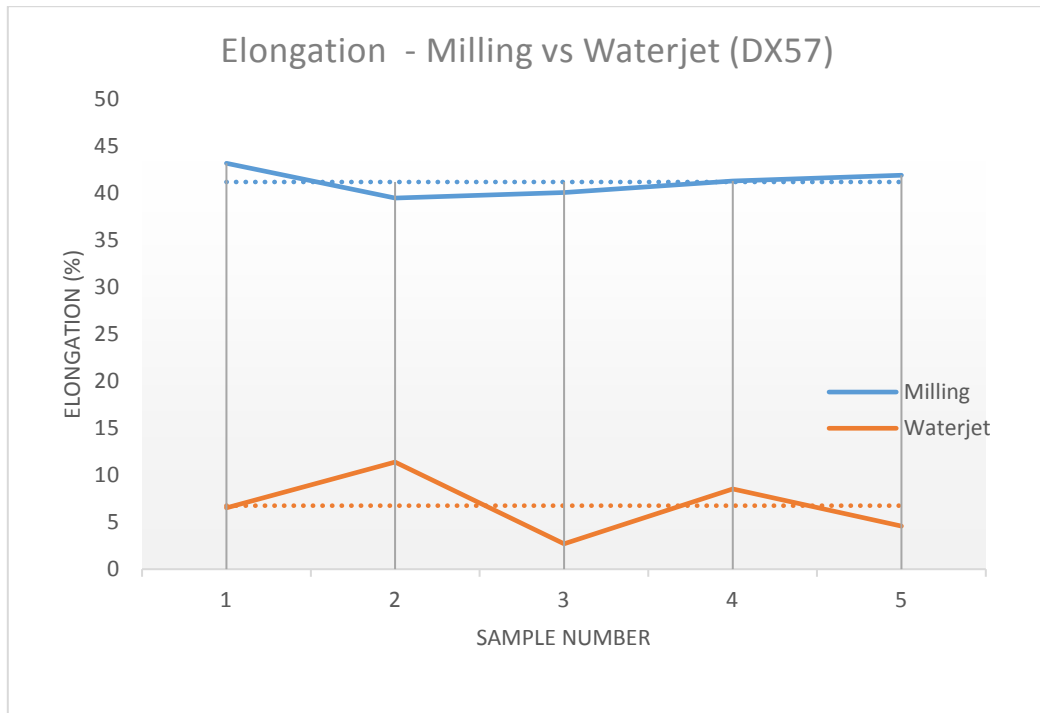


FIGURE 87 GRAPH PLOTTING ELONGATION FOR MILLED AND WATERJET CUT SAMPLES FOR DX57 MATERIAL.

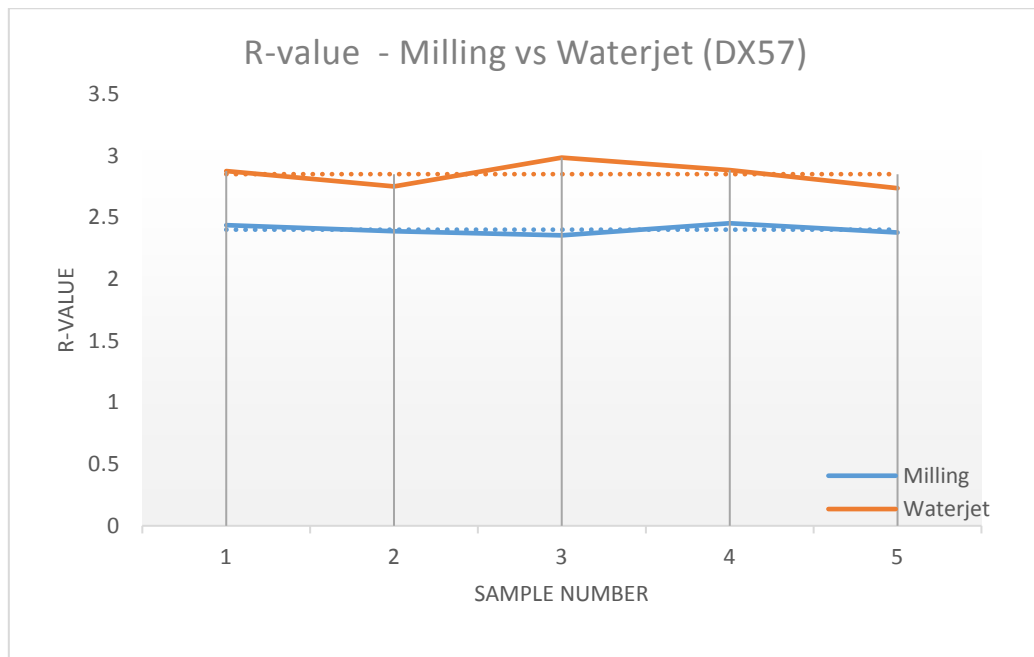


FIGURE 88 GRAPH PLOTTING R-VALUE FOR MILLED AND WATERJET CUT SAMPLES FOR DX57 MATERIAL.

Variation Results

TABLE 41 TABLE SHOWING PERCENTAGE VARIATION FOR MECHANICAL PROPERTIES FOR DX57, FOR WATERJET CUT SAMPLES COMPARED TO MILLED, BASED ON MEAN RESULTS, RED INDICATING A DECREASE, GREEN INDICATING AN INCREASE.

Method	+/- Yield	+/- UTS	+/- A	+/- R-value
Waterjet	4.02%	0.85%	83.6%	18.75%

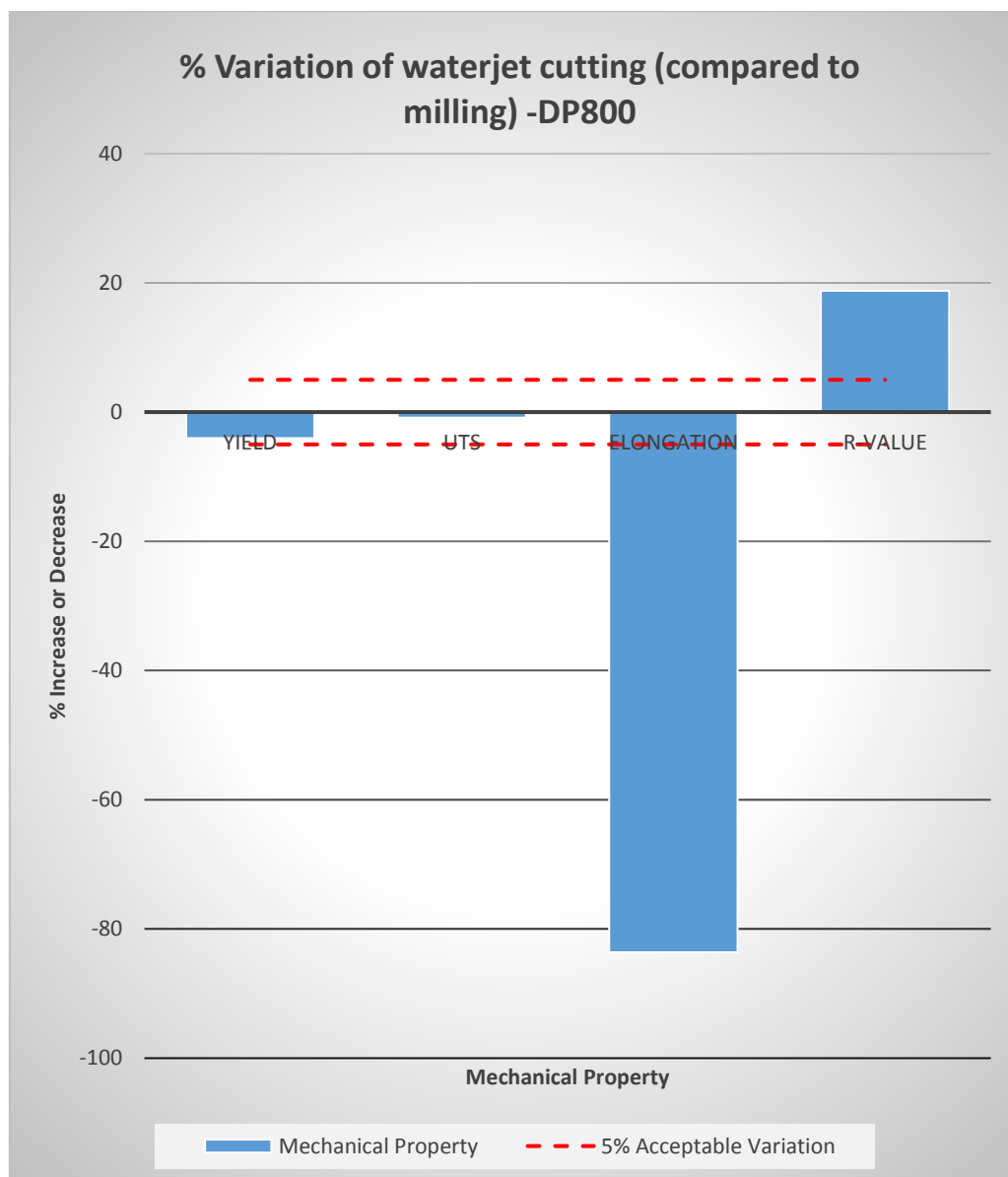


FIGURE 89 HISTOGRAM SHOWING VARIATION OF MECHANICAL PROPERTIES OF DX57 SAMPLES PREPARED BY WATERJET CUTTING, COMPARED TO MILLING, INDICATING THE ACCEPTABLE LEVEL OF VARIATION OF 5%.

T-Test Results

The variation results show that a t-test is appropriate for elongation and R-value. Although Yield in the variation results (table 41) is not above 5%, the t-test will be used to test for any statistically significant change at a level of 4.02%, being nearer the limit.

