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An alternative method of supporting refractory anchors inside high temperature rotating kilns using stud welding

Christopher Paul Cobain
University of Wollongong

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**AN ALTERNATIVE METHOD OF SUPPORTING
REFRACTORY ANCHORS INSIDE HIGH TEMPERATURE
ROTATING KILNS USING STUD WELDING**

A dissertation submitted in fulfilment of the requirements for the award of the degree

MASTER OF WELDING ENGINEERING

from

UNIVERSITY OF WOLLONGONG

by

CHRISTOPHER PAUL COBAIN

FACULTY OF ENGINEERING

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ABSTRACT

Rotary kilns fired by coal or gas burners are widely used to process mineral sands to extract pure minerals, most commonly titanium dioxide, (TiO_2), in Western Australia. The kilns vary in size depending on refinery throughput, however most are very large items up to 70 metres long and 6 meters in diameter. The kilns are constructed from carbon manganese structural and pressure vessel plates and welded in the same manner as large pressure vessels, however structural welding standards are applied.

The mineral sands are purified using a pyrometallurgical process where the internal operating temperature reaches approximately 1200°C . These temperatures are outside the operational limits of carbon manganese steel, so a protective internal layer of refractory approximately 250mm thick is required to reduce the shell temperature to between 100°C and 200°C . The refractory is poured in strips along the bottom of the kiln incorporating refractory anchors to stabilise the refractory upon drying. The refractory anchors are 253MA stainless steel, secured to the kiln shell via a welded lug incorporating a slot. This design is referred to as a “rotor lok” assembly.

Failure of the welded lug is relatively common during service, requiring costly kiln shutdown for remedial work and casting new refractory. The failures are mainly attributable to stress concentrations present at the fillet weld toes, with fatigue the failure mechanism in all cases. When failures arise, movement of the refractory lining over time causes a loss of lining where irreversible damage to the kiln shell occurs.

This dissertation researches and discusses alternative methods for securing the 253MA stainless steel refractory anchor to the kiln shell to provide a higher level of serviceability and reliability to prevent costly unexpected refinery shutdown. Over time, total replacement of the refractory is necessary, and renewing the anchor attachments using current methods is time consuming and expensive without consideration to lost production revenue.

Stud welding is proposed as a realistic option for the application of securing the refractory anchor. The author has attempted to persuade operators of rotary kilns that this option is viable, by applying mechanical testing regimes to selected studs which show the stud welded option outperforms the welded lug in all testing applied

DECLARATION

This declaration is to certify that I, Christopher Paul Cobain, being a candidate for the award of Master of Welding Engineering, am aware of the University of Wollongong's regulations and procedures relating to the preparation, submission, retention and use of higher degree dissertations, and the policy on intellectual property.

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I declare the work reported in this dissertation is my own, except where clearly specified and referenced.

I declare this dissertation has not been submitted previously for any degree at other universities or institution.

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This course of study would not have been possible without the encouragement and support offered by my colleague and friend, Mr George Alexander. I am sincerely appreciative for all your support over the last four years.

I would like to express significant gratitude to Mr John Norton of Iluka Resources Limited, for agreeing to move forward with this proposal on refinery rotary kilns, and providing the funds needed to progress the project.

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TABLE OF CONTENTS

Title page.....	i
Abstract.....	ii
Declaration.....	iii
Acknowledgements.....	iv
Table of contents.....	v
Abbreviations.....	viii
Notations.....	ix
List of tables	x
List of figures.....	xi
1 INTRODUCTION	1
1.1 Refractory anchor current practice	2
1.2 Scope of research	4
2 STUD WELDING TECHNOLOGY OVERVIEW	4
2.1 Stud welding options	4
2.2 Welding equipment for the DASW process	6
2.3 Stud materials for welding trials	6
3 APPLICATION TO ROTARY KILNS.....	8
3.1 Weldability and metallurgical considerations	8
3.2 Weld integrity and quality control considerations	8
3.3 Welding Process Limitations	9
4 JOINT WELD STRENGTH & FATIGUE CONSIDERATIONS	10
4.1 Weld strength / load capacity comparisons.....	10
4.2 Weld fatigue considerations	11
4.3 Temperature, stress concentrations and weld quality.....	12
5 STUD WELDING TIMES COMPARISON	15
5.1 DASW welding time estimates	15
5.2 MMAW approximate cost.....	16
5.3 DASW approximate cost.....	16
5.4 Costing conclusion	16
5.5 Safety.....	17

6	STUD WELDING STANDARDS	18
6.1	Australian standard AS/NZS: 1554 Part 2 - 2003	18
6.2	Other relevant standard AWS D1.1 - 2006	19
7	SUMMARY OF FEASIBILITY STUDY	20
8	STUD WELDING COMPARISON TRIAL WELDING	21
8.1	Sample description and evaluation test regime	21
8.2	Macro samples and hardness survey	24
8.3	Tensile testing	24
8.4	Fatigue testing	24
8.5	Discussion	27
8.6	Conclusions	28
8.7	Recommendations	28
9	STUD WELDING QUALIFICATION	29
9.1	Determination of optimum stud welding paramaters	29
9.2	Welding procedure qualification	31
9.3	Base materials	32
9.4	Welded stud samples	33
9.5	Stud traceability information	33
9.6	Samples to qualify the applied welding standards	36
9.7	Additional test regimes	36
9.8	Results of tensile testing and bend samples	36
9.9	Results of hardness testing using Vickers pyramid tester (HV10)	40
9.10	Results of elevated temperature fatigue test	41
9.11	Results of metallography to typical stud weld samples	43
9.12	Conclusions	46
10	FINALISED STUD DESIGN	47
10.1	Option 1 stud design	48
10.2	Option 2 stud design	48
10.3	Proposed test regimes for final stud design	49
11	APPLICATION TO ROTARY KILNS	50
11.1	Welding procedure	50
12	FINITE ELEMENT ANALYSIS MODELS	52
12.1	Geometry and mesh	52
12.2	Material data	53
12.3	Loads and constraints for compression, tensile and bending forces	53

12.4 Results	54
12.5 FEA contour figures	54
Deformation contour figures	55
Equivalent stress figures.....	56
Maximum principle stress figures	57
Minimum principle stress figures.....	58
Safety factor figures	59
Bibliography and list of references.....	60
Appendix 1 – Stress range and load capacity calculations.....	61

ABBREVIATIONS

AISI – American Iron and Steel Institute
ANSYS – Analytical system
AS – Australian Standard
AS/NZS – Australian and New Zealand Standard
ASTM – American Society for testing and materials
AWS – American Welding Society
CDSW – Capacitor discharge stud welding
DASW – Drawn arc stud welding
DCEN – Direct current electrode negative
E – Percentage of elongation
FEA – Finite element analysis
FL – Fusion line.
FSW – Friction stud welding
HAZ – Heat affected zone
HV – Hardness: Vickers pyramid method, (HV10 – 10 kg load)
kN – Kilonewton
kg – Kilogram
MMAW – Manual metal arc welding
MPa – Megapascal
NDE – Non destructive examination
N - Newton
N/mm – Newton / millimetre
OD – Outside diameter
QA / QC – Quality control / Quality assurance
PT – Penetrant test
R of A – Reduction of area
SMYS – Specified minimum yield strength
SN – Stress / Number of cycles
TiO₂ – Titanium Dioxide
TWI – The Welding Institute
UGI – Upgraded Ilmenite
UTS – Ultimate tensile strength
WTIA – Welding Technology Institute of Australia

NOTATIONS

f_{rs} – Uncorrected fatigue strength

β_{tf} – Thickness correction factor

tp – Plate thickness

Φ – Capacity factor

f_{rsc} – Corrected fatigue strength

f^* – Design stress range

F – Force

σ – Stress

A – Area

μm - Micromillimetre

$^{\circ}\text{C}$ - Degrees centigrade

LIST OF TABLES

Table 1 – AS/NZS: 1554 Part 2 - Table 2.1. Minimum stud material properties other than shear connectors

Table 2 – AS: 1443 Table 6 Grade D3 M1020 minimum tensile properties

Table 3 – AS: 4100 load capacity comparisons between welded lugs and stud welds

Table 4 – AS: 4100 fatigue comparisons between welded lugs and stud welds

Table 5 – Results of AS: 1443 Grade D3 M1020 elevated temperature tensile tests

Table 6 – Summary of comparison test values

Table 7 – Summary of tensile tests welded at optimum current

Table 8 – Summary of tensile tests welded 5% below optimum current

Table 9 – Summary of tensile tests welded 5% above optimum current

Table 10 – Summary of bend tests at optimum current

Table 11 – Summary of typical hardness testing within welding current range

Table 12 – Summary of elevated temperature fatigue test parameters

Table 13 – Stud and FEA model statistic

Table 14 – Stud material statistic

Table 15 – Load and Constraint definitions

Table 16 – Constraint reactions

Table 17 – Analysis results – Compression

Table 18 – Analysis results – Tensile

Table 19 – Analysis results – Bending

LIST OF FIGURES

- Figure 1 – Rotor lok anchor arrangement
- Figure 2 – Fillet welded lug using MMAW
- Figure 3 – Nelson 6000 power source
- Figure 4 – Nelson P-NS 20 BHD stud gun
- Figure 5 – Stud samples and ferrules
- Figure 6 – Stud samples showing grade 1100 H16 aluminium flux ball
- Figure 7 and 8 – Preliminary stud weld bend tests
- Figure 9 and 10 – Shell sections demonstrating PT examination
- Figure 11 - Stud weld sample
- Figure 12 - Welded lug, 6mm fillet weld
- Figure 13 – Fatigue testing setup
- Figure 14 -Fatigue testing machine
- Figure 15 - Stud fracture face
- Figure 16 - Stud / shell interface
- Figure 17 - Lug weld fatigue fracture
- Figure 18 - Lug / shell interface
- Figure 19 – Stud macro at higher current and cycle time
- Figure 20 – Stud macro at lower current and cycle time, with modified lift / plunge data
- Figure 21 – Stud macro at optimum current and cycle time
- Figure 22 – Kiln shell section marked out for stud welding
- Figure 23 – Weld zone oxide removal
- Figure 24 – Stud sample test plate during welding
- Figure 25 – Completed test plate
- Figure 26 – Close up of stud sample A6

Figure 27 – Close up of stud sample B6

Figure 28 – Close up of stud sample B8

Figure 29 – Stud sample tensile test setup

Figure 30 / 31 – Typical necking and stud failure

Figure 32 / 33 – Typical bending sample

Figure 34 – Typical macro sample incorporating HV10 survey welded within acceptable parameter ranges

Figure 35 – Elevated fatigue test setup

Figure 36 – Elevated fatigue test sample

Figure 37 – Stud base material micrograph

Figure 38 – Stud HAZ micrograph

Figure 39 – Weld zone micrograph

Figure 40 – Plate HAZ micrograph

Figure 41 – Plate base material micrograph

Figure 42 – Original AS/NZS: 3679 Grade 300 lug design

Figure 43 – Option 1 stud design

Figure 44 – Option 2 stud design

Figure 45 - Deformation compression

Figure 46 - Deformation tension

Figure 47 - Deformation bending

Figure 48 - Equivalent stress: compression

Figure 49 - Equivalent stress: tension

Figure 50 - Equivalent stress: bending

Figure 51 - Maximum principle stress: compression

Figure 52 - Maximum principle stress: tension

Figure 53 - Maximum principle stress: bending

Figure 54 - Minimum principle stress: compression

Figure 55 - Minimum principle stress: tension

Figure 56 - Minimum principle stress: bending

Figure 57 - Safety factor: compression

Figure 58 - Safety factor: tension

Figure 59 - Safety factor: bending

1 INTRODUCTION

As briefly detailed in the abstract, the rotary kilns where this work will be applied are fabricated from AS:1548-7-460R carbon manganese steel and are approximately 70.0 metres long and 6.0 metres in diameter. The kilns are supported and turned by a geared rotation arrangement via an AISI 4140 tyre attached to the shell using a complex assembly of blocks and wedges. These allow expansion of the shell beneath the tyres to ensure constant tyre / rotator contact during thermal cycling and associated dimensional variations.

The kilns are coal fired resulting in an internal operating temperature of approximately 1200°C and rotate at approximately one revolution per minute. The kilns are located at Iluka's mineral separation plant situated approximately 450 kilometres north of Perth in the industrial area of Geraldton, Western Australia. The mineral ilmenite, an iron/titanium oxide, is transported to the refinery to be upgraded to a synthetic rutile mineral, (upgraded ilmenite or UGI), containing between 88% and 95% highly valued titanium dioxide (TiO₂).

Upgrading the ilmenite involves a two stage process. The first pyrometallurgical stage involves heating the mineral within a rotary kiln in the presence of a reductant. This converts the iron oxide impurities within the ilmenite to metallic iron, which is then removed by the second stage of refining treatment. The rotary kilns discharge between 24 to 31 tonnes of reduced ilmenite per hour. The second hydrometallurgical stage involves the removal of metallic iron by oxidation and leaching resulting in upgraded ilmenite.

By incorporating specific additives such as sulphur or hydroboracite during the pyrometallurgical stage and modifying the leaching conditions in the hydrometallurgical stage, three grades of titanium dioxide are produced. Each grade reflects the purity of the titanium dioxide due to removal of different portions of the non-titanium elements from the original ilmenite.

Due to the 1200°C operating temperature inside the rotary kiln to reduce the ilmenite, the shell is protected internally by applying a cast refractory. This reduces the kiln shell temperature beneath the refractory to below 200°C maximum.

1.1 Refractory Anchor Current Practice

The refractory is poured in strips within a mould approximately 1000mm wide and 250mm deep along the bottom of the kiln and allowed to set. Attachment to the kiln shell is achieved using AS/NZS: 3679 Grade 300 mild steel lugs fillet welded using the manual metal arc welding process, AS: 1553 Part 1 E4818 electrodes and welding procedures qualified to AS/NZS:1554 Part 1 SP. The lug incorporated a slotted hole, through which a 253MA stainless steel anchor is supported. This anchor sits within the poured refractory. This arrangement is supplied by Pressform Engineering and is referred to as a “rotor lok” anchor, details are shown in figure 1 and 2 below.

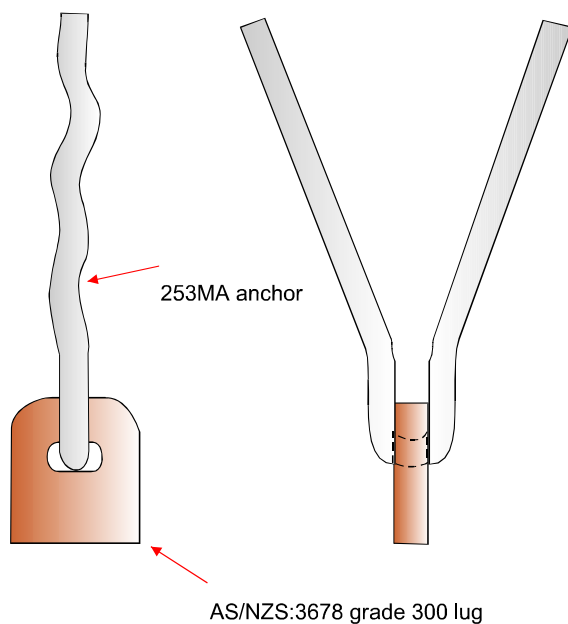


Figure 1 – Rotor lok anchor arrangement

Figure 2 – Fillet welded lug using MMAW

There are approximately 13,000 welded lugs within the kiln, each supporting a 253MA stainless steel anchor. Over a 3 year period of service, degradation of the internal refractory requires the kiln to be shut down and the refractory replaced. The refractory is broken up using hydraulic jack hammers. During this operation, many refractory anchors and welded lugs are damaged beyond repair, so replacement is necessary. In addition, many welded lugs show signs of unacceptable wear within the slotted hole, also requiring replacement.

During service, failure of a welded lug is a common problem, resulting in significant loss of refractory lining and overheating of the kiln shell. Whilst water spray is directed at the kiln shell during service to reduce the shell temperature where refractory failure is present, this occurrence always results in costly shutdown and repair operations. There have also been several occasions where permanent damage to the shell material has transpired, caused by long term exposure to elevated temperature and spheroidising of cementite plates within the pearlite leading to total collapse of the shell material. This is demonstrated by severe full thickness cracks in areas subjected to prolonged elevated temperature exposure in the region of 700°C - 800°C. In these cases, sections of affected shell material are removed and replaced.

The quality of the welded lug is critical to ensure refractory integrity during kiln operation and the welding stage must be strictly controlled. The current welding operations and procedures require a high level of qualification and surveillance activities to ensure acceptable quality on a consistent basis. Moves to apply AS/NZS:1554 Part 5 have been resisted, as the process of welding the lugs inside the kiln shell is already a very expensive exercise, and factors contributing to lug failure including undercut, notches etc, are avoided. The time required to smoothly blend all the fillet welds to comply with the visual acceptance criteria of AS/NZS:1554 Part 5 would greatly contribute to the overall cost during the shutdown period, and based on the weld quality evident on lugs that do not fail during the service period, AS/NZS:1554 Part 5 criteria is deemed unnecessary.

Despite this, applying reliable 100% surveillance / assurance activities to some 13,000 welded lugs is difficult, and the onus is on the welding operator and non destructive testing technician to guarantee weld quality. It is inevitable some undesirable discontinuities are either overlooked or missed entirely during the examination stage. The presence of defects directly contributable to welded lug failure during service is considered high despite the QA / QC regimes applied.

The lug welding stage during kiln shutdown normally takes between 3 to 4 weeks, hence the high costs associated with this work. Based on site observations during a shut down period, the idea of using welded studs to support the refractory anchor appeared logical. The stud welding proposal was presented to Iluka Resources and accepted with enthusiasm, therefore the idea of applying studs was to be investigated and researched with support from Iluka Resources.

1.2 Scope of research

The first stage of research will involve investigating stud welding technology available with regard to refractory anchor attachment, welding of sample coupons for direct comparison to current practices, and considering the advantages and disadvantages of the process compared to current practice, with regard to:

- Technical and practical application of the process to rotary kilns
- Joint integrity and comparison work with regard to weld strength and fatigue factors
- Quality assurance and quality control aspects
- Cost benefit analysis compared to current practices
- Application of national & international stud welding standards

The second stage of research involved qualification of the stud weld in accordance with the latest edition of recognised standards including AWS D1.1 and AS/NZS:1554 Part 2.

2 STUD WELDING TECHNOLOGY OVERVIEW

2.1 Stud Weld Process Options

Institutes and organisations including the American Welding Society, (AWS), The Welding Institute, (TWI), and The Welding Technology Institute of Australia, (WTIA) were used to evaluate the stud welding options available, and any history of stud welding applied to refractory lining of rotary kilns. Whilst ample data is available regarding the attachment of insulation on the external side of equipment including pressure vessels, pressure piping to maintain temperatures and provide a safe environment where hot surfaces are present, little data is available associated with the use of refractory in a protective role, eg: reduce the surface temperature of materials in an elevated temperature environment.

There is information concerning the protection of base materials in the boiler industry, where capacitor discharge stud welding is used to weld small diameter studs that support refractory, however this was not perceived to be of any use in our application involving larger diameter studs exposed to cyclic loading at elevated temperature.

Three stud welding processes were reviewed being:

- Drawn arc stud welding, (DSAW)
- Friction stud welding, (FSW)
- Capacitor discharge welding, (CDSW)

Based on research conducted, the DASW process option has been applied on carbon steel base material of heavy wall thickness. DASW is the process of attaching a steel stud to another steel base material almost instantaneously by using an arc to melt the region to be joined. Welding current for the drawn arc process is delivered via a solid state transformer / rectifier power supply. Studs are typically welded using DC current and supported in a stud welding gun. The resultant welds are of high quality and exhibit mechanical properties equal to, if not better than the base and stud material. Drawn arc studs can be manufactured in a wide range of shapes, the design is limitless.

Capacitor discharge stud welding is similar to the drawn arc process, however instead of drawing welding current from a mains supply welding power source, capacitor discharge stud guns have a bank of charged capacitors that rapidly discharge between the stud and base material to create the welding arc. The weld is completed within a few milliseconds. The main disadvantage of the capacitor discharge method is that it can only be used successfully on stud diameters up to 10mm. For this reason, the capacitor discharge process is not suited to this application where large diameter studs are required.

Friction stud welding is a solid-state process where the stud is rotated at high speed and brought into contact with the base material to produce sufficient heat via friction to achieve a metallurgical bond. No melting of material occurs. There is a fusion line and heat-affected zone which is relatively narrow compared with fusion welding processes involving melting and admixture of the two base materials. Inclusions and porosity are reduced due to the non liquid state of the bond. A disadvantage of this process is the sensitivity to carbon equivalent resulting in high hardness regions due to the rapid heating / cooling cycle. Material impurities can also be a problem where they remain within the bond region, effectively reducing overall bond strength. The process has been used successfully where the stud and base material are not readily welded using fusion type processes, eg: copper and aluminium to carbon steels.

Based on the stud welding process research, DASW has been selected for the initial welding comparison work based on the following:

- High quality welds produced between carbon steel base materials.
- Simplicity, portability and reliability of welding equipment.
- Short welding cycle time.

- Ability to cope with varying contact conditions.
- Low skill level and minimum training requirements for operators.
- Simple QA / QC regime during production welding.
- High level of weld integrity and repeatability.

2.2 Welding equipment for the DSAW process

- Constant current transformer / rectifier solid state power source
- Stud welding gun complete with suitable chuck for stud design
- Current and stud gun control cables
- Work/earth cable with good quality screw type clamp.

The solid state stud welding power source used for welding trials is the Nelson 6000 which allows a duty cycle to apply fifteen 25mm diameter studs to be welded each minute. The welding current and weld time is adjusted using the analogue controls. This power source utilizes a simple microprocessor which displays the actual current and arc cycle time following each stud weld. It was found during stud welding trials, variation in actual parameters during welding varied little from the digital reading set using the analogue adjustment knob. Comparison of the welding current delivered to the stud and displayed at the power source following the welding cycle against a calibrated Fluke tong multi-meter showed the displayed current to be very accurate. In all cases, welding arc cycle time was identical to the preset time at the power source. The stud gun used for welding trials was a Nelson P- NS 20 BHD heavy duty model, fitted with a chuck suitable for a 25mm OD stud.

2.3 Stud materials for welding trials

Drawn arc stud diameters are typically 6 to 25mm and lengths can extend up to 150mm. There are a variety of stud forms used for special applications. For refractory anchor application inside the kilns the studs must be suitable to accept the 253MA anchor wire.

AS/NZS: 1554 Part 2 specifies studs shall be made from cold-drawn stock complying with the requirements of AS: 1443 Grades 1010 through to 1020, either semi-killed or fully-killed. Alternatively, AWS:D1.1 states that the stud material should conform to the requirements of ASTM A108, specification for steel bars, carbon, cold-finished, standard quality grades 1010 through 1020, inclusive either semi-killed or killed aluminium or silicon deoxidized.

Stud materials will be selected based on AS/NZS: 1554 Part 2 table 2.1 for studs other than shear connectors as below:

**Table 1 – AS/NZS: 1554 Part 2 - Table 2.1.
Minimum stud material properties other than shear connectors**

Property	Requirement
Minimum tensile strength	380 MPa
Minimum yield strength	N/A
Minimum % E on a 50mm gauge length	10%
Minimum R of A	50%

For the purpose of stud welding comparison trials and stud welding qualification, AS: 1443 Grade D3 - M1020 has been selected. This material exhibits all the AS/NZS: 1554 part 2 mechanical property requirements at ambient temperature for shear connectors and studs other than these, and the minimum tensile and yield strength is maintained at 200°C, based on elevated temperature tensile testing values referenced in table 5 of this report. Reference can also be made to table 3.3.9 in AS: 1210 where carbon, manganese steels of similar composition exhibit no reduction in design strength up to 200°C.

Table 2 – AS: 1443 Table 6 Grade D3 M1020 minimum tensile properties

Property	Requirement
Minimum tensile strength	460 MPa
Minimum yield strength	370 MPa
Minimum % E on a 50mm gauge length	12%

Studs used for welding comparisons and welding qualification will be AS: 1443 Grade D3 - M1020 material 25mm OD and 150mm long. This will enable a suitable test piece to be completed to enable mechanical testing. The final design of the stud at this stage is not finalised. I am working closely with Pressform Engineering to determine the final stud design. If hot or cold forming operations are required, metallography and material assessments will be conducted to ensure no deleterious microstructure alteration / damage has occurred. Once the design is confirmed, and metallography completed, the information gathered will be incorporated further into this report.

3 APPLICATION TO ROTARY KILNS

3.1 Weldability and metallurgical considerations

When considering the weldability factors for the base materials required for the stud welding application, AS: 1443 Grade D3 M1020 cold finished bar and AS: 1548-7-460R plate possess good weldability characteristics. The studs are to be welded inside a kiln with no access problems, and both these materials do not exhibit detrimental hardenability characteristics. In addition, the heat affected zones of these base materials will not exhibit a microstructure susceptible to hydrogen assisted cold cracking based on the welding process. There is no need to conduct post weld heat treatment following welding. It is expected completed stud welds will demonstrate adequate ductility and toughness to withstand the service environment. When these factors are considered, it can be confidently stated that there will be no perceived weldability issues.

However, there are areas of heat damaged kiln shell material present with suspected partial spherodisation. Where the kiln shell material has “collapsed” due to refractory failure and long term exposure to elevated temperatures, the section is removed and replaced. The initial stud welding evaluation and comparison trials will be completed on sections of kiln shell removed due to heat damage. Areas immediately adjacent to material exhibiting cracks will be utilised for initial stud welding trials.