TABLE 42 T-TEST RESULTS DEMONSTRATING ANY STATISTICALLY SIGNIFICANT CHANGES IN DATA FOR YIELD DURING THE WATERJET TRIAL FOR DX57 MATERIAL.

Yield Data Set 1	Yield Data Set 2	Trials	Confidence Level	P Value	Statistically Significant Difference?
Thin Packing	Thick Packing	2	95%	0.0001	Yes

TABLE 43 T-TEST RESULTS DEMONSTRATING ANY STATISTICALLY SIGNIFICANT CHANGES IN DATA FOR ELONGATION DURING THE WATERJET TRIAL FOR DX57 MATERIAL.

Elongation Data Set 1	Elongation Data Set 2	Trials	Confidence Level	P Value	Statistically Significant Difference?
Thin Packing	Thick Packing	2	95%	2.921×10^{-8}	Yes

TABLE 44 T-TEST RESULTS DEMONSTRATING ANY STATISTICALLY SIGNIFICANT CHANGES IN DATA FOR R-VALUE DURING THE WATERJET TRIAL FOR DX57 MATERIAL

R-value Data Set 1	R-value Data Set 2	Trials	Confidence Level	P Value	Statistically Significant Difference?
Thin Packing	Thick Packing	2	95%	1.95×10^{-5}	Yes

Discussion and Further Work

The roughness average results have increased by an approximate factor of four for the samples cut by the waterjet method, for both materials similarly.

The waterjet WLI images show a clear difference of pattern and texture in comparison with the milled samples in figures 78 and 84.

Assessment of the effect on yield for waterjet cut samples shows that DP800 material shows no significant change. However, although the decrease in yield for DX57 was within the 5% level of acceptance, the t-test determined that this was in fact a significant change. The 5% tolerance measuring unacceptable variation is evidently not set tight enough to detect all significant changes, which should be noted for any future works. Furthermore, during normal laboratory operation, a 4% downward step change in yield for any product would likely be unacceptable for Tata Steel.

UTS does not show a significant change, however the DP800 waterjet trial has shown the largest effect of all the trials to UTS, with a reduction of 1.36%. Although not statistically significant, due to the high UTS values for this material of approximately 800 MPa, this percentage decrease translates to >10 MPa variation, which may be of concern when a material must meet the tight grade specification.

Unlike the other trials, the R-value has increased for both materials, which is unexpected. The reason for this is difficult to explain without further investigation. After the cutting of waterjet specimens, the dimensions were not verified using a micrometer, therefore it is not certain that the dimensions were correct. Variation in parallel width or inaccurate shoulder radii of the specimen would affect the cross-sectional area, having a direct impact upon R-value calculation. The dimensions could not be retrospectively verified post-test as the test pieces are deformed, therefore a further work would be required to determine if this was the cause of the R-value increase.

Elongation has shown the most significant change, particularly to DX57 with a dramatic decrease from a mean elongation of 41.21% to 6.76% in the waterjet cut samples. DP800 also shows a drop in elongation of around a fifth.

It was predicted that waterjet samples would perform similarly to milled samples during a tensile test, so the results were unexpected.

Both methods of material removal have resulted in visibly different surface finishes, that resulted in a significant contrast in tensile test performance. As with the other trials, the primary characteristic affected is elongation, also correlating to the surface quality results. Roughness average results were at their highest in the waterjet trial, and elongations were at their lowest.

Krahmer compares the differing methods for preparation of test pieces for tensile testing in his literature. He states that both surface integrity and functional characteristics related to surface state, such as tensile strength, are influenced by the material removal process (Krahmer, et al., 2016). When comparing the methods of milling, abrasive waterjet (AWJ), punching, laser and electrical discharge machining (EDM) he found that the effects on tensile strength was lower than 5%. This is consistent with the results obtained during this project.

The UTS and yield strength in this project aligned with the results reported in Krahmers work, in as much as they were all below the 5% variation threshold. His literature did not consider R-value, so no comparison could be made. Krahmer reported no significant change to elongation, whereas significant reductions in elongation were observed in this experiment.

His literature also performs surface roughness analysis of steel samples cut by the various technologies, noting a significant increase in readings produced by the waterjet cut samples compared to milled specimens.

Method	Steel sheet		Inconel 718	
	Rt min. (μm)	Rt max. (μm)	Rt min. (μm)	Rt max. (μm)
Milling	5.2	9.5	2.34	2.69
Laser	15.0	32.0	36.94	38.17
AWJ	30.0	38.0	17.10	17.35
WEDM	22.0	27.5	22.70	23.75
CNC Punching	12.0	22.0		

FIGURE 90 SURFACE ROUGHNESS RESULTS (RT) FOR STEEL SAMPLES CUT USING DIFFERENT METHODS OF MATERIAL REMOVAL TO EVALUATE SURFACE FINISH (KRAHMER, ET AL., 2016).

The 'Rt' value measures the total height of the roughness profile which takes into account the maximum peak-valley distance on each sample. Although not measured using the same surface parameter as this trial, both the results in this paper and in this trial demonstrate a marked difference in waterjet samples from milled.

However, the final conclusion of this literature was that waterjet cutting was a method that was suitable for tensile test preparation.

Metallography analysis is used to assess the surface of the waterjet samples, which are also compared against the scanning electron microscope (SEM) images produced in Krahmers work, shown in figure 91.

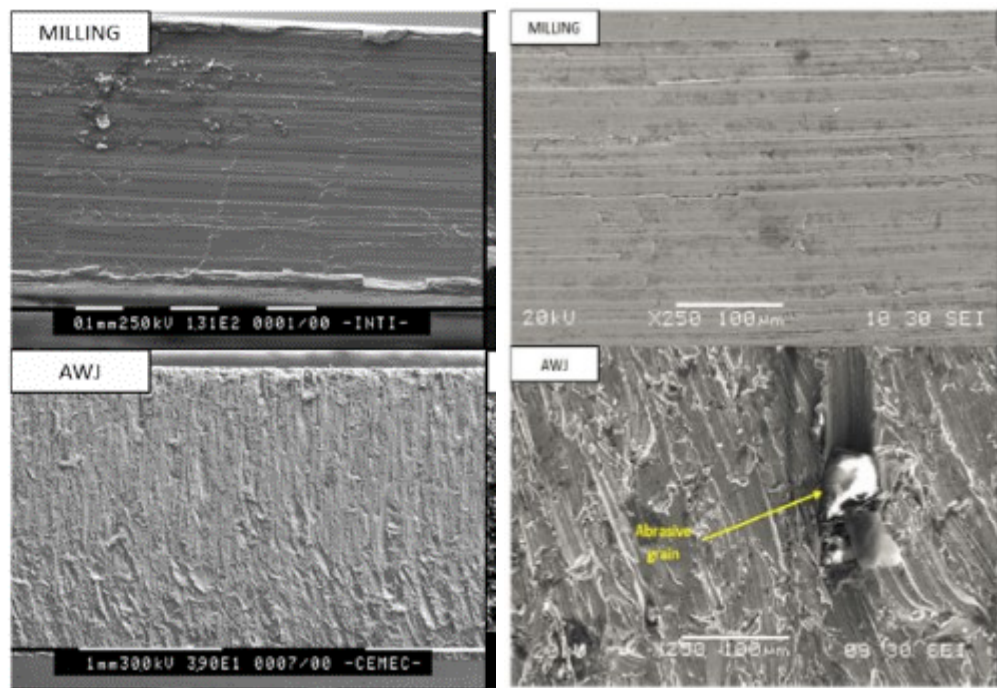


FIGURE 91 SEM IMAGES FOR (LEFT) MILD STEEL OF 300MPA UTS, AND (RIGHT) INCONEL, PREPARED BY MILLING AND ABRASIVE WATERJET (KRAHMER, ET AL., 2016)

Figures 92 and 93 show high magnification SEM images of the surfaces produced by the waterjet method for both DX57 and DP800 material.

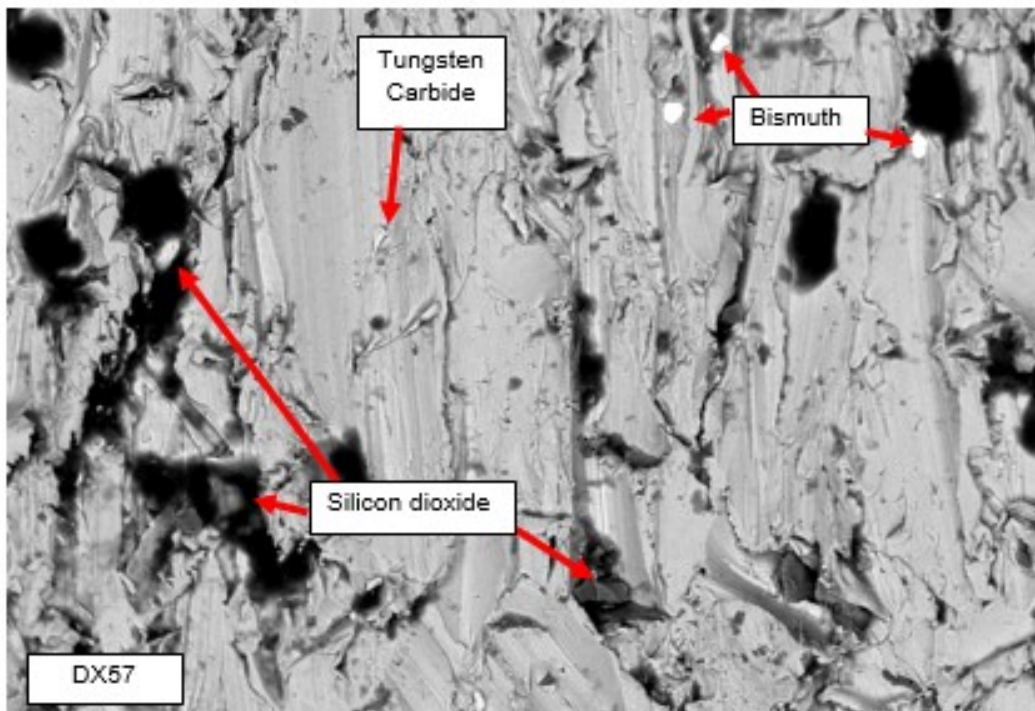


FIGURE 92 SEM HIGH MAGNIFICATION IMAGE OF DX57 WATERJET CUT SURFACE.