3.2 Weld integrity and quality control considerations

Where welding trials focus on worst case scenarios, and appropriately qualified welding procedures according to the applied welding standards are used, a stud weld is considered to be as good as, if not better than current practices. Quality control prior to and during production welding will include the following points:

- Pre-production tests – Two studs each will be welded at 5% above and 5% below the optimum current setting, hammer tested and bent to a minimum of 45° from the welded axis.
- Daily tests to be completed at the start of each shift – Two studs will be welded at the optimum setting and visually examined. The studs shall exhibit 360° full flash material. The studs shall also be hammer tested and then bent to a minimum of 45° from the welded axis.

- The stud welding equipment planned does not record each welding cycle. Obtaining arc monitoring equipment suitable for solid state power sources for stud welding has proven difficult. Persuading stud welding contractors to purchase equipment that records welding parameters is problematic, they prefer to use robust type power sources with minimal electronics. However the Nelson 6000 power source does display the actual welding current and arc time used for each stud weld, and this is relatively easy to monitor during production. The welding procedure will be qualified at 5% above and below optimum settings, (based on a 25mm stud), therefore there is a reasonable scope for welding parameters where mechanical properties, stud weld integrity and visual properties can be assured during mechanical testing regimes.
- Due to the use of non arc monitoring equipment referenced above, any change in welding procedure within the 5 % range each side of the optimum settings during production shall require the daily tests off the job to be completed prior to recommencement of production welding.
- In addition, a quality control regime for production welding will incorporate two off the job tests as per the daily test method for each 250 studs applied on the kiln shell.
- Each stud on the kiln shell shall be subjected to a hammer test and visual examination. All studs welded on the kiln shell shall exhibit 100 % exposed flash and pass a hammer test. Those not complying with the tests applied, not welded in accordance with the qualified welding procedure or any other doubt exists regarding the weld integrity, eg; base material condition etc, the stud shall be removed by grinding methods and rewelded.

3.3 Welding process limitations

Section 3.1 of AS/NZS: 1554 Part 2 outlines the criteria for the prequalification of studs. The code states that studs that are “applied in the flat position to a flat and horizontal surface are deemed prequalified” and need no further testing. In this requirement, the flat position is defined as a <15° slope on the applicable surface.

It is planned to conduct welding procedure qualifications and manufacturer qualification regimes for stud welding within the 15° limitations. All studs will be welded within the 15° limits during production. This is taking operator safety into consideration, where welding outside the 15° limit inside the rotary kiln may lead to slips and falls. With dozens of studs welded to the kiln shell adjacent to the operator, there is significant risk of injury, therefore the 15° limit will be imposed for production welding.

It was found during stud welding trials, that the flash contour is affected by gravity when studs were applied at $> 15^\circ$. On occasion, the flash was not established 360° around the stud base. At 0° to 10° , there is little effect on the flash extent and contour.

4 JOINT WELD STRENGTH AND FATIGUE CONSIDERATIONS

Prior to commencing any stud welding trials and comparisons to current practices, weld joint load capacity has been evaluated using AS: 4100. Calculations detailed in this standard were used to compare welded lugs and stud welds based on load capacity at 1000 kg. This data was used to determine an appropriate stud diameter to achieve the equivalent strength to the currently used AS/NZS: 3678 Grade 300 mild steel lug of 40mm x 10mm welded using a 6mm and 8mm fillet weld leg length.

4.1 Weld strength / load capacity comparisons

The data collated in Table 3 below is based on low hydrogen 480 MPa tensile strength consumables to AS: 1553 Part 1 and AS/NZS: 1554 Part 1 SP category for the fillet welds. The equations used are detailed in Appendix A

Table 3 – AS: 4100 load capacity comparisons between welded lugs and stud welds

Item	40 x 10 lug 6mm fillet	40 x 10 lug 8mm fillet	20mm OD stud	22mm OD stud	25mm OD stud	27mm OD stud	30mm OD stud
Stress at 1000 kg	23.5 MPa	17.5 MPa	31 MPa	25 MPa	20 MPa	17 MPa	13 MPa

Based on the information gathered using calculations from AS:4100 in table 3 above, it is apparent a 25mm stud is required to replace a 40mm x 10mm lug with a 6mm fillet and a 27mm stud to replace a 40mm x 10mm lug with an 8mm fillet. Considering a 6mm fillet is used as the basis of design for the welded lugs on the kiln shell, a 25mm stud diameter will be selected based on the data from table 3.

It should be noted that 8mm fillets have been applied to the lugs inside the kiln shell, however there has been no reported improvement in service life based on a larger fillet weld applied. In addition, the application of an 8mm fillet requires multiple passes, hence greater cost and attempts to complete the weld in one pass has resulted in discontinuities outside acceptable limitations under AS/NZS:1554 Part 1 SP acceptance criteria.

4.2 Weld fatigue considerations

The lugs that support the 253MA refractory anchor were perceived to be subject to shear stresses, tensile and compression forces during each kiln rotation cycle. Based on discussions with Iluka design engineers, the bending moment / shear stress applied to the welded lug is negligible due to the nature of the refractory, and compression is not perceived to be an issue. The estimated weight supported by each stud is approximately 250kg, imposing in the region of 7.5 MPa of stress. This is applied to the welded lug at the top section of the kiln during rotation, where the weight of the refractory is hanging from the anchor applying a direct tensile force.

Fatigue performance comparisons at the design stress range between fillet welded lugs and stud welds were evaluated using AS:4100 Section 11. The data is based on the stud being the same length as the welded lugs currently in production. To predict values for direct comparison purposes between fillet weld lugs and stud welds, a 10^6 cycle factor has been used. The following sections and tables in AS:4100 have been used as reference:

- All joint designs based on category 80 in table 11.5.1 (2)
- SN curve data for uncorrected fatigue strength (f_{rs}) from figure 11.6.2
- Thickness correction factor (β_{tf}) taken as 1.0 from $11.1.7 \leq 25\text{mm}$ thickness
- Thickness correction factor (β_{tf}) calculated using 11.7.1 for $> 25\text{mm}$ thickness
- Capacity factor (Φ) taken as 0.7 from 11.1.6
- Using corrected fatigue strength (f_{rsc}) equation from 11.1.7
- Calculating the design stress range, (f^*), using equation from 11.8.1.

Table 4 – AS: 4100 fatigue comparisons between welded lugs and stud welds

Item	40 x 10 lug 6mm fillet	40 x 10 lug 8mm fillet	20mm OD stud	22mm OD stud	25mm OD stud	27mm OD stud	30mm OD stud
Design Stress Range	63.0 MPa	63.0 MPa	63.0 MPa	63.0 MPa	63.0 MPa	61.75 MPa	59.85 MPa
Allowable Force	275.0 kN	367.0 kN	204.0 kN	255.0 kN	321.0 kN	377.0 kN	438.0 kN
Allowable Load	2700 kg	3600 kg	2000 kg	2500 kg	3150 kg	3700 kg	4300 kg

Looking at the values obtained in table 4, it is apparent a stud diameter between 22mm and 25mm stud is required to replace a 40mm x 10mm lug with a 6mm fillet. Considering standard bar sizes available, and to provide an extra degree of comfort, a 25mm stud again will be selected. Based on the load and stress imparted by the refractory during service, a 20mm stud is adequate, however there is little difference in cost and weld cycle time in selecting the larger stud with the added confidence in serviceability under the rigorous conditions, including elevated temperature.

4.3 Temperature, stress concentrations and weld quality

In addition to the strength and fatigue factors discussed above in the text and tables, other factors need to be considered which may contribute to premature failure of the stud weld. These include:

- Elevated temperature and loss of properties
- Stress concentrations reducing the fatigue life
- Overall weld quality

Provided temperatures do not exceed 200°C at the interface between the stud and the kiln shell, there will be no detrimental reduction in mechanical properties of the AS:1443 grade D3 M1020

stud material. Temperatures above 200°C result in a reduction of tensile properties, however the minimum requirements of AS/NZS:1554 part 2 are still maintained up to 350°C, and the mechanical test values exhibited at 350°C are still adequate to cope with advised service loads and stresses.

Table 5 – Results of AS: 1443 Grade D3 M1020 elevated temperature tensile tests

Property	Ambient	200°C	250°C	300°C	350°C
SMYS (MPa)	420	375	359	344	340
UTS (MPa)	554	516	480	477	476
Elongation	17%	17%	16%	17%	16%
R of A	69%	63%	68%	66%	68%

Based on the information gathered in Table 5 above, the stud base material demonstrates adequate properties to ensure reliable service. The tensile testing regime was performed by Amdel laboratories, located in Thebarton, Adelaide, South Australia.

Partial failure of the welded lug allows the refractory to move around a little, leading to cracking and a rise in temperature at the shell. The overall improvements using stud welding is expected to prevent partial failure during service. The existing welded lugs have failed by a fatigue mechanism during service well below cycles modelled in table 4 above. Fatigue failure is directly related to stress concentrations present at the fillet weld 90% of reported cases. This results in loss of protective refractory and unacceptable heating of the kiln shell. This leads to expensive shut down and repair operations.

The most common cause of failure is undercut at the fillet weld toe against the lug. This is especially prevalent at the weld returns on the MMAW fillet welds on the kiln. The use of stud welding is expected to eliminate the incidence of undercut, hence a much reduced stress concentration at the stud that supports the refractory anchor. This is considered to be a major

improvement over welded lugs, and a more reliable service life and increased resistance to fatigue initiated cracks is expected.

The overall weld quality and repeatability using stud welding is improved in comparison to manual metal arc welding, (MMAW), due to a number of factors. There are no consumables required for stud welding removes the husbandry required for currently used low hydrogen welding electrodes. Poorly handled welding electrodes can result in elevated levels of hydrogen in the deposited welds, leading to possible hydrogen assisted cold cracking problems. Stud welding requires no consumables other than the stud, however cleanliness of the base material and stud is still necessary to prevent elevated levels of hydrogen. Stud weld chemistry is predictable, as the base and stud materials vary little in composition. Operator fatigue has an effect on MMAW weld quality, where the desired fillet weld size and shape deteriorate and presence of stress concentrations including undercut can increase to a point of non compliance. Also, other unseen defects including lack of root fusion can severely reduce the fatigue properties of MMAW welded lugs. Stud weldmetal volumes and absence of deleterious discontinuities is highly repeatable based on set welding cycles therefore reliable mechanical properties are assured for each stud that passes the quality control regimes applied to all production studs.

The environment for attaching the welded lugs does not lend itself to comfortable MMAW, so welders can suffer loss of concentration in a short space of time. The same is apparent for the NDE operators and welding inspectors, where non compliant stress concentrations and discontinuities are often missed. Stud welding reduces all these issues as the stud welding cycle is very short, and operators are far more comfortable applying the stud welds. In addition the NDE regime is far simpler, consisting of simple visual examination of exposed flash materials and hammer test followed by simple identification, eg paint mark, to show quality control regimes have been completed on that particular stud.

5 STUD WELDING TIMES COMPARISON

Following consultation with the Perth based stud supply and welding company, STUDCO, and data from Iluka Resources for the conventional MMAW anchor welding times, the following data has been compiled to demonstrate the significant cost savings if stud welding is applied to support the refractory inside the kiln shell:

5.1 DASW welding time estimates

Based on two stud welding machines, each with a two man team capable of completing 200 stud welds per hour, approximately 4,800 studs can be installed per 24 hour period with two day shift and two night shift teams, (eight personnel). At this production rate, a kiln with 13,000 studs could theoretically be completed in three days.

This can be reduced further as the stud weld cycle time is only 1.2 seconds, and based on good teamwork, five studs can easily be applied per minute, equating to 300 per hour enabling 7200 studs to be completed in a 24 hour period. Note that the three day estimate includes production testing, and quality control regimes to the production studs.

This estimate also assumes the spot grinding and marking out of stud locations inside the kiln are completed before stud welding begins and the welding environment needs to be clean and with good visibility so that the welders can work efficiently.

The 25mm studs can only be welded in the flat position or with a relatively small inclination up to 15°. This is based on welding trials conducted to old kiln shell sections to gauge the effect of gravity on the flash shape and extension around the stud base. At 15°, the flash exhibited less than 100% coverage around the stud base. Whilst preliminary bend testing against the area of little or no flash highlighted no immediate issues, it is planned to weld the studs within a 10° tolerance where welding trials demonstrated no effect on flash extent.

To apply studs within the 10° limitation each side of 0°, several kiln rotations will be required. Factoring in the kiln rotations increases the overall welding time. A 30° kiln rotation will take approximately one hour to complete, considering removal of all equipment, gaining permits and conducting the rotation. Based on the area not incorporating studs between each 20° section, 11 rotations would be required, effectively adding half a 24 hour period to the total time required to

complete 13,000 stud welds. Based on the stud welding time, the total hours required to complete the stud welding would be approximately 84 hours.

Based on previous MMAW refractory anchor lug welding operations, 3,000 + man hours is required. This accounts for six welders and two supervisors, this equates to approximately fifteen 24-hour days. This is significantly more than the estimated 3.5 to 4 days required for the stud welding approach.

5.2 MMAW approximate cost

Iluka Resources have advised the welding 13,000 refractory anchor lugs using MMAW requires approximately 3,000 man-hours costing around \$ 300,000.00 and the material cost for the anchor lugs is \$13,000.00. Welding consumables, welding equipment cost is around \$6,000.00 based on 400 kg of electrodes at \$ 2,500 and \$ 3,500.00 for equipment hire. In addition, third party non destructive testing costs approximately \$ 4,800.00. This equates to a total cost of around \$ 324,000.00.

5.3 DASW approximate cost

Based on 25mm diameter studs, aluminium flux ball as well as machining to accept the 253MA anchor, the estimated cost per stud is \$4.00, hence a cost of \$52,000.00 for the studs. Labour costs including equipment based on \$ 150.00 per hour equates to \$ 72,000.00. This allows for one supervisor on each shift in addition to the four stud welding operators, total of five personnel on each shift. No other consumables are required and quality control regimes are controlled by the operators monitored by supervision personnel. This equates to a total cost of \$ 124,000.00.

5.4 Costing conclusion

Stud welding provides a direct saving of around \$ 200,000.00 over the conventional MMAW refractory anchor lug welding practices. Additional production earnings will be available by shortening the shut down period by ten days. In summary, there are significant savings and additional earnings available if stud welding was employed.

5.5 Safety

Safer work environment and reduced injury risk during shut down periods offer further cost savings. Stud welding is a far safer welding process in the intended application by offering the following benefits:

- Welding arcs are restricted by the ceramic ferrule, reducing the risk of ultraviolet and infrared radiation causing arc burn and eye damage. The operators need not use welding helmets, hence vision is less restricted reducing the risk of trips and falls. It is envisaged some stray arcing will be apparent, however provided operators wear approved safety glasses, lightweight hoods, and cover all exposed skin with appropriate clothing the risk of arc burn and eye damage is eliminated.
- Ancillary grinding and chipping equipment is not required as necessary during the MMAW process. This eliminates sparks and hot slag which cause burns and foreign bodies in the eyes. In addition, the serious injuries that occur with grinding equipment will be negated. Another advantage is the reduced amount of power leads used for grinders and electrode hot boxes inside the kiln that augment tripping hazards.
- Stud welding produces little fume, negating the need for respirators and heavy duty fume extraction equipment. Provided adequate fresh air introduction is provided, air quality inside the kiln is perceived to be very good.
- The stud gun is inactive during non welding periods as the operator is required to activate the welding current via a trigger during the weld cycle. This eliminates the risk of electrocution as present with MMAW equipment. MMAW equipment requires voltage reduction devices to be used to reduce this risk, however these are not always activated as required.
- On previous MMAW refractory anchor lug welding operations, preheat is necessary. Stud welding does not require preheat, based on trials completed thus far, therefore the risk of explosion and burns is eliminated.
- Stud welding produces little waste, with the exception of broken ceramic ferrules. With MMAW, electrode stubs and slag are always present, adding to the injury risk.
- The stud welding operator will be far more comfortable during long periods inside the kiln, reducing operator fatigue associated with MMAW. A more alert operator is less likely to experience an injury causing accident.

6 STUD WELDING STANDARDS

6.1 Australian Standard AS/NZS: 1554 Part 2

AS/NZS: 1554. Part 2 is the welding standard for stud welding of steel studs to steel. This standard provides details of qualified stud materials, application of the process, qualification of welding procedures, pre-production testing, production testing and stud weld acceptance criteria.

Section 2 outlines details for the general requirements of stud design. This includes stud, ferrule, flux, stud base and manufacturing requirements and restrictions. Clause 2.2 lists requirements for the mechanical properties of the stud material and the procedures for testing. Tensile testing is required as per Clause 2.2.2.2; a typical tensile test fixture is shown in Figure 6. The parent material must comply with the requirements of Clause 2.3.

Section 3 details the stud application qualification requirement. Studs applied in the flat position (i.e. less than 15° inclination) are deemed prequalified within the extent of the manufacturer's stud base qualification tests. Based on the welding trials conducted so far, this will not be exceeded, however sensible welding procedure qualification based on manufacturer's qualification requirements will be completed due to the criticalness of the application intended, regardless of the prequalified conditions of AS/NZS:1554 part 2. Stud manufacturers rarely conduct the qualification requirements stated in this standard, therefore the onus is on the end user to ensure the proposed stud base and substrate material is qualified in accordance with the relevant sections of this standard prior to purchase.

Section 4 details the requirement for production weld testing. The procedures and requirements for pre-production testing and production welding depend on whether or not the stud welding power source records weld cycle parameters. Where the power source does not record parameters, as is our case, the procedure for preproduction testing is as per clause 4.1.2 where daily tests are required for the first two welded studs each day as per Clause 4.1.2.1. Once production welding has begun, any changes as defined in Clause 4.1.2 shall require further pre-production testing. Furthermore, all stud welding operators must comply with and are qualified by the general and technical knowledge requirements as per Clause 4.3.

Section 5 covers all aspects of production techniques and workmanship. This includes preparations before welding and studs, stud bases, and parent materials have to be free from deleterious materials. Ferrules shall be dry and recommendations for re drying ferrules is provided. Welding technique must comply with that stated in Clause 5.2. This clause also outlines alterations for welding in adverse weather and discusses options for alternative welding processes and their requirements. Clause 5.3 places restrictions on minimum stud spacing and finished weld treatment is covered in Clause 5.4. Clause 5.6.1.2 is specific to our stud welding scenario and will be applied to all production and preproduction test studs as detailed earlier in this report.

Section 6 of this standard details the testing of finished welds, in this case clause 6.1.2 in particular, where equipment used does not record welding parameters.

Appendix C in AS/NZS: 1554 Part 2 details the requirement for stud manufacturers to qualify the stud design and provides guidance for the stud manufacturer certification of a stud base for welding under shop or field conditions. The standard outlines details for the following:

- Responsibility for tests
- Extent of qualification
- Duration of qualification
- Preparation of test specimens
- Number of test specimens
- Testing procedure
- Qualification requirements
- Retesting procedure
- Manufacturer's qualification test report

In particular, clause C6.2 will be applied to in this case. The welded samples and testing regime will be completed to qualify the stud welding procedures for the rotary kiln application.

6.2 Other relevant standard AWS D1.1-2006

A review of this standard has shown an overall similarity with AS/NZS: 1554 Part 2. Details with regards to material qualification, applications, procedure and testing are virtually identical

based on prequalified stud welding requirements. The manufacturer's qualification requirements will be completed as part of stud welding qualification to AWS D1.1, due to the critical nature of the intended application. The following stud welded samples will be produced to satisfy the Stud welding procedure and stud manufacturer qualification requirements to both applied stud welding standards.:

1. 15 studs welded at optimum current / required time
2. 10 studs welded at 5% reduction in optimum current / required time
3. 10 studs welded at 5% above optimum current / required time

Stud samples in point 1 above welded at optimum current / required time subjected to 10 x tensile tests to satisfy 3.3.3.2 in AS/NZS:1554 Part 2 and Annex G / G6 and G7 in AWS D1.1 and 5 x 90° bend along the original axis to satisfy 3.3.2 in AS/NZS:1554 Part 2

Stud samples in point 2 above welded at 5.0 % below optimum current / required time subjected to 10 x tensile tests to satisfy Annex G / G7 in AWS D1.1

Stud samples in point 3 above welded at 5.0 % above optimum current / required time subjected to 10 x tensile tests to satisfy Annex G / G7 in AWS D1.1

In addition, other tests deemed relevant to the intended application will be completed. The full mechanical and metallurgical test regime applied to the stud weld samples will be described later in this report.

7 SUMMARY OF FEASIBILITY STUDY

The stud welding process as discussed above in sections one to six with regard to suitability for rotary kiln refractory anchor attachment lugs appears promising. Calculations performed demonstrate a 25mm diameter stud is required to achieve similar mechanical properties to those of the MMAW welded lugs and that the final studs will meet or exceed current practice service life.

Based on the information gathered and presented in this report, welding trials to directly compare MMAW lugs to proposed stud welds have been conducted. The results reported for the comparison trial welding samples are detailed and discussed in section 8 of this report.

8 STUD WELD COMPARISON TRAIL WELDING

Utilising stud welding for the refractory anchor lug in rotary kilns appears feasible, and welding trials were performed to evaluate the stud weld properties in comparison to current practices. These welding trials will determine if the stud weld properties can be achieved on sections of kiln shell material, and if results are favourable, qualification of a stud welding procedure for future kiln refractory anchor lug replacement programmes.

The purpose of the stud welding trials was to compare two methods of attaching refractory anchor lugs. Stud weld and heat affected zone properties, tensile properties and fatigue performance were evaluated on the refractory attachment methods below:

1. Current method: 6mm fillet weld between AS: 1548-7-460R kiln shell plate and 40mm x 40mm x 10mm AS/NZS: 3679 Grade 300 flat bar.
2. Proposed method: AS: 1443 Grade D3 M1020 25mm OD stud incorporating grade 1100 H16 aluminium flux ball welded to AS 1548-7-460R kiln shell plate.

8.1 Sample description and evaluation test regime

A Perth based stud welding company, STUDCO, was contracted to weld the test samples. Sections of rotary kiln shell and AS/NZS: 3679 Grade 300 anchor lugs were supplied by Iluka Resources Limited.

Equipment for stud welding included a high output stud welding transformer delivering drooping characteristic DC welding current and stud welding gun with a stud retaining chuck suited to a 25mm OD stud. The studs incorporated Grade 1100 H16 aluminium flux balls placed in a small centre drilled hole at the stud base. The purpose of the flux ball is to tie up any impurities including oxygen and nitrogen, and to refine the weldmetal grain size. 25mm ceramic ferrules were used to control and contain the expelled flash material. The stud gun used for welding trials was a Nelson P- NS 20 BHD heavy duty model, fitted with a chuck suitable for a 25mm OD stud. The equipment planned for the welding trials is shown in figures 3 and 4 below:



Figure 3 – Nelson 6000 power source



Figure 4 – Nelson P-NS 20 BHD stud gun



Figure 5 – Stud samples and ferrules



Figure 6 – Stud samples showing grade 1100 H16 aluminium flux ball.

Prior to commencing the test samples, many studs were welded to scrap steel sections to determine optimum parameters. Once confirmed, two studs were welded to a section of AS/NZS: 3678 Grade 350 plate to assess by bend test. In figure 7 below, the left stud did not exhibit a full 360° flash. The bend test on this stud placed the zone exhibiting no flash to tension. The fusion between the stud and the base material was not affected, and it performed as well as the stud exhibiting the full 360° flash. The parameters used during the stud welds were:

- Welding current: 1900 amps
- Polarity DCEN
- Weld cycle duration of 1.0 second.
- Lift of 4.0mm
- Plunge distance of 6.0mm



Figure 7 and 8 – Preliminary stud weld bend tests

The kiln shell plate sample blocks supplied by Iluka Resources were removed from a section of kiln shell adjacent to an area exhibiting degradation due to long term elevated temperature exposure. . Whilst metallography was not conducted these samples, it is assured partial pearlite spheroidisation is present. The sample surfaces were dye penetrant examined following oxide removal to confirm freedom from surface discontinuities.



Figure 9 and 10 – Shell sections demonstrating PT examination

A total of four stud samples were welded as per the parameters stated above for the following tests:

- Two for tensile testing
- One for macroscopic evaluation and hardness tests, (1 stud each side of plate to enable two samples)
- One for fatigue test evaluation

A total of two lug samples were welded for the following tests:

- One for macroscopic evaluation and hardness test
- One for tensile testing

Typical samples are shown below:



Figure 11 - Stud weld sample



Figure 12 - Welded lug, 6mm fillet weld

Following welding operations and visual acceptance, the samples were delivered to The Marine Inspection Service NATA accredited laboratory to undergo the applied test regime. Results of the tensile, macroscopic, hardness and fatigue testing regimes are briefly summarised below and actual values recorded for the MMAW lug and stud weld are listed in table 6 of this report.

8.2 Macro samples and hardness survey

The stud weld zone exhibited very similar hardness in comparison to the welded lug. Hardness values recorded are typical of those expected on material combinations involved subjected to the thermal cycles imposed during welding. See table 6 for results.

8.3 Tensile testing

The tensile performance of the stud weld samples was superior to the welded lug samples:

- Stud tensile breaking load: 256 and 271 kN with fracture occurring at the stud.
- Welded lug tensile test result: 191 kN with fracture occurring at the flat bar.