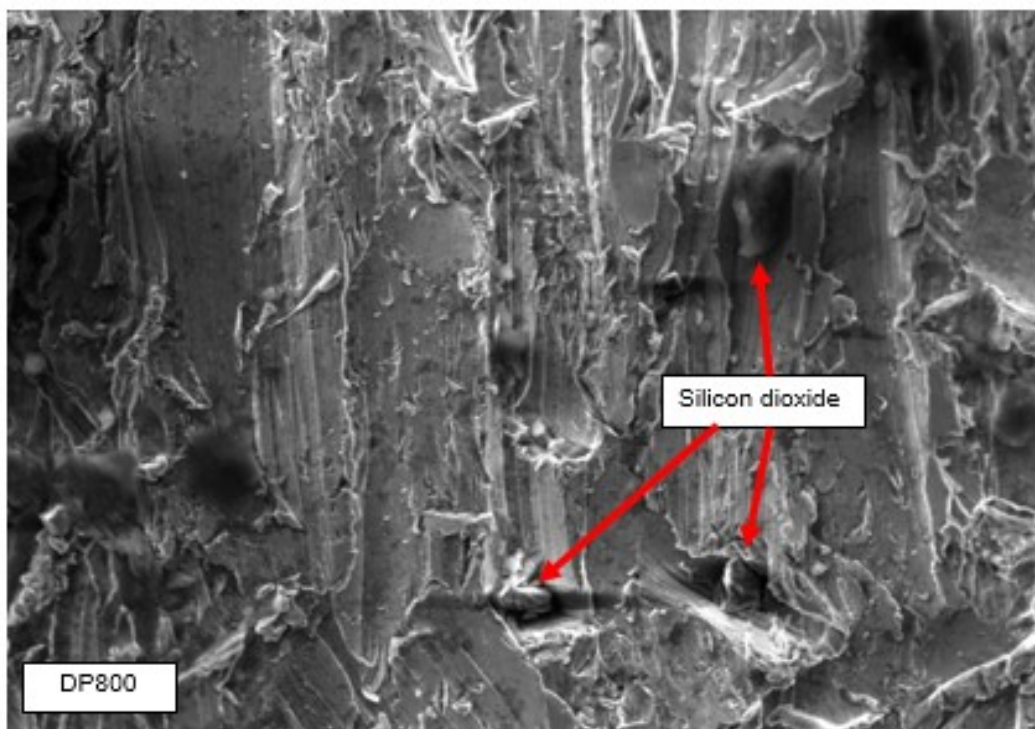


FIGURE 93 SEM HIGH MAGNIFICATION IMAGE OF DP800 WATERJET CUT SURFACE.

Both the DX57 and DP800 had particles of silicone dioxide, which is the abrasive grit used in waterjet cutting, embedded into the surface, with evidence of grit drag marks on the surface. This is also evident in Krahmers images, suggesting that this may be a common feature of

waterjet cut samples, thus may not be the cause of the unexpected mechanical property results observed in this trial.

The DX57 surface, shown in figure 92, also found particles of bismuth and tungsten carbide. The source of the latter may be a part the waterjet nozzle assembly, as machined parts are often made from this strengthened material. However, the bismuth is not a common element and its origin is more difficult to ascertain. It is known that this particular waterjet equipment is regularly used to cut templates, stencils and shapes for art students. It could be that previous sample of bismuth had been cut and the waterjet had become contaminated. Without further investigation the likelihood of such contamination cannot be confirmed, and only with further research could it be determined if contamination of the waterjet could affect the surface and therefore the mechanical property results.

To further investigate the cause of the decline in mechanical properties in this trial further metallography testing was performed. The SEM images in figure 94 show the samples before and after fracture for milled and waterjet cut specimens. Figure 95, shows optical images of a cross section of the gauge length for both methods of cutting.

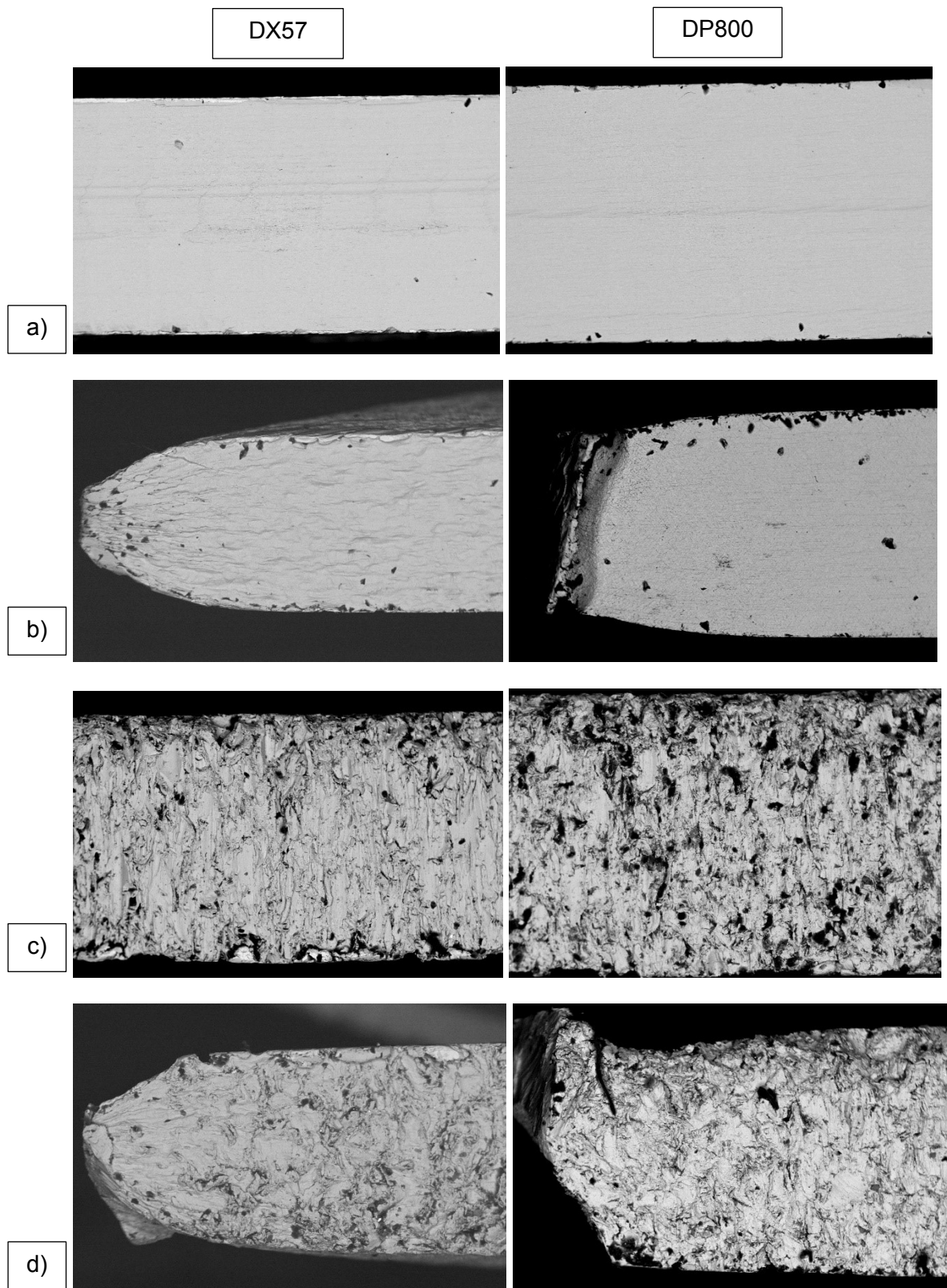


FIGURE 94 SEM IMAGES FOR DX57 AND DP800 MATERIAL FOR ROW A) MILLED EDGE BLANK PIECE B) PULLED TEST PIECE AT FRACTURE FOR MILLED SAMPLE C) WATERJET EDGE BLANK PIECE D) PULLED TEST PIECE AT FRACTURE FOR WATERJET SAMPLE.

Figure 94 shows that the milled edge and surface for both materials are visually much cleaner than the waterjet specimens, which are uneven. There are clear differences in surface texture. Row 'b' shows a typical ductile fracture for these materials, whereas the fractured waterjet pieces in row 'd', particularly in the DP800 specimen, show a different shape at break. For typical fracture, the void leading to fracture is usually formed within the specimen, whereas any edge irregularities may result in the void propagating from the edge. The research carried out by Krahmer on surface finish identified that milling gave the smoothest and most regular cut surface and most desirable roughness results with the shallowest grooves, and that the waterjet cut edge produced far deeper grooves. The images in this trial support this. The introduction of deeper grooves in the surface would lead to the development of cracks under load which would spread towards the centre, subsequently a loss in elongation before fracture.

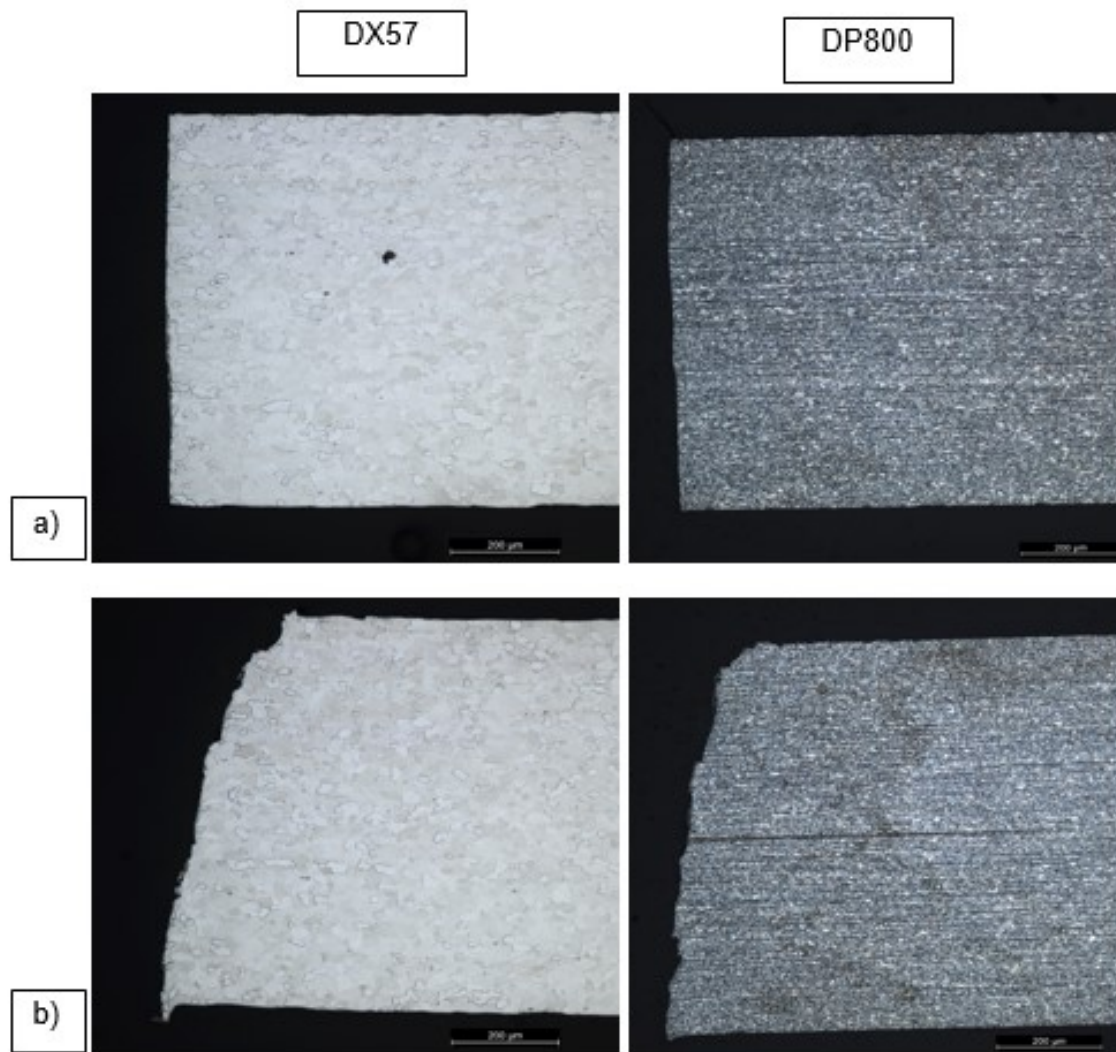


FIGURE 95 METALLOGRAPHY OPTICAL IMAGES FOR DX57 AND DP800 SHOWING A CROSS SECTION PROFILE IN THE GAUGE LENGTH FOR ROW A) MILLED SAMPLES, AND ROW B) WATERJET SAMPLES.

What is interesting is that cross sectional profile pictured in figure 95 shows a notable taper from the top to bottom of the waterjet specimens. From literature review it was understood that a taper should not be expected on cut materials of this gauge. However a taper is evident in these samples of <1mm thickness. This may be responsible for the increase in R-values for these samples, due to the cross sectional area used in the R-value calculation being altered. Further investigation would be required to clarify if this is the case.

Further work – Waterjet Cutting

The waterjet cutter that was used for this experiment is part of an art and design facility, where its primary function is to produce stencils from various materials including woods and plastics. There may be value in accessing an engineering based waterjet cutter to further investigate samples cut by this method. The reduced tensile test performance observed in this project would not be acceptable for engineered components, yet there are many successful waterjet engineering firms, such as Precision Waterjet Ltd, suggesting this method can be capable.

If further investigation using another machine were successful, there are other considerations that must be made in greater depth if trials were to be successful. An overview of these considerations follows.

Figure 96 shows a sample of brick, of approximately 80mm thickness, observed at the UWTSD waterjet facility showed drag commencing roughly half way down the sample. Precision Waterjet Ltd claim that they achieve no draft angle on square edges, and no drag when cutting thicker samples by use of a 5 axis head (Precision Waterjet, 2017).



FIGURE 96 A CYLINDER OF BRICK CUT BY WATERJET AT UWTSD, EXHIBITS THE “DRAG” PHENOMENON

Other aspects of waterjet cutting that should be considered are the jet angle and inability to stack, and therefore mass cut samples due to taper. The results in this trail showed evidence of taper on very thin samples. The nozzle ejects a jet of water that exits at an angle, opening the jet as it travels downward, as illustrated in figure 97.

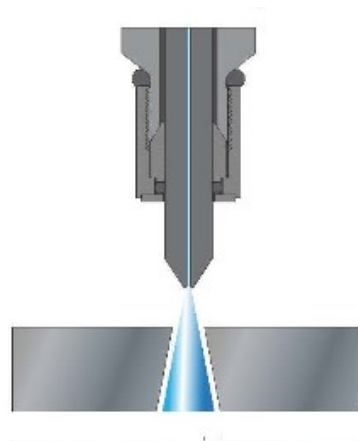


FIGURE 97 SCHEMATIC REPRESENTATION OF A WATER JET AS IT EXITS THE NOZZLE (SCHGO ENGINEERED PRODUCTS, N.D.)

Taper would be unacceptable at the metallurgical laboratory as a tensile test piece must be produced within the dimensional tolerances set out in the testing standard. It is possible that the effects of taper by the jet angle may be avoided by a design alteration. The tight tolerances required by precision engineered components are cut using a tilted nozzle to correct the taper, as seen in figure 98.

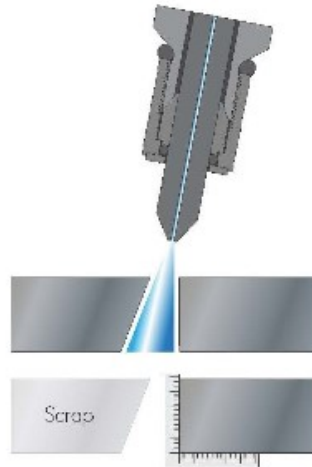


FIGURE 98 SCHEMATIC REPRESENTATION OF A TILTED NOZZLE WITH CORRECTED TAPER ON CUT EDGE OF COMPONENT (SCHGO ENGINEERED PRODUCTS, N.D.)

Further considerations are the speed of waterjet cut, and the inability to stack specimens. Both of these would compromise cutting cycle times, which is unacceptable for the laboratory. Waterjet cutting cycles vary considerably depending on the material type. For example, of 1mm thickness mild steel is cut with a speed of 450mm/s, whereas the same material at 10mm

would be cut at a speed of 50mm/s (Butler, 2017). Waterjet cycle times were observed during this trial, taking approximately 90 seconds of machine time to produce one tensile at 50% speed, and 45seconds at 100% speed.

The waterjet bed determines the maximum amount of samples that can be held, which must be secured and cut separately. Increased set up times may be associated with this method, which could be lessened with the bespoke automation design. Current milling practices allow the operator to perform other duties while the miller completes large batches of machining. The waterjet equipment used in this trial would require an operator remain at the station to repeatedly unload and load samples, in order to complete laboratory throughput. A high level of operator input data and set up would be necessary, which not only adds time, but may increase the likelihood of human error. A semi-automated set up may resolve this.

Some benefits of waterjet cutting for the laboratory may be the eradication of primary preparation of sheet to strip for milling, reducing preparation time. Sheet may be loaded directly to a waterjet bed. Furthermore, after initial investment the cost of consumables would be low, with less expensive and infrequent maintenance, the actual cost of which has not been ascertained during this project due to unsuccessful trial results. Abrasive grit is the only consumable required, which is fairly inexpensive (Butler, 2017), compared to the expensive cost of tooling and inserts required for milling.

If further trials of waterjet cutting for tensile test preparation prove successful, there are far more considerations and extensive investigations to be made in many aspects, before a change of method could be realistically considered.

If further investigated, a summary of considerations are;

1. Effects of drag.
2. Can quality be achieved and consistent tensile test results, within current ranges for each product range. Require extensive trials and validation work.
3. Availability of bespoke automation.
4. Possibility of mass fixing and cutting of samples.
5. Cost of investment.
 - a. Additional compressor (1300 Horsepower)
 - b. Waterjet cutter (approx. £80k)
 - c. Additional extras such as guarding
 - d. IGEMS software (approx. £6k)
 - e. Additional Automation Options (programs)
 - f. Clamping

Conclusion

There were several aims of this project. The primary purpose was to determine whether or not surface quality of steel tensile test specimens had an effect on the mechanical properties. The elements of this included;

- to determine at what level of surface deterioration did an effect occur.
- to determine if different types of material behaved in the same way in relation to varying surface finishes produced.