8.4 Fatigue testing

Despite more rigorous fatigue parameters, the fatigue performance of the stud sample far exceeded that of the welded lug. Following the fatigue test applied to a MMAW lug and stud weld sample, the fracture surfaces of the welded lug and stud sample were evaluated with the following conclusions:

Welded lug

- One side of the fillet weld fusion line exhibited the fatigue crack, initiating at the uppermost weld toe against the flat bar centrally along the flat bar, eg: approximately 20mm along the weld toe. This crack propagated downward and outward toward the weld returns and downward toward the root region.
- The other side of the flat bar fillet weld exhibited overload failure, initiating at the fillet weld root region and extending upward to the upper weld toe along the fusion line.
- There was no evidence of embedded weld defects on the fracture surfaces.
- This failure mode is typical of the majority of failures that occur to the welded lugs in service, where the flat bar appears to have pulled away from the weld. In some instances, a section of flat bar is left behind between the fillet weld.
- It can be concluded the fatigue failure is typical of those experienced during service.
- Load conditions: 220 MPa, 8.8 kN, 7 Hertz, 27,456 cycles to failure

Stud weld sample

- The area of fatigue apparent by the traverse area of crack growth at the interface of the stud and base material was approximately 35% of the area of the stud.
- The balance of the fracture face was typical of overload ductile fracture where the area of fatigue became a critical percentage of the total area.
- The fracture surface appeared to be in both the base material and the stud weld upper fusion line. The fatigue crack initiated in the base material heat affected zone adjacent to a smooth spherical zone.
- There were smooth areas on the fracture surface, associated with to be gas pores in the stud weldmetal.
- Load conditions: 220 MPa, 10.8 kN, 7 Hertz, 64,835

In summary, the stud sample achieved double the fatigue cycles at higher loading conditions when compared to the welded lug. Although the fatigue testing was conducted at room temperature, (not exactly reflective of service conditions), the results show the stud welded sample far exceeded the welded lug with regard to fatigue performance, and this aspect is not expected to alter where elevated temperature fatigue test trials are planned during stud welding procedure qualification regimes.



Figure 13 – Fatigue testing setup



Figure 14 -Fatigue testing machine



Figure 15 - Stud fracture face



Figure 16 - Stud / shell interface



Figure 17 - Lug weld fatigue fracture



Figure 18 - Lug / shell interface

Arrows indicate approximate fatigue crack initiation points in figures 16 and 18 above

8.5 Discussion

The stage 1 test results demonstrate the stud weld option is a viable alternative to welded lug refractory anchor design. Whilst some inclusions were present in the stud weld, superior fatigue performance is evident, despite fatigue crack initiation adjacent to an inclusion within the stud weld.

Inclusions of this nature are typical of stud welds due to the quick weld cycle and solidification time. It is inevitable some escaping gases will become entrapped in the weld and not become part of the flash or expelled material.

There are options available to improve the weld soundness and reduce the percentage of inclusions present. Whilst an aluminium nipple designed for deoxidisation was fitted to the stud, it is not recommended to increase the volume of aluminium present, as there is a risk of residual aluminium within the microstructure, increasing crack susceptibility and possible reduced fatigue life.

Alternatively, a longer arc time can be used to increase the total stud weld cycle time, to enable gases produced during the welding cycle to escape into the expelled material during welding cycles. This option will be investigated further prior to stud welding procedure qualification.

8.6 Conclusions

It can be concluded the stud weld refractory anchor proposal demonstrated improved fatigue performance and overall strength in comparison to the current welded lug design, without detriment to weld zone hardness. The results achieved are summarised in table

Table 6 – Summary of comparison test values

Test type →	BM Hardness (HV 5)	Weld Hardness (HV 5)	HAZ Hardness (HV 5)	Force to fracture (kN)	Fatigue data	Cycles to failure
Welded lug	180 - 190	223 - 234	182 – 190 (bar)	191	220 MPa 8.8 kN 7 Hertz	27,456
Stud weld	174 - 180	232 - 246	177 – 202 (stud)	256 - 271	220 MPa 10.8 kN 7 Hertz	64,835

8.7 Recommendations

Stage two stud weld qualification regimes will proceed. This would entail the following stages:

1. Establish ideal parameters / conditions to reduce the incidence of stud weld interface inclusions.
2. Conduct stud weld qualification testing in accordance with AS/NZS: 1554 Part 2 and AWS D1.1 using large kiln shell section to simulate actual site conditions.
3. Perform elevated temperature fatigue test to determine fatigue performance in comparison to ambient conditions.
4. Complete further macro and hardness evaluations to ensure repeatability of results

9 STUD WELD QUALIFICATION

The qualification of stud welding to recognised welding standards has been performed. A large section of rotary kiln shell was supplied by Iluka Resources and stud samples supplied by STUDCO. The following welding standards were used as reference to determine stud qualification requirements:

- AS / NZS 1554.2 2004 - Structural Steel Welding Part 2: Stud Welding
- AWS D1.1 2006 - Structural Welding Code Section 7: Stud Welding

Both the above standards allow stud welding prequalification status where the following requirements are present or verified:

- The stud manufacturer's qualification testing as described in Appendix C of AS/NZS: 1554 Part 2 and AWS D1.1-2006 is completed and verified as compliant.
- Base material to which the studs are to be welded complies with the materials listed in clause 2.3 of AS/NZS: 1554 Part 2 or material groups I or II as per table 3.1 in AWS D1.1. In this case, AS: 1548-7-460R is used for the kiln shell material and good engineering judgement would group this material as group I.
- Stud base material complies with the requirements of AS: 1443 or ASTM A108 Grade 1010 or 1020. In this case AS: 1443 grade D3 M1020 is selected.
- Stud welding procedural controls in accordance with section 4 of AS/NZS: 1554 Part 2 are in place and documented.
- Studs are not welded through decking and surface coatings or in damp conditions.
- Studs are to be welded in a flat position within the range of 0° to 15°

The above requirements for pre qualification of stud welding are all valid for the application on rotary kilns, however qualification of welding procedures will be performed based on the stud base manufacturer's qualification to both the referenced standards to ensure there is no doubt regarding the weld quality, repeatability, mechanical performance and degree of reliability required to assure adequate service performance.

9.1 Determination of optimum stud welding parameters

Prior to performing the welding procedure qualifications, further work was undertaken to determine optimum settings. The values used during initial comparison trials were:

- Welding current: 1900 amps. Polarity DCEN
- Weld cycle duration of 1.0 second.
- Lift of 4.0mm. Plunge distance of 6.0mm

The aim of determining optimum current settings is to reduce the presence of gas pores and inclusions within the stud weld. Based on results obtained during the initial comparison trials, it is evident we are very close to optimum settings based on the above values. Below is a summary of results obtained using macro specimens to determine the presence of inclusions or gas pores.



- Welding current: 2100 amps.
- Polarity DCEN
- Weld cycle of 1.5 seconds.
- Lift of 4.0mm.
- Plunge distance of 6.0mm

Figure 19 – Stud macro at higher current and cycle time

The macro specimen in figure 19 above exhibits freedom from inclusions and porosity, however the flash tends to be excessive and is poor in appearance. During this weld it was apparent the cycle time was excessive, as an increased percentage of spatter. In addition, the sound produced during the weld cycle gave the impression of excess current.



- Welding current: 1900 amps.
- Polarity DCEN
- Weld cycle of 1.5 seconds.
- Lift of 3.0mm.
- Plunge distance of 4.0mm

Figure 20 – Stud macro at lower current and cycle time, with modified lift / plunge data

The macro specimen in figure 20 above also exhibits freedom from inclusions and porosity, however the flash again tends to excessive and is poor in appearance. During this weld the lift and plunge parameters were modified slightly. Based on observations during the weld cycle, it was thought this weld would feature poor fusion, however this was not the case. In conclusion, the expelled material leans to excessive weld cycle times.



- Welding current: 2000 amps.
- Polarity DCEN
- Weld cycle of 1.2 seconds.
- Stud stick out of 4.0mm
- Lift of 4.0mm.
- Plunge distance of 6.0mm

Figure 21 – Stud macro at optimum current and cycle time

The macro specimen in figure 21 above exhibits freedom from inclusions and porosity, and is alleged to be optimum settings for this stud welding scenario. The cycle time is ideal, and 0.2 seconds longer than the comparison trail welding stage. This weld features excellent flash form and contour, with a notable absence from fusion problems and the weld zone appears ideal with regard to width and outline. In conclusion, the welding parameters utilised to produce the results above are judged to be optimum and will be used during welding procedure qualification.

9.2 Welding procedure qualification

As discussed above, it was necessary to perform the manufacturer's stud base qualification requirements to gather some real data based on mechanical testing regimes so dependable welding procedures can be developed. The company undertaken to supply the final stud design does not have the capacity to conduct the testing as per AS/NZS:1554 Part 2 and AWS D1.1 Appendix G.

9.3 Base materials

The base materials used for procedure qualification consisted of a 3.0m x 1.5m x 90mm thick section of AS:1548-7-460R removed from a discarded strake cut from the kiln.. The heat number is unknown due to the lack of material certificates available from Iluka traceable to that particular section. The stud samples were 150mm x 25mm diameter AS: 1443 grade D3 M1020 carbon steel bright finished bar, heat number: 601348. Other consumable items included the grade 1100 H16 aluminium flux ball and AF-1”F ceramic ferrule.



Figure 22 – Kiln shell section marked out for stud welding

The section of base material in figure 22 above was marked out to ensure the welded stud samples could be removed with enough base material to allow mechanical testing. Figure 23 below is a STUDCO employee removing the oxide layer at each weld zone where stud welds will be applied.



Figure 23 – Weld zone oxide removal

9.4 Welded stud samples

A total of 42 studs were welded for welding procedure qualification purposes and simulation of worst case site conditions.. In addition two test studs were welded prior to commencing the official qualification studs to simulate the daily test regime. Both these studs were bent 90° to the base plate, with no apparent defects highlighted.

Each stud was welded at 125mm centres to allow a square sample of base plate to be removed, producing 42 separate samples suited to the mechanical testing regimes planned. Each stud was clearly marked with the allocated identification number.

This stage of work simulated actual site conditions which enabled stud weld cycle times to be recorded to assemble some real data so site welding scenarios can be accurately predicted. The stud welding procedure qualification operation was witnessed by representatives from Iluka Resources, the proposed stud manufacturer and the author. A short movie was recorded during the stud welding process, and is included with this dissertation on a compact disc.

9.5 Stud traceability information

1. 17 stud samples A1 to A17 welded at optimum settings and time
2. 11 stud samples B1 to B11 welded at 5.0 % below optimum current settings using optimum time.
3. 11 stud samples C1 to C11 welded at 5.0 % above optimum current settings using optimum time.
4. Stud sample D1 was welded onto an oxide covered uneven surface of the base plate at a location where a welded lug had been previously removed. Also we simulated the worst case conditions involving failed arc start and restart using the same stud.
5. Stud sample D2 was welded onto bright metal incorporating an uneven surface. The location was ground to bright metal with a 4.0mm deviation present at the base material surface at the stud weld zone.
6. Stud sample D3 was welded onto an oxide contaminated flat surface of base material. This would simulate an area of kiln shell in production exhibiting poor preparation with regard to oxide removal.



Figure 24 – Stud sample test plate during welding

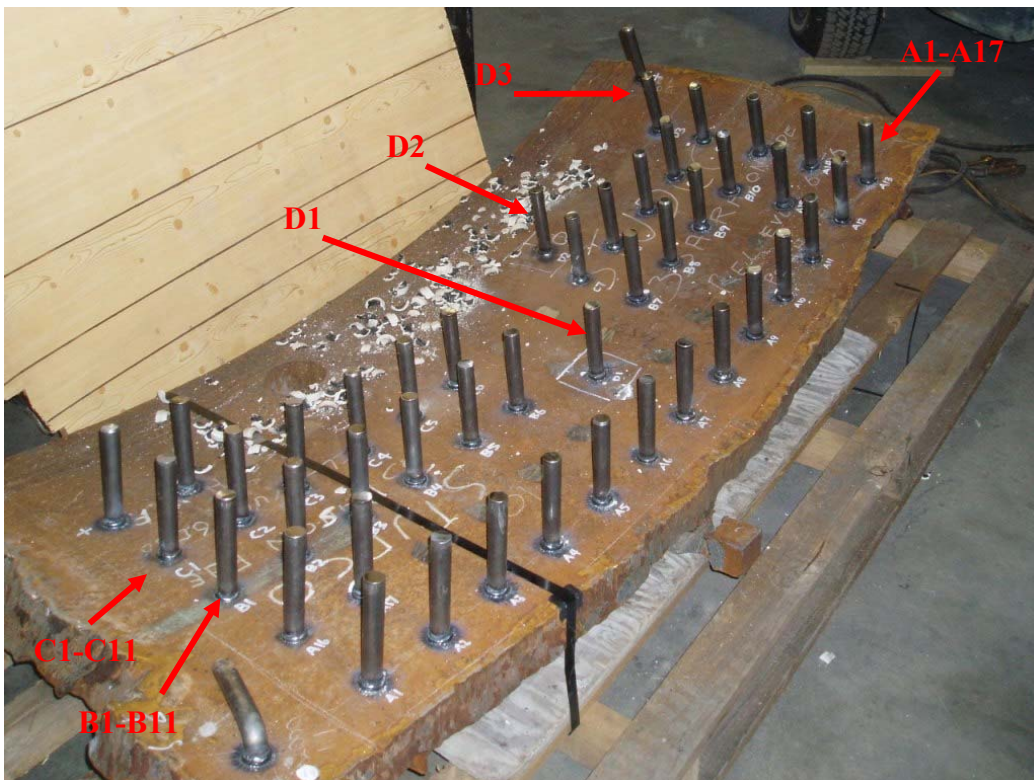


Figure 25 – Completed test plate



Figure 26 – Close up of stud sample A6



Figure 27 – Close up of stud sample B6



Figure 28 – Close up of stud sample B8

9.6 Samples to qualify the applied welding standards

1 - Studs welded at optimum current and time. Stud samples A1 to A15

- 10 x tensile tests
- 5 x 90° bend along the original axis.