The secondary aim was to compare milling with the waterjet cutting method of preparing tensile test specimens, measuring results in terms of surface finish and mechanical properties.

Two operator influenced parameters of milling were investigated; tool wear and packing gauge. The hypothesis expected that these parameters would produce a deteriorating surface finish, predominantly affecting elongation and R-value.

The results showed a significant drop in elongation for both materials tested. However little effect was observed for R-value, which remained consistent until elongation had dropped significantly, thus appeared to be a function of this rather than the surface itself.

The results conclude that there is a link between surface finish and the mechanical properties achieved when tested. Furthermore, the graphs generated for surface roughness and elongation show a correlation, when comparing the shape and trend.

The softer DX57 material was affected to a higher degree than DP800. Softer material is in practice more difficult to machine; it can stick to the tool and leave poorer surface finish. Machining of harder materials removes material more effectively and cleanly and achieves a better surface finish, which could explain the higher roughness average values for DX57.

The tool wear trial concluded that the optimum time to replace a tool is at 0.3mm of wear, as there was no effect to properties until beyond this point. If a tool is worn beyond 0.3mm an increase in tensile test failures may be expected, primarily for elongation. The results also show that there is no benefit in replacing a tool prematurely. An inspection of random used tools in the laboratory showed wear considerably below the 0.3mm recommended limit, probably caused by prudent behaviours in attempt to prevent quality issues. There may be a cost saving as a result of eliminating premature tool replacement, however this may be offset against the cost of tools that will no longer remain in service for longer periods of time being worn beyond 0.3mm.

Similar effects were observed on the mechanical properties in the packing trial, although the use of thin packing did not affect the properties or surface finish to the extent of a worn tool. The trial was limited to only two gauges of packing. The trial concludes that 5mm packing performed best, and that it would be prudent to insist packing of 5mm thickness be mandatory, which is widely available through scrap material, requiring no investment.

The effects of edge defects, by use of SEM analysis, suggest that premature or irregular fracture propagates from these cracks. This may explain the phenomenon noted by Product Specialist Kate Watts, where DP800 samples are found to break on or outside of gauge length occasionally.

The third trial compared the current method of milling with preparing tensile test specimens by waterjet cutting. Many methods of material removal exist, but often inflict a heat affected zone into the material which is unacceptable for tensile testing according to the testing standard. Waterjet is a cold cutting process. The mechanical property results were far below the level that would be acceptable at the laboratory, particularly for the DX57 material. Properties that has been unaffected during the other trials, such as yield also started to become affected.

This particular project would conclude that the method of waterjet cutting would not be a suitable method for preparing samples for tensile testing.

That being said it is noted that waterjet cutting is used successfully in many engineering applications, and is growing in popularity. Other literature supported waterjet cutting as an appropriate alternative to milling when preparing tensile test specimens. It may be that the use of an art and design based waterjet cutter in a non-profit organisation are the cause of unacceptable results, and that further investigation into this field using an engineering based waterjet equipment may be beneficial.

Due to the results, other aspects of waterjet cutting were not investigated extensively, although this would be required if pursued further. It should be noted that waterjet cutting is however unfamiliar ground, and would not only require a hefty initial investment, but extensive investigation and research work before implementation could be considered, due to the risk and impact on testing and steel production if problems were encountered. It is more realistic and feasible to pursue improvements to current milling practices, by implementing relatively low cost solutions discussed in the recommendations of this project.

The data gathered and observations made throughout the project identified that there are a several contributory factors responsible, alone or in combination, for poor surface finish of milled tensile specimens;

1. excessive tool wear
2. insufficient packing gauge
3. excessive axial forces due to tool helix angle
4. insufficient clamping of the length of the specimen

The recommendations to reduce or eliminate these is discussed later on.

The level of acceptable variation of 5% used in this trial may not have been set tightly enough, as results below the 5% threshold statistically proved significant change. This should be considered for further works. It may also be the case that 5% of variation is not acceptable in terms of laboratory testing due to the already tight tolerances of product specifications, and a 5% step change in any product properties due to implementation of a change would not be accepted. It should also be noted that the sample selection in this trial was small, and where further trial work may be pursued larger amounts of data over a prolonged timescale may present higher accuracy.

Although this trial was limited to two types of material they can be considered as representative of a broader product range. The surface finish achieved for the optimum conditions of this trial were very similar for both materials, but showed some different effects to surface finish when subject to different variables, portraying the different behaviours of differing materials. It may be possible to predict the possible effects on many similar materials based on the results obtained through this trial. However there may be little benefit to this, as any improvements made to milling as a result of this trial would affect the whole product range, all being prepared by the same method.

When concentrating on milling improvements, it is shown that elongation is the primary property affected, which is directly linked deteriorating surface finish produced by an exceedingly worn tool and use of insufficient gauge of packing material. All material that had an affected R-value, also had a more significant effect to elongation. No R-value changes were observed where there had been no effect to elongation. What this means in practice is that where an effect may be encountered for both properties, in these instances the material would fail primarily for elongation, based on the evidence in this trial. Due to this it would be expected that there can be no R-value failures that are caused by milling surface finish.

From this it can be concluded that the cost of elongation failures calculated earlier on in this project, a portion of which can be attributed to surface defects induced by the poor milling practices investigated here, is the potential cost saving of implementing a successful recommendation. The cost of R-value calculated earlier cannot be reliably attributed to this cause and is therefore dismissed. Therefore the possible cost saving of this project is £57,465 annually.

There may also be significant cost saving attached to the protection of reputation, with the reduction or elimination of quality issues that may reach the customer.

To summarise the main conclusions;

- Elongation is the primary mechanical property affected when the edge finish of a tensile test specimen deteriorates.
- Metallography results link poor surface finish to premature and irregular fracture.
- Tool wear is acceptable until a level of wear of 0.3mm has been surpassed, as the mechanical properties are unaffected until this point. Tools should be replaced at 0.3mm of wear.
- DX57 was affected to a higher extent than DP800 in all of the trials, although the effects on both materials were significant.
- Use of insufficient packing gauge (2mm) was shown to affect the surface quality and the tensile test results detrimentally.
- A packing gauge of 5mm produced the best results.
- A packing gauge of 5mm produced the best results.
- The milling machine clamping system and tooling helix angle could be improved and may be contributing to surface quality issues.
- Waterjet results in this trial were not acceptable as the results were affected adversely to a high degree.
- Resolution of the problems highlighted in this project would result in an estimated annual cost saving of £57,465

Final Timeline

This project was more extensive than originally expected, in terms of the level of research and interaction with other industries, companies and colleagues. Tasks and deadlines had to be amended throughout, particularly due to a reliance on the external resources of waterjet cutting and WLI testing. The final timeline details the order in which events occurred to complete the project. Progress was documented during the supervision meetings, which are listed in the appendices (appendix 6, 7 and 8).

<i>Week Number</i>	<i>Task Description</i>
42	Determine main project sections.
43	Write project plan and timelines. Meet with mentor. Obtain research material.
44	Source and prepare material for testing. Organise trials required. Write introduction. Arrange to meet milling technicians
45	Write contents page. Complete trial for broken ends. Complete trial for milling tips. Write one section
46	Write about milling. Arrange to meet Kelvin next week.
47	Prepare material. Organise meeting Richard Morgan to discuss milling. Contact Sandvik
48	Meet Kelvin. Meet Richard. Write one section. Complete tests good v bad milling. Meet milling technicians-on hold
49	Arrange to meet water cutting in new year. Meet guy about surface roughness machine. Contact coolant supplier, or manufacturer. Speak to Gareth Staddon to solve measuring surface roughness problem
50	Prepare Slides for Oral Exam. Extra- meeting with Kelvin Lake. Speak to Gareth Staddon – couldn't find last week.
51	Oral Exam. Don't forget to add 2 week delay to get assignments done and out the way
52	Prepare plan for trials
1	Write section. Arrange Sandvik Visit
2	Meet with water cutting. moved
3	Begin section on water cutting
4	Break for exam. Organise Andrew Wilkes from Sandvik meeting. Find solution for surface roughness testing
5	Prepare samples using waterjet cutter. Meet Andrew Wilkes
6	Meet with Tom Taylor to organise WLI at Swansea University
7	Break for exam. Meet with Brother Engineering – confirm milling set up using software
8	Decide on analysis tools/technique. Complete trials by preparing samples - milling
9	Begin analysing data. Test retained samples (not gone for WLI), start to assess data
10	Write waterjet cutting, surface roughness and WLI theory. Write theory on crack propagation
11	Collect waterjet samples at end of week if ready
12	Use SEM to analyse samples before tensile testing
13	Obtain quotes for recommendations. 3 days off work to do analysis of data, conclusion and recommendations. Phoned precision waterjet for quote on cutting samples
14	Illness
15	Illness
16	Illness
17	Review Dissertation, spelling, references and layout. Finalise results. Complete metallography of samples in report
18	Submit Final Dissertation
19	Final Oral Preparation
20	Final Oral Exam

FIGURE 99 FINAL PROJECT PLAN

11. Improve

This section will include

- Recommendations for improvement

Recommendations for Improvement

There are several options proposed for the consideration of Tata Steel.

Payback period is estimated using the annual cost of elongation failures calculated in the costings section of this report of £57,465 and it is assumed that implementation of each option is successful.

A payoff matrix, as shown in figure 100, is applied to score each recommendation on a benefit versus effort basis. The ideal score would be 3, reflecting a low effort solution with maximum benefit.

Benefit	High		
		3	2
Low		2	1
		Low	High
		Effort	

FIGURE 100 PAYOFF MATRIX TEMPLATE FOR SCORING COST VERSUS BENEFIT FOR IMPLEMENTATION OF A PROJECT, WITH 3 BEING THE IDEAL SCORE.

It is recommended at this time that it is more beneficial to pursue improvements to the current milling machines, being relatively new at two years old, at approximately £80k of capital investment. The current milling operation has been affected by operator influenced factors, which has effected quality. This project has shown that the milling machines are capable of producing high quality specimens, with some equipment improvements and/or reducing the effects of the operator induced variation.

Any recommendations that are opted for will require the necessary updates made to current safe working procedures (SWP) and work instructions, and be updated in the control plan for the current FMEA.

Tool Wear

Option 1 – Eye Glass

A magnifying glass with an LED light and rule was used to measure tool wear during this trial. This would be the most inexpensive option for measuring tool wear.

Operator interpretation may result in varied readings, and there is a possibility that measurements may be misjudged, or missed altogether, due to the busy working environment.

The procedure for machining should include a section on tool changing detailing the set intervals for tool assessment using the eye glass, and the level of wear (0.3mm) it should be replaced. Operators should sign off against the amended procedure.

The eye glasses should be included in the local stock control system to ensure a level of spares are available. A usage of one eye glass per month should be expected, due to wear and tear in a machine shop environment. Wearing of the scale due to extended use of the eye glass during this trial was noted, which would prevent the operator from reading the level of tool wear. Minimum and maximum stock levels of 2 and 3 respectively would be recommended.

This method for tool wear measurement relies on the operator performing frequent checks and may not be as reliable or beneficial as other options.

The cost of an eye glass - £9.95 x 12 months

Annual cost required for implementation: £119.40

Payback period: <1 week

Payback matrix score: 2

Benefit	High	3	2
	Low	2 	1
		Low	High
		Effort	

FIGURE 101 PAYOFF MATRIX FOR TOOL WEAR RECOMMENDATION OPTION 1.

Option 2 – Timers

A counter can be installed within the Fanuc programming control system to monitor the number of boxes milled. When a predetermined number is reached, a warning message will instruct the operator that a tool change is due. The machine will be disabled until the tool is changed, thus there is confidence that the tools will be replaced when they should be. The set-up of this is straight forward.

This trial determined that 33 boxes were milled in order to reach 0.3mm of wear. The Actual level of wear may vary slightly, as the measurement is number of cycles not the tool wear itself, although this is expected to be minimal. Further trials could validate the number of boxes to be counted, and variation analysed to check if it is within levels that are acceptable.

Implementation of this system would result in a possible cost saving in tool cost by avoiding premature tool changes, however this may be offset against tools that are often worn beyond 0.3mm and should have been changed sooner.

The real saving is in much improved sample quality, and reduced failures due to milling defects.

Investment required for implementation: £2,400

Payback period: 2-3 weeks

Payback matrix score: 3

Benefit	High	3 X	2
	Low	2	1
		Low	High
		Effort	

FIGURE 102 PAYOFF MATRIX FOR TOOL WEAR TRIAL RECOMMENDATION OPTION 2.

Option 3 – Tool Wear Probe

Renishaw Ltd are a company that produce machine tool probes for various purposes such as tool setting and detecting tool breakage and wear. These are ideal for automated milling systems.

Installation of a probe that measures the finished piece with such precision it can detect levels of tool wear in microns. Installation of these devices would indicate the precise moment a tool reaches 0.3mm of wear and should be changed.

Depending on intervals that the probe is set to take measurements, this could increase cycle time slightly.

As with Option 2, implementation of Option 3 result in a possible cost saving in tool cost by avoiding premature tool replacement, however this may be offset. The system would have a higher level of accuracy than option 1 and 2. As with option 2, the machine would be disabled until the tool is replaced.

The real saving is in much improved sample quality, and reduced failures due to milling defects.

Investment required for implementation: £46,865

Payback period: 43 weeks

Payback matrix score: 3

Benefit	High	3 X	2
	Low	2	1
		Low	High
		Effort	

FIGURE 103 PAYOFF MATRIX FOR TOOL WEAR TRIAL RECOMMENDATION OPTION 3.

Packing

Option 1. Determine Optimum Packing Gauge

It has been determined that the gauge of packing influences the tested mechanical properties through poor surface finish.

Further trials involving a range of gauges at smaller intervals would determine the minimum gauge at which the mechanical properties start to deteriorate. A range of packing gauges between 2-5mm should be included to determine the gauge at which the properties become affected, and make a prudent choice to select packing that is from the comfortable range and not at the boundary where the change occurs. The 5mm gauge used in this trial produced consistent results which may imply some safety.

Surface roughness testing may again prove difficult or costly, and as the tensile test results are the primary measure of performance the surface roughness testing is not essential.

TABLE 45 TRIAL DESIGN FOR FURTHER INVESTIGATION INTO PACKING MATERIAL		
Packing Gauge	DP800	DX57
2mm	WJ01, WJ02, WJ03	WJ10, WJ11, WJ12
3mm	DP01, DP02, DP03	DX01, DX02, DX03
4mm	DP06, DP07, DP08	DX06, DX07, DX08
5mm	DP11, DP12, DP13	DX11, DX12, DX13

A trial design suggested in table 45 would be suitable. This material is readily available from Central Stores as sheet retained for standard reference material with no cost attached. The stock details are;

Stock Number 80133342 Description SAMPLE BANK:0.8X1470X1500MM,M89835030,DX57

Stock Number 80120109 Description SAMPLE BANK:DP800-1.2X1380X1000,4487501

There are no cost implications for obtaining differing packing material as it is obtained from scrap material. Used packing material is also returned to recycling, so scrap volumes will not be affected detrimentally. The working procedures require updating to include selection of packing material.

Investment required for implementation: £0

Payback matrix score: 2

Benefit	High	3	2
	Low	2	1
		Low	High
		Effort	

FIGURE 104 PAYOFF MATRIX FOR PACKING TRIAL RECOMMENDATION OPTION 1.

Option 2. Design New Fixtures

It is possible that thick packing is required to compensate for ineffective clamping in the milling machines. An upgrade to clamping fixture should improve this situation. Quotations have been obtained for a fixed hardened steel clamp that offers support across the entire length of the material to be milled, as suggested by an illustration in figure 74. Brother Engineering returned the most competitive quotation at £675 per vice. This solution would be more effective than option 1, as it is not operator reliant, and use of the fixed clamp cannot be avoided.

£675 per vice x 8 vices (4 per machine)

Investment required for implementation: £5,400

Payback period: 6 weeks

Payback matrix score: 3

Benefit	High	3 X	2
	Low	2	1
		Low	High
		Effort	

FIGURE 105 PAYOFF MATRIX FOR PACKING TRIAL RECOMMENDATION OPTION 2.

Option 3. Reduce Axial forces

Reducing axial forces in milling would result in a decrease the phenomenon of the “pulling apart” of stacked material, and should therefore reduce the creation of burrs. However, the radial forces would increase and may present other issues. Further work is required to compare a 30° helix tool with the current 45° tool. Time limitations prevented further investigation during this project. This trial is time consuming and requires effort.

The prices of these tools with the approved vendor of machining consumables are;

Cost of 30°cutter £99.40 (IP231-1600-XA 1630 Carbide End Mill)

Cost of 45° cutter £100.10 (CUTTER-END MILL:1P330-1600-XA,16MM,92MM)

Reduction in price is £0.70 per tool.

It is recommended that the purchase of three tools would be sufficient for the trial. The 45° cutter are available at the laboratory as they are set up as stock.

Newer milling technology combines alternating angles of cutting surfaces in a variable helix angle cutting tool. A variable flute of 37°and 40° is designed to reduce vibration. This would be a more expensive trial and higher ongoing cost if implemented, with tooling price increasing to £153.75 per tool. This would not be recommended at this point, unless other options were unsuccessful, due to the 50% price increase and effort involved.

Implementation of other options are advised to be considered before pursuing this further.

Investment required for trial: £298.20

Payback period: <1 week

Annual saving of tooling if successful: £187.60 (based on annual use of 268 tools)

Payback matrix score: 2

Benefit	High	3	2 
	Low	2	1
		Low	High
		Effort	

FIGURE 106 PAYOFF MATRIX FOR PACKING TRIAL RECOMMENDATION OPTION 3.

Waterjet Cutting

No confident recommendations for investment into waterjet cutting technology can be made as an outcome of this project due to the results obtained. Extensive further work would be required with a large amount of data to support a change in cutting method, of which absolute confidence is necessary. Furthermore, a detailed cost analysis and risk assessment case should be developed if further trials prove successful.

Option 1. Further Testing

It is recommended that an engineering based waterjet cutting facility perform further testing. Precision Waterjet Ltd have experience in producing tensile test specimens, particularly for the oil and gas industries. A quotation for preparation of ten dual phase and ten interstitial free steel, including return carriage has been obtained. If results are successful, a substantial amount of work would still be required and only if waterjet cutting was implemented as an improved method would any real benefit be realised.

Investment required for further work: £119.40

Payback period: N/A - further analysis

Payback matrix score : 2

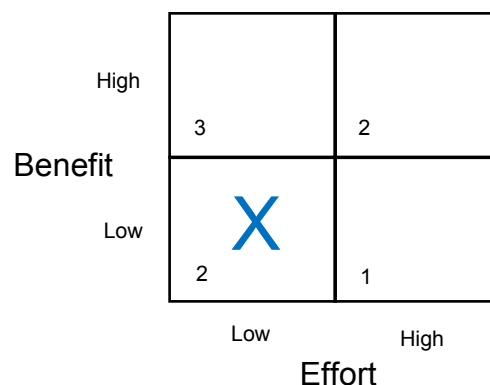


FIGURE 107 PAYBACK MATRIX FOR WATERJET TRIAL RECOMMENDATION OPTION 1.