2 - Studs welded at 5% below optimum current and optimum time. Stud samples B1 to B10

- 10 x tensile tests

3 - Studs welded at 5% above optimum current and required time. Stud samples C1 to C11

- 10 x tensile tests

9.7 Additional test regime

1 – Macro and HV10 survey to weldmetal, heat affected zone and base material.

- Stud samples A16 / B11 / C11, representative of each current setting used under optimum surface conditions.

2 – Macro to determine stud to base material interface where less than optimum surface conditions are present prior to welding the stud.

- Stud samples D1 / D2 / D3

3 – Elevated temperature fatigue test at 300°C along the stud axis, at the following parameters: 10 kN force applying approximately 220 MPa stress at 8 to 10 cycles per second. This will be for information only, to determine any reduction in fatigue performance compared to the ambient fatigue test performed during the initial comparison stud welding trials.

- Stud sample A17

9.8 Results of tensile testing and bend samples.

The stud samples were individually cut out using a profile cutting machine and delivered to Amdel for evaluation. The tables below detail the results from the testing regime applied to qualify the stud welds based on the manufacturer's stud base qualification in accordance with AS/NZS: 1554 Part 2 and AWS D1.1.

Table 7 – Summary of tensile tests welded at optimum current

Sample Number	UTS (kN)	Comments
A1	256.0	Failed in stud
A2	252.4	Failed in stud
A3	247.0	Failed in stud
A4	254.9	Failed in stud
A5	256.8	Failed in stud
A6	253.5	Failed in stud
A7	255.7	Failed in stud
A8	260.2	Failed in stud
A9	248.6	Failed in stud
A10	254.1	Failed in stud

Table 8 – Summary of tensile tests welded 5% below optimum current

Sample Number	UTS (kN)	Comments
B1	263.0	Failed in stud
B2	250.6	Failed in stud
B3	248.0	Failed in stud
B4	251.0	Failed in stud
B5	252.7	Failed in stud
B6	253.8	Failed in stud
B7	256.6	Failed in stud
B8	252.7	Failed in stud
B9	247.2	Failed in stud
B10	258.3	Failed in stud

Table 9 – Summary of tensile tests welded 5% above optimum current

Sample Number	UTS (kN)	Comments
C1	260.6	Failed in stud
C2	260.7	Failed in stud
C3	252.9	Failed in stud
C4	248.4	Failed in stud
C5	258.7	Failed in stud
C6	249.9	Failed in stud
C7	248.0	Failed in stud
C8	254.3	Failed in stud
C9	256.5	Failed in stud
C10	251.3	Failed in stud

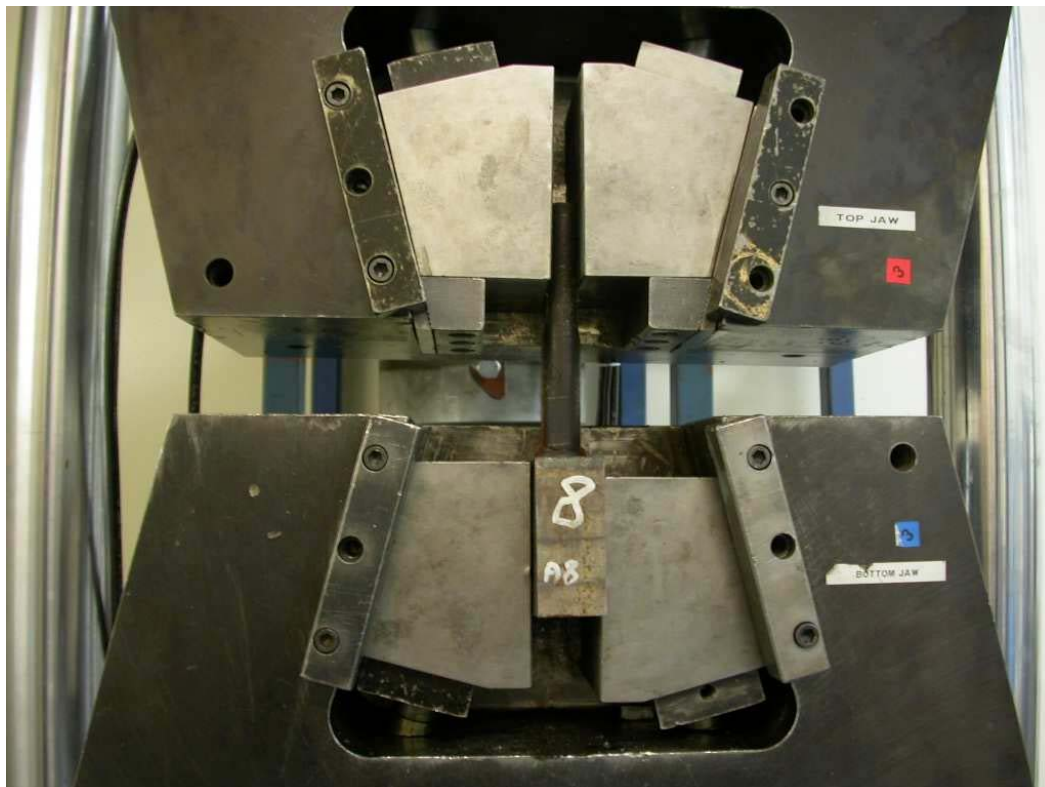


Figure 29 – Stud sample tensile test setup

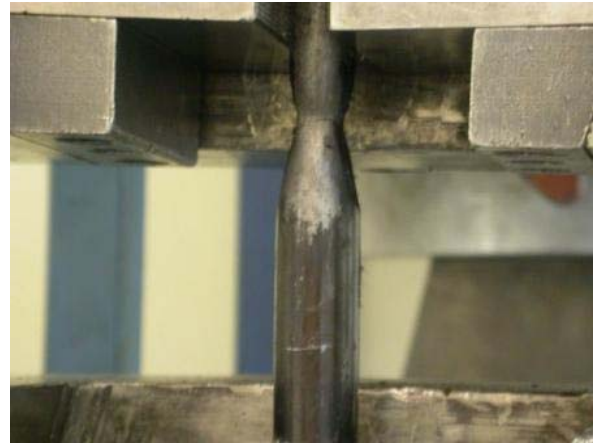
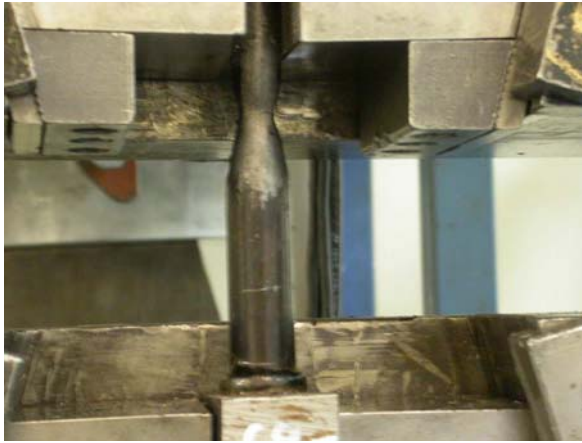


Figure 30 / 31 – Typical necking and stud failure

Table 10 – Summary of bend tests at optimum current

Sample Number	Test	Comments
A11	90° bend	Passed – No disbondment
A12	90° bend	Passed – No disbondment
A13	90° bend	Passed – No disbondment
A14	90° bend	Passed – No disbondment
A15	90° bend	Passed – No disbondment



Figure 32 / 33 – Typical bending sample

9.9 Results of hardness testing using Vickers pyramid tester (HV 10)

The values recorded during the mechanical test regime and detailed in tables 7, 8, 9 and 10 above satisfy the requirements for tensile and bend testing in the applied welding standards. In addition to the welding standard stud manufacturer's requirements, further tests were completed. These included hardness testing to stud welds within the acceptable range of parameters and elevated temperature fatigue testing to compare the results achieved in contrast to those reported for fatigue testing completed at room temperature.

Table 11 – Summary of typical hardness testing within welding current range

Traverse 1	HV 10	Traverse 2	HV 10	Traverse 3	HV 10
Base material	187.5	Base material	176.8	Base material	176.6
	179.4		184.4		180.4
	183.1		193.8		182.2
Base material HAZ	209.5	Base material HAZ / FL	208.8	Base material HAZ	199.6
	238.7		252.1		215.2
	296.7		309.7		239.3
	320.2		287.7		258.9
Weld	275.5	Weld FL Stud HAZ	226.4	Weld	321.7
	280.5		221.6		245.0
	289.5		187.0		231.8
	244.0		172.4		208.0
Stud HAZ	199.2	Stud Base material	168.8	Stud HAZ	184.7
	182.1		168.0		184.3
	162.9		172.9		169.2
	166.4		-		167.5
Stud Base material	162.7	-	-	Stud Base material	165.7
	194.2	-	-		173.7
	181.3	-	-		178.6
	176.1	-	-		185.0

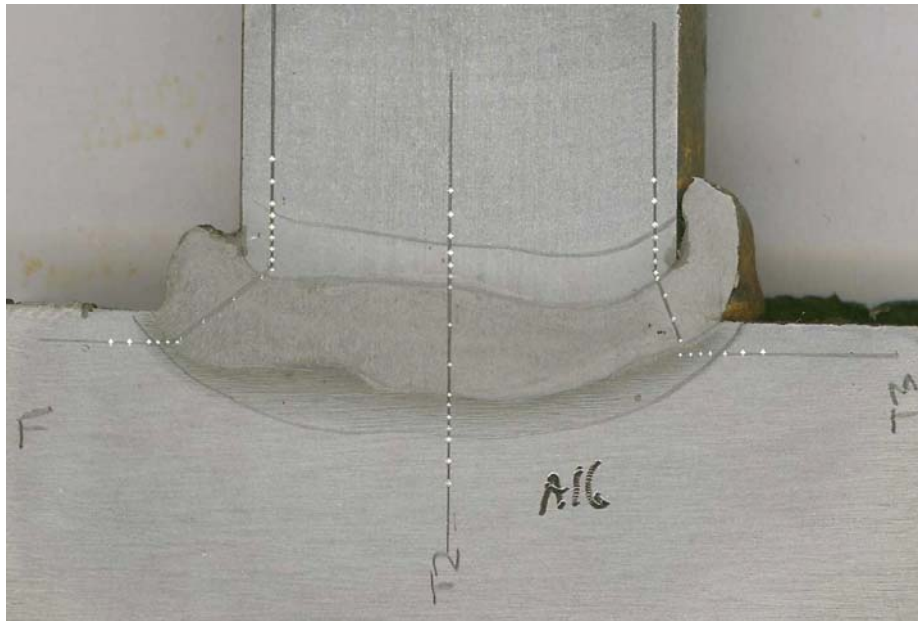


Figure 34 – Typical macro sample incorporating HV10 survey welded within acceptable parameter ranges

Macro samples to determine weld zone fusion where worst case scenarios incorporating heavy oxidation, uneven surfaces, stud refiring and where welded lugs had been removed were completed. Under all these conditions, excellent fusion was achieved in all cases. This proves the stud welding process can tolerate all these less than ideal surface conditions.

During production, the weld zone location will be ground flat to bright metal, however deviations in contact area between the base material and stud are likely in some cases. The observations made to macro sections representative of this condition, and conditions far worse provide a degree of comfort that the resultant stud weld is sound and typical of those welded under ideal surface conditions.

9.10 Results of elevated temperature fatigue test.

Stud sample A17 was subject to an elevated temperature fatigue test at 300°C to compare results with those obtained for the ambient temperature fatigue test. It was decided to machine a sample from the stud, as the autoclave fitted to the fatigue testing machine would not accommodate the standard stud to base plate configuration.