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15. Appendices

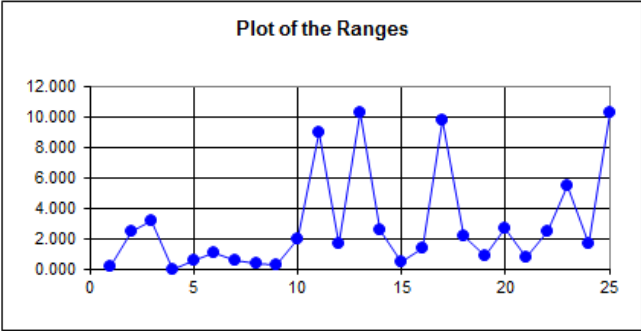
Appendix 1 – Raw Data for DP800

Coil ID	Ra	Rp0.2	UTS	A	r10
DP01	1.18	504.1	852.9	17.34	0.682
DP02	1.73	501.2	854.6	17.23	0.632
DP03	1.48	500.9	853.9	16.65	0.641
DP04		504.3	855.2	17.72	0.619
DP05		502.5	856.9	17.4	0.627
DP06	1.14	506.7	858.1	16.79	0.656
DP07	1.54	499.6	851.2	16.34	0.653
DP08	1.72	496.7	848.6	17.2	0.641
DP09		497.1	850.8	17.2	0.662
DP10		500.4	854.1	17.42	0.642
DP11	1.18	503.1	851.2	17.61	0.668
DP12	1.86	504.1	849.6	16.87	0.631
DP13	1.74	506.7	857	17.39	0.677
DP14		502.5	857.5	18.04	0.67
DP15		496.6	848.5	17.37	0.689
DP16	3.34	502.1	859.2	10.21	0
DP17	2.98	506.1	853.1	8.12	0
DP18	3.65	502.1	856.2	10.97	0
DP19		504.8	856.6	11.28	0
DP20		505.2	854.1	6.74	0
DP21	1.51	502.5	849.1	16.31	0.642
DP22	1.63	504.6	856.1	16.43	0.651
DP23	1.28	503.8	855.4	15.98	0.653
DP24		501	850.3	15.42	0.641
DP25		501.7	849.9	16.76	0.651
WJ01	4.92	496.5	844	14.76	0.67
WJ02	6.33	499.4	844.6	13.21	0.682
WJ03	5.42	501.5	843	12.76	0.691
WJ04		497.2	840.1	13.65	0.796
WJ05		498.5	843.6	14.2	0.673

Appendix 2 – Raw Data for DX57

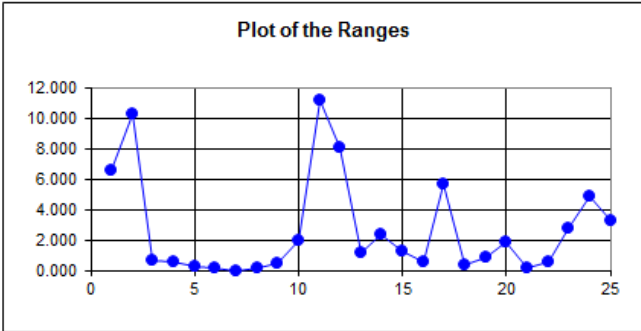
Coil ID	Ra	Rp0.2	UTS	A	r10
DX01	1.18	150.4	304.9	43.2	2.437
DX02	1.73	152.1	305.2	39.5	2.387
DX03	1.48	154.2	301.6	40.1	2.354
DX04		150.9	304.1	41.33	2.452
DX05		149.4	300.9	41.93	2.377
DX06	1.14	154	306.1	37.48	2.426
DX07	1.54	152.2	304.3	39.07	2.379
DX08	1.72	152.2	302.1	41.53	2.318
DX09		152.8	304.3	41.55	2.39
DX10		154.6	304.9	39.2	2.545
DX11	1.18	151.9	302.6	42.5	2.435
DX12	1.86	151.5	305.1	37.5	2.351
DX13	1.74	154	304.1	39.2	2.342
DX14		157.4	306.9	40.34	2.312
DX15		151.3	301.8	38.1	2.423
DX16	3.34	154.1	306.1	24.2	2.412
DX17	2.98	152.8	302.4	19.8	2.135
DX18	3.65	154.6	307.4	25.6	2.259
DX19		149.4	302.1	23.2	2.354
DX20		154	307.8	19.2	2.211
DX21	1.51	151.28	301.5	38.32	2.452
DX22	1.63	151.28	303.4	37.8	2.398
DX23	1.28	151.28	304.2	35.65	2.406
DX24		151.28	301.9	37.98	2.378
DX25		151.28	302.7	38.65	2.404
WJ11	4.92	145.2	300.8	6.54	2.874
WJ12	6.33	146.5	300.9	11.4	2.75
WJ13	5.42	144.5	300.2	2.7	2.984
WJ14		145.5	300.4	8.54	2.882
WJ15		144.7	301.5	4.6	2.736

Appendix 3 – MSA Study for Yield Strength Measurement

SP-UK	Measurement Capability Procedure 3 (Gauge R&R) No Operator Influence								
Measuring Equipment:		Characteristic:							
Gauge Location:	Test House	Measured Part: Range of Production parts							
Gauge Description:	Tensile Test Machine	Drawing No.: n/a							
Gauge Number:	Instron 2	Characteristic: Proof 2%							
Gauge Resolution:	0.001	Nominal value: n/a							
		<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td>Total Tolerance:</td> <td></td> <td>Mpa</td> <td rowspan="2" style="text-align: center; vertical-align: middle;">%GRR RESULT IN BLUE IS ONLY CONSIDERED.</td> </tr> <tr> <td></td> <td>Total Tolerance</td> <td>Unit</td> </tr> </table>	Total Tolerance:		Mpa	%GRR RESULT IN BLUE IS ONLY CONSIDERED.		Total Tolerance	Unit
Total Tolerance:		Mpa	%GRR RESULT IN BLUE IS ONLY CONSIDERED.						
	Total Tolerance	Unit							
Measurement Procedure									
Result of Procedure 1:									
Record No.:	Sheet:	Date: Cg = Cgk =							
Table values in: Mpa Deviation from: N/A									
Obj. No.	Series 1	Series 2	Mean Xi bar	Range Ri	Plot of the Ranges 				
1	348.700	348.900	348.800	0.200					
2	351.100	348.600	349.850	2.500					
3	368.300	365.100	366.700	3.200					
4	425.400	425.400	425.400	0.000					
5	389.400	390.000	389.700	0.600					
6	241.400	240.300	240.850	1.100					
7	230.200	229.600	229.900	0.600					
8	145.700	146.100	145.900	0.400					
9	147.000	147.300	147.150	0.300					
10	385.300	387.300	386.300	2.000					
11	366.200	357.200	361.700	9.000					
12	351.800	350.100	350.950	1.700					
13	345.200	355.500	350.350	10.300					
14	360.000	362.600	361.300	2.600					
15	510.200	510.700	510.450	0.500					
16	352.200	353.600	352.900	1.400					
17	365.500	375.300	370.400	9.800					
18	256.600	258.800	257.700	2.200					
19	293.800	292.900	293.350	0.900					
20	370.000	367.300	368.650	2.700					
21	324.000	324.800	324.400	0.800					
22	268.400	270.900	269.650	2.500					
23	350.100	344.600	347.350	5.500					
24	381.100	379.400	380.250	1.700					
25	459.900	470.200	465.050	10.300					
R _p		364.550							
<table style="width: 100%;"> <tr> <td style="width: 33%;"> %GRR %GRR = 100[GRR/TV] = 2.57 % </td> <td style="width: 33%;"> %GRR %GRR = (EV / TOL) 100 = #VALUE! % </td> <td style="width: 33%;"> ndc (number of distinct categories) = 54 </td> </tr> </table>						%GRR %GRR = 100[GRR/TV] = 2.57 %	%GRR %GRR = (EV / TOL) 100 = #VALUE! %	ndc (number of distinct categories) = 54	
%GRR %GRR = 100[GRR/TV] = 2.57 %	%GRR %GRR = (EV / TOL) 100 = #VALUE! %	ndc (number of distinct categories) = 54							
<table style="width: 100%;"> <tr> <td style="width: 33%; text-align: center;"> %GRR ≤ 10 % X Acceptable </td> <td style="width: 33%; text-align: center;"> 10% < %GRR ≤ 30 % May be Acceptable </td> <td style="width: 33%; text-align: center;"> %GRR > 30 % Measurement System needs Improvement </td> </tr> </table>						%GRR ≤ 10 % X Acceptable	10% < %GRR ≤ 30 % May be Acceptable	%GRR > 30 % Measurement System needs Improvement	
%GRR ≤ 10 % X Acceptable	10% < %GRR ≤ 30 % May be Acceptable	%GRR > 30 % Measurement System needs Improvement							
Remarks:									
Date:		Department:		Signature: (Electronic)					

Appendix 4 – MSA Study for UTS Measurement

SP-UK	Measurement Capability Procedure 3 (Gauge R&R) No Operator Influence			
Measuring Equipment:		Characteristic:		
Gauge Location:	Test House	Measured Part:		
Gauge Description:	Tensile Test Machine	Range of Production parts:		
Gauge Number:	Instron 2	Drawing No.:		
Gauge Resolution:	0.1	Characteristic:		
		Ultimate Tensile Strength of material		
		Nominal value:		
		Total Tolerance:		
		Mpa		
		Unit		
%GRR RESULT IN BLUE IS ONLY CONSIDERED.				
Measurement Procedure				
Result of Procedure 1:				
Record No.:	Sheet:	Date:		
		Cg =		
		Cgk =		
Table values in: Mpa Deviation from: N/A				
Obj. No.	Series 1	Series 2	Mean Xi bar	Range Ri
1	619.700	613.100	616.400	6.600
2	632.100	621.800	626.950	10.300
3	651.700	651.000	651.350	0.700
4	532.000	532.600	532.300	0.600
5	501.000	500.700	500.850	0.300
6	350.500	350.300	350.400	0.200
7	345.500	345.500	345.500	0.000
8	290.700	290.500	290.600	0.200
9	291.800	291.300	291.550	0.500
10	587.500	589.500	588.500	2.000
11	471.000	459.800	465.400	11.200
12	472.400	464.300	468.350	8.100
13	471.200	470.000	470.600	1.200
14	474.700	477.100	475.900	2.400
15	606.300	607.600	606.950	1.300
16	460.200	460.800	460.500	0.600
17	486.100	491.800	488.950	5.700
18	404.500	404.900	404.700	0.400
19	410.200	411.100	410.650	0.900
20	448.800	450.700	449.750	1.900
21	485.600	485.800	485.700	0.200
22	397.800	398.400	398.100	0.600
23	477.600	480.400	479.000	2.800
24	502.400	497.500	499.950	4.900
25	525.300	528.600	526.950	3.300
R_p		<u>360.750</u>		



Plot of the Ranges

Evaluation:

Mean Range R bar = 2.5522 Mpa

Equipment Variation (EV) $K_1 = 0,886$
 $EV = R \text{ bar} * K_1 = 2.2617 \text{ Mpa}$

Part Variation (PV) $K_2 = 0,250$
 $PV = R_p * K_2 = 90.1875 \text{ Mpa}$

Repeatability and Reproducibility (GRR)
 $GRR = \sqrt{EV^2} = 2.2617$

Total Variation (TV)
 $TV = \sqrt{GRR^2 + PV^2} = 90.2159$

%GRR $\%GRR = 100[GRR/TV] = 2.51 \%$

%GRR $\%GRR = (EV / TOL) 100 = \#VALUE! \%$

ndc (number of distinct categories) = 56

$\%GRR \leq 10 \%$ X

Acceptable

$10\% < \%GRR \leq 30 \%$

May be Acceptable

$\%GRR > 30 \%$

Measurement System needs Improvement

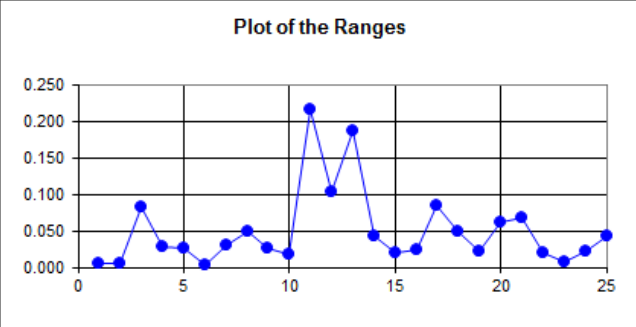
Remarks:

Date:

Department:

Signature:
(Electronic)

Appendix 5 – MSA Study for R-value Measurement

SP-UK	Measurement Capability Procedure 3 (Gauge R&R) No Operator Influence				
Measuring Equipment:		Characteristic:			
Gauge Location:	Test House	Measured Part: Range of Production parts			
Gauge Description:	Tensile Test Machine	Drawing No.: n/a			
Gauge Number:	Instron 2	Characteristic: R-value of material			
Gauge Resolution:	0.001	Nominal value: n/a			
		Total Tolerance: Total Tolerance Unit %GRR RESULT IN BLUE IS ONLY CONSIDERED.			
Measurement: Procedure					
Result of Procedure 1:					
Record No.:	Sheet:	Date: Cg = Cgk =			
Table values in: 0.000 Deviation from: N/A					
Obj. No.	Series 1	Series 2	Mean $\bar{X}_i$	Range R_i	Plot of the Ranges 
1	0.813	0.819	0.816	0.006	
2	0.817	0.823	0.820	0.006	
3	0.986	1.068	1.027	0.082	
4	1.040	1.011	1.026	0.029	
5	1.038	1.011	1.025	0.027	
6	1.942	1.939	1.941	0.003	
7	2.016	1.985	2.001	0.031	
8	2.497	2.447	2.472	0.050	
9	2.381	2.408	2.395	0.027	
10	0.703	0.720	0.712	0.017	
11	0.428	0.644	0.536	0.216	
12	0.544	0.647	0.596	0.103	
13	0.588	0.775	0.682	0.187	
14	0.689	0.731	0.710	0.042	
15	0.587	0.606	0.597	0.019	
16	0.660	0.637	0.649	0.023	
17	0.566	0.651	0.609	0.085	
18	0.982	0.933	0.958	0.049	
19	0.867	0.889	0.878	0.022	
20	0.921	0.983	0.952	0.062	
21	0.855	0.787	0.821	0.068	
22	0.810	0.830	0.820	0.020	
23	0.769	0.777	0.773	0.008	
24	0.732	0.710	0.721	0.022	
25	0.709	0.751	0.730	0.042	
$R_p = 1.936$					Evaluation:
					Mean Range R bar = 0.0514 0
					Equipment Variation (EV) $K_1 = 0.886$
					EV = R bar * K1 = 0.0455 0
					Part Variation (PV) $K_2 = 0.250$
					PV = R _p * K3 = 0.4840 0
					Repeatability and Reproducibility (GRR)
					$GRR = \sqrt{EV^2}$ = 0.0455
					Total Variation (TV)
					$TV = \sqrt{GRR^2 + PV^2}$ = 0.4861
					%GRR $\%GRR = 100[GRR/TV]$ = 9.37 %
					%GRR $\%GRR = (EV / TOL) 100$ = #VALUE! %
					ndc (number of distinct categories) = 14
%GRR ≤ 10 % X Acceptable 10% < %GRR ≤ 30 % May be Acceptable %GRR > 30 % Measurement System needs Improvement					
Remarks:					
Date:		Department:		Signature: (Electronic)	

Appendix 6 – Supervision Form for 21.10.16



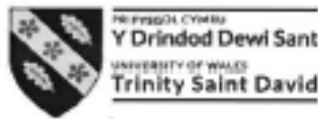
Supervision Form	
MODULE: Dissertation (M6X00417)	
ASSIGNMENT: The influence of edge quality on tensile test specimens at tata	
STUDENT: Terry-Louise Betambeau	SUPERVISOR: Kelvin Lake
DATE: 21/10/16	Length: 1hr
Objective of the meeting	
To establish the aims/objectives of the project	
Work Submitted by the student	
None	
Issues discussed at the meeting	
- Currently high levels of automotive grade steel (bake hardening, TP800, DX37) are being downgraded. - quantify the cost. How much is being downgraded? What is the cost of this? (reduction in value, rework etc) - what is the cost of machining? How often are tip replaced? can this be monitored during this project? - speak to tip manufacturer. Is this the correct tip? how often should it be replaced? - take a sample where tests that have failed can be examined to see if this failure is due to edge quality. (use microscopes?) - can some samples be cut on the waterjet cutter? speak to Shelley Doonan. What other cutting techniques could be used - speak to Andrew Tibbot. - samples to be tested in longitudinal or transverse direction? - variability of the samples? - apply 6 sigma to the methodology? - research the theory of machining - see Groover and speak to Richard Morgan.	
Student action BEFORE next meeting	
- as above	
Date of next meeting: TBC	
Signed (Student):	
Signed (Supervisor):	

Appendix 7 – Supervision Form for 16.12.2016



Supervision Form	
MODULE: Dissertation (M6X00417)	
ASSIGNMENT: The influence of edge quality on tensile test specimens at tata	
STUDENT: Terry-Louise Betambeau	SUPERVISOR: Kelvin Lake
DATE: 16/12/16	Length: 1hr
Objective of the meeting	
To establish the aims/objectives of the project	
Work Submitted by the student	
None	
Issues discussed at the meeting	
- quantify the cost - ongoing. How much is being downgraded? What is the cost of this? (reduction in value, rework etc) - tip manufacturer coming in in the new year to discuss tips used. - machine code to be changed in the new year to adjust feed/speed rates - samples that have been tested have been inspected for edge quality by eye. - samples to be cut on the waterjet cutter. - samples to be tested in longitudinal or transverse direction. This is specified by the customer. - apply 6 sigma to the methodology? - speak to AT. - viva and report structure.	
Student action BEFORE next meeting	
- as above	
Date of next meeting: TBC	
Signed (Student): 	
Signed (Supervisor): 	

Appendix 8 – Supervision Form for 17.02.2017



Supervision Form	
MODULE: Dissertation (M6X00417)	
ASSIGNMENT: The influence of edge quality on tensile test specimens at tata	
STUDENT: Terry-Louise Betambeau	SUPERVISOR: Kelvin Lake
DATE: 17/02/17	Length: 40 mins
Objective of the meeting	
To establish the aims/objectives of the project	
Work Submitted by the student	
None	
Issues discussed at the meeting	
- costing meeting held with finance manager and costings understood - this is to be calculated for last year etc. - Tip manufacturer has reviewed the process and is happy that speed/feeds etc are ok. Potentially the packing of the samples before they are milled is an issue. Can this be investigated. - White light interferometry to be used at swansea uni through a tata eng doc student to measure surface roughness. Plan B? Speak to Peter Charlton (peter.charlton@uwtsd.ac.uk) to see if there is anything else that could be used. - Waterjet samples have been cut - initial thoughts are that these have a worse surface finish. - six sigma methodology to be used? speak to andrew thorn. - tool forces to be 'recommended future work'?	
Student action BEFORE next meeting	
- as above	
Date of next meeting: TBC	
Signed (Student): <i>T. Betambeau</i>	
Signed (Supervisor): <i>K. Lake</i>	