The machined sample did not exhibit the stress concentrations present on the ambient sample, however metallurgical notches were present where the stud HAZ, weld admixture, and base

material HAZ are considered. The same fatigue load parameters were applied and are summarised in table 12 below.

Table 12 – Summary of elevated temperature fatigue test parameters

Test temperature	Applied force	Resultant stress	Cycles per second	Duration of test	Cycles applied	Results
300°C	8 to 10 kN	220 MPa	8 Hz	24 hours	350,000 Approx	No failure reported

The above sample was expected to outperform the ambient temperature fatigue sample which failed at approximately 65,000 cycles, however there was no fatigue failure in the elevated temperature sample assessed. It is assumed the absence of stress concentrations on the test sample contributed to the values reported. Due to cost constraints, the elevated temperature fatigue test was abandoned following 24 hours.

In addition to the sample design, detailed in figure 36 below, the optimised stud welding parameters have resulted in freedom from weld porosity, hence improved fatigue performance. The fatigue crack initiation point on the ambient temperature sample was located at an inclusion within the weld. Based on the values reported, it can be concluded the fatigue performance of the stud weld is not adversely affected by temperatures up to 300°C.

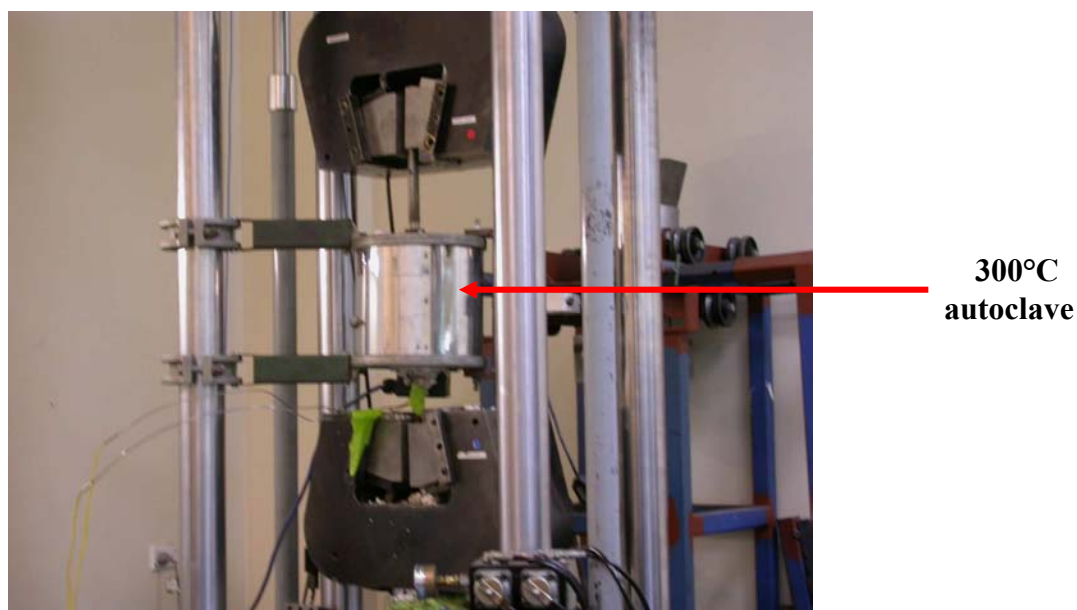


Figure 35 – Elevated fatigue test setup

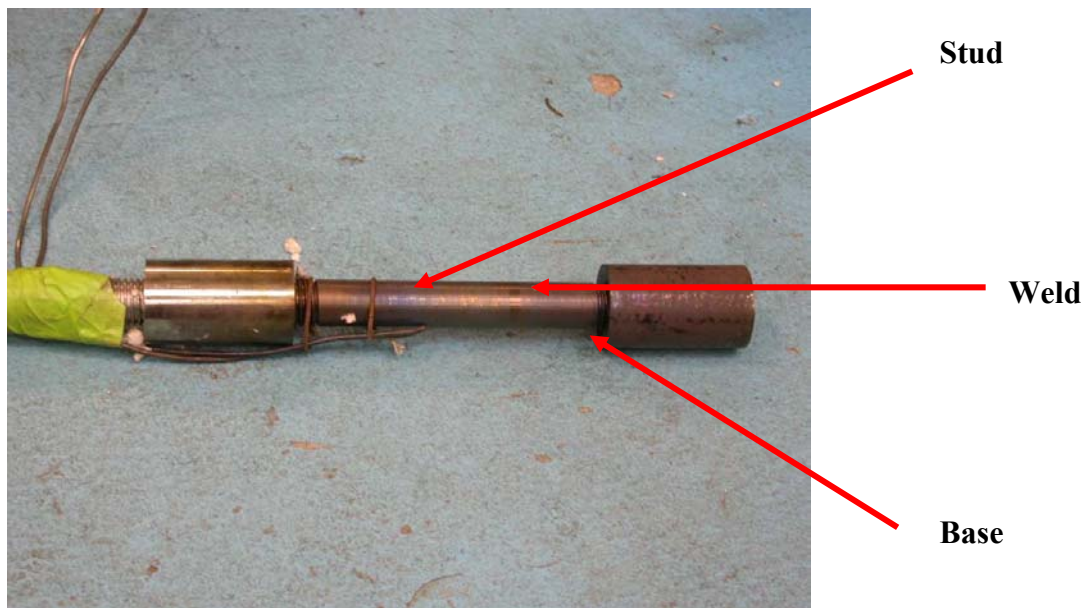


Figure 36 – Elevated fatigue test sample

9.11 Results of metallography to typical stud weld samples.

Stud sample A16, (as shown in figure 34 above), was subject to metallography to determine the microstructure present across the welded zone including the base materials. The sample was prepared using silicon carbide paper to a P1200 finish, polished using diamond paste to 0.25 μm finish and etched using a 2% nital solution. The samples were evaluated at 100 times magnification using a metallurgical microscope. The following features in each microstructure were observed:

Stud base material – The microstructure exhibited equiaxed grains of ferrite and pearlite. The percentage of pearlite was in the vicinity of 20%, typical of that expected with carbon, manganese steel containing 0.2% carbon. A photo of the microstructure in this region is presented in figure 37 below.

Stud heat affected zone, (HAZ) – The microstructure exhibited grain boundary ferrite in a matrix of finely distributed pearlite. A percentage of the ferrite exhibited a widmanstatten morphology, typical in weld microstructures where rapid thermal cycles occur. (It is interesting that this ferrite feature is also present in meteorites which experience a similar thermal cycle). The pearlite appeared degraded, suggesting a rapid thermal cycle where not enough time is available to form the typical plate like appearance. A photo of the microstructure in this region is presented in figure 38 below.

Weld zone – The microstructure exhibited ferrite in a matrix of pearlite. The ferrite exhibited a side plate morphology, interspersed amongst the pearlite. The pearlite again appeared degraded, without the typical layered appearance. The weldmetal created by an admixture of both base materials had more pearlite than expected. This is assumed due to the elevated percentage of carbon in the weld zone as opposed to typical low carbon, ($< 0.02\%$), weldmetal produced using conventional fusion welding techniques. In summary, the overall microstructure exhibited a columnar appearance, typical of weldmetal. A photo of the microstructure in this region is presented in figure 39 below.

Base material heat affected zone – This microstructure was very interesting to observe, incorporating at least four phases. In general, it consisted of ferrite and pearlite, combined with small regions of acicular bainite and tempered martensite. The overall microstructure is typical of the fast cooling rates associated with stud welding. Whilst very small isolated regions of martensite are present, this is normal for welded heat affected zones, and is not considered detrimental. A photo of the microstructure in this region is presented in figure 40 below.

Plate base material – This microstructure consisted of equiaxed grains of ferrite and pearlite with a distinct banded appearance. These bands are typical of “as rolled” plates, where as cast agglomerations of pearlite and ferrite are stretched out and flattened as a result of hot rolling operations. Some of the pearlite appeared to be degraded, assumed to be spherodised due to prolonged periods at elevated temperature during service as a kiln shell section. A photo of the microstructure in this region is presented in figure 41 below.

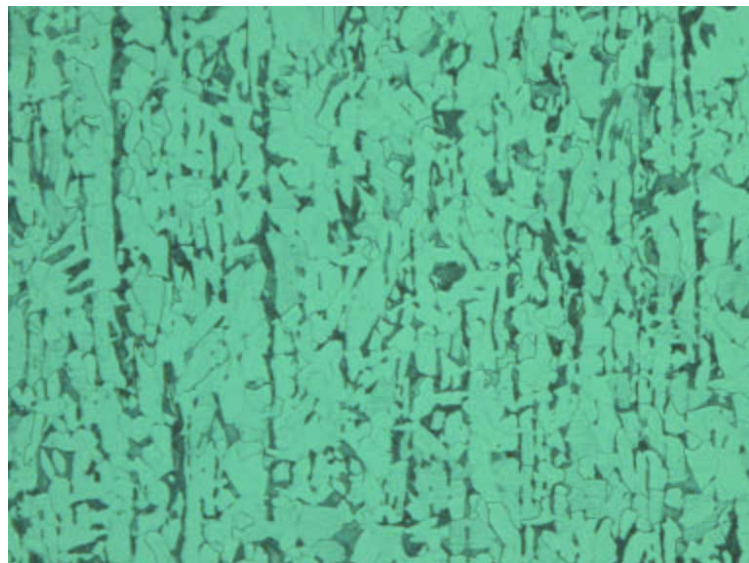


Figure 37 – Stud base material micrograph



Figure 38 – Stud HAZ micrograph

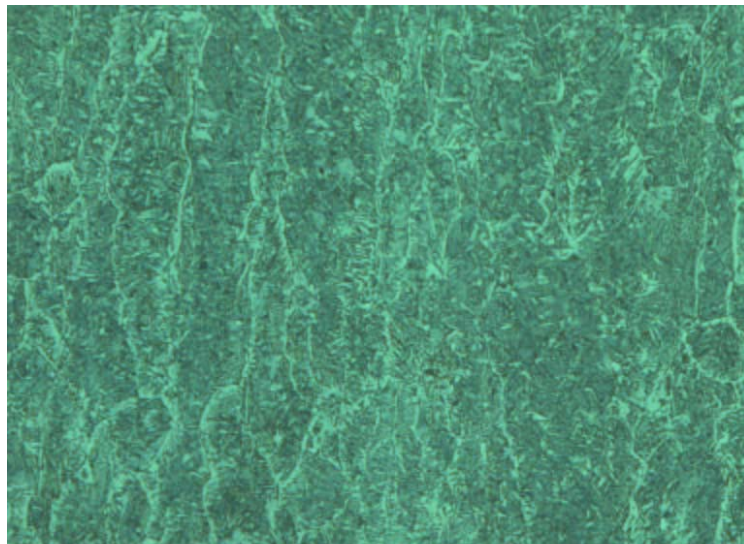


Figure 39 – Weld zone micrograph

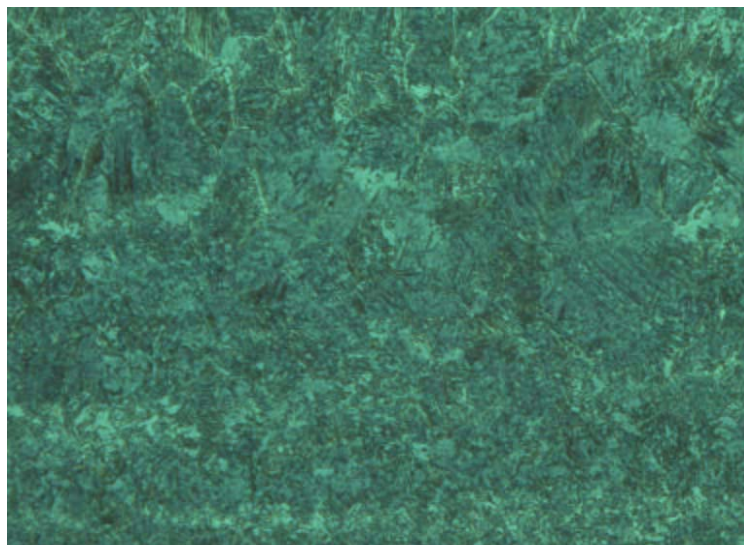


Figure 40 – Plate HAZ micrograph

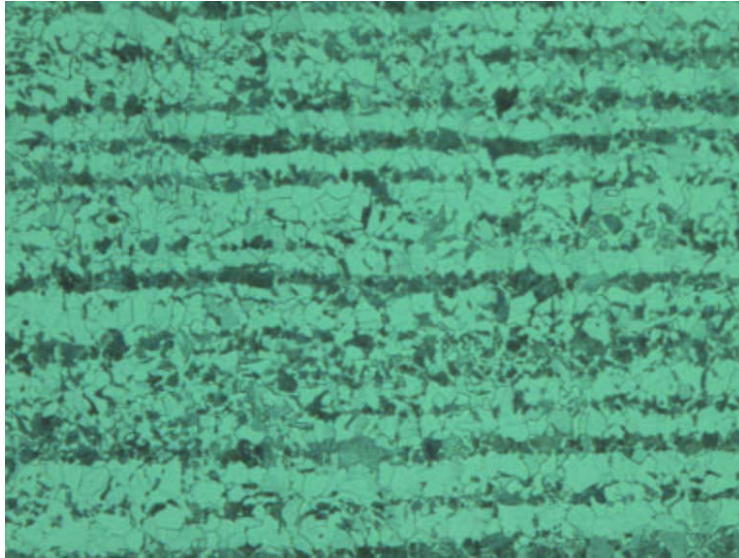


Figure 41 – Plate base material micrograph

9.12 Conclusions

Following the mechanical and metallurgical testing regimes applied to the stud welding qualification samples, it can be concluded the stud welds exhibit mechanical properties exceeding the standard attachment method utilising MMAW welded lugs.

The microstructures reported for the stud welds reveal no serious deleterious phases, and are typical of those expected for the base materials following the thermal cycles applied during welding operations and the samples tested reflect the materials of construction.

Based on the information gathered, the author is certain the stud welding proposal can be used as an alternative method for attachment of refractory anchors in rotary kilns and provide reliable service under the conditions imposed.

If the stud welding proposal is adopted, there are significant savings to owners and operators of rotary kilns by reducing the costly shut down periods where refractory anchors require replacement, and eliminating service failures associated with MMAW lug refractory anchor attachments.

10 FINALISED STUD DESIGN

The final design of the stud is based on the welded flat bar model in principle. With the current welded flat bar design as shown earlier in this report, (Figure 1), the 10mm diameter 253MA stainless steel anchor is threaded through the 12mm diameter x 20mm long slotted hole and stood up to lock against the flat bar. This is necessary, to lock the anchor in the upright position and prevent movement during refractory pouring. There are two options available for the stud end to reflect the welded lug and anchor assembly.

Design of the studs for the rotary kiln application is at the prototype stage, with final design confirmed once simple test regimes demonstrate the studs outperform the welded lug utilising a pull out test using the 253MA stainless steel anchor. At this point in time, option 2 looks most favourable, as it is preferred not to alter the design of the the 253MA stainless steel anchor.

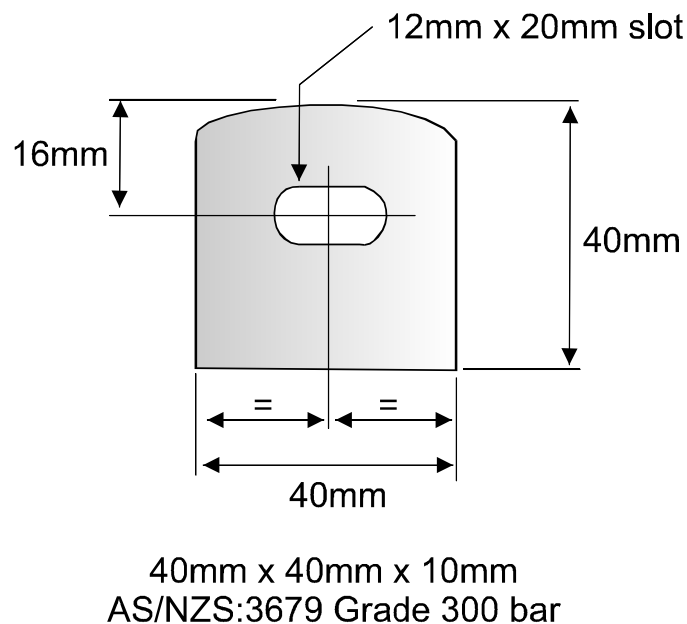


Figure 42 – Original AS/NZS: 3679 Grade 300 lug design

10.1 Option 1 stud design

The first option involves machining a small face at the end of the stud and drilling a hole to accept the 253MA stainless steel anchor. The current 253MA anchor design needs to be altered to enable fitment through the drilled hole as opposed to the current slotted hole. Whilst this is a feasible and simple stud design method, it is preferred not to change the design of the 253MA stainless steel anchor.

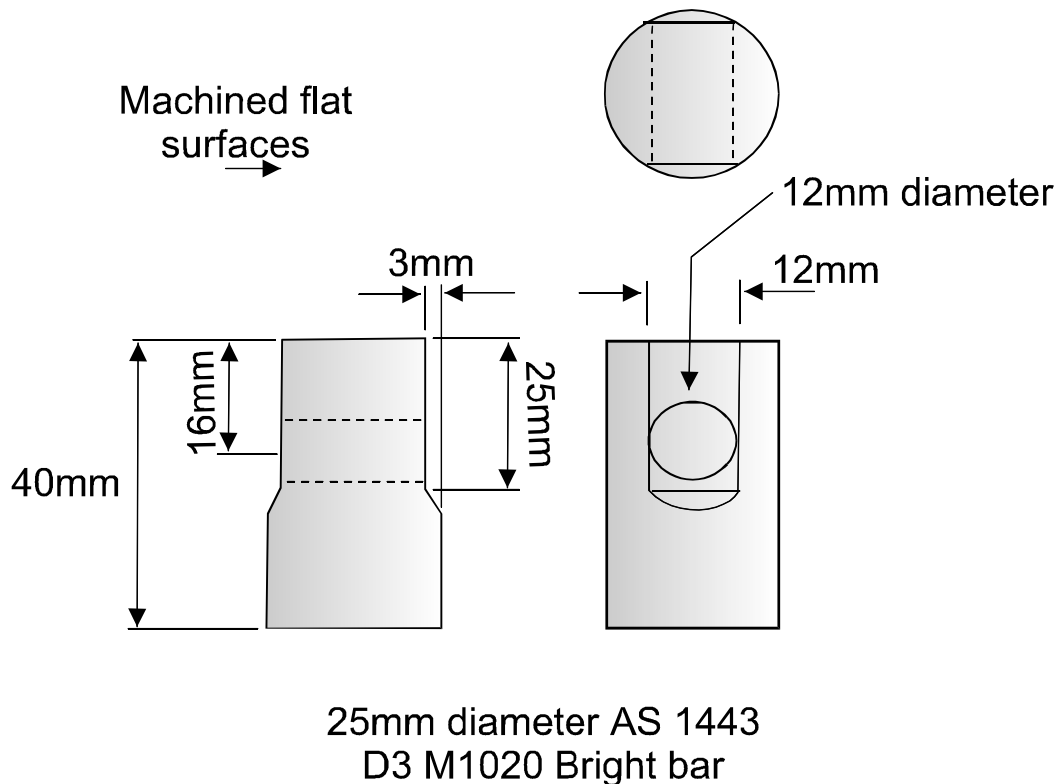


Figure 43 – Option 1 stud design

10.2 Option 2 stud design

The second option involves a hot forming operation to produce a flat face on the end of the stud, incorporating a slotted hole. This design facilitates the use of the current design 253MA stainless steel anchor and is the preferred option. The flattened end and slotted hole can be produced in one stage using a press incorporating a suitable die. The slotted hole does not need to be 20mm long to facilitate the fitment of the current design 253MA anchor, and is therefore reduced to 12mm diameter x 16mm long.

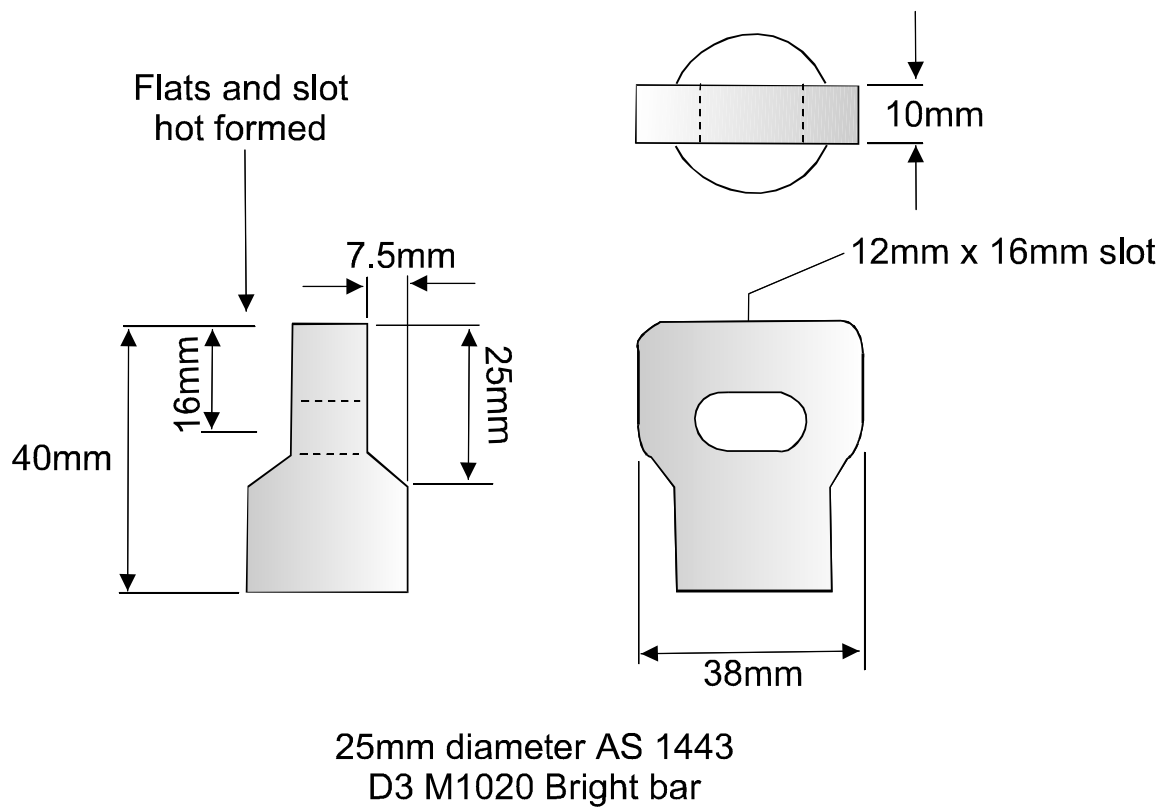


Figure 44 – Option 2 stud design

10.3 Proposed test regimes for final stud design

Design of the studs is at the prototype stage, with final design confirmed once simple test regimes demonstrate the studs outperform the welded with regard to a pull out test using the 253MA stainless steel anchor. This involves assembling the stud and anchor in a tensile testing machine and testing to destruction. The perceived outcome is the 235MA stainless steel anchor will elongate and fracture without any deformation occurring in the stud.

In addition to the pull out test described, metallography is planned to determine the final microstructure following hot forming operations. Heat treatment is not planned, and the hot forming procedure will facilitate a normalised structure in the deformed region.

11 PLANNED APPLICATION TO ROTARY KILNS

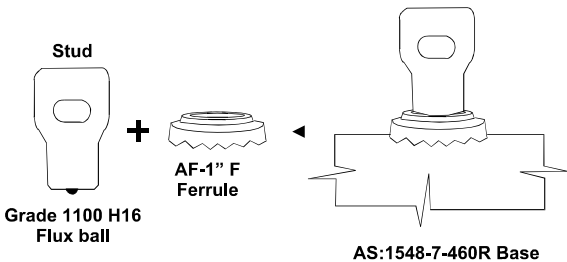
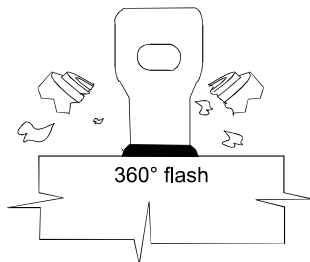
Iluka Resources Limited have undertaken to trial the stud welding proposal to a section of rotary kiln at the earliest possible convenience during a shut down period where remedial refractory operations are planned. A ten metre section at the end of the rotary kiln where the highest service temperatures are present is the proposed section where the studs that support the refractory anchor will be applied. It is in this region where the majority of welded lug service failures have occurred in the past. This region represents the worst service conditions and will be a good test for the studs to determine the success of the project. It is unfortunate the production application of the studs inside the rotary kiln is not scheduled until the second half of 2008, however a production and serviceability report for the stud refractory anchor supports will be prepared and incorporated as separate dissertation volume in future.

11.1 Welding procedure

A welding procedure in accordance with AS/NZS:1554 Part 2 and AWS D1.1 has been developed based on the mechanical testing regime applied to the qualification samples and applying the welding data recorded during the stud weld procedure qualification regime.

The welding procedure assures production welding is completed under controlled conditions and studs welded in accordance with the instructions provided will provide reliable service. It is important the welding procedure conveys all the vital operational data clearly and concisely, in a format that is easily understood. The following information is documented within the procedure:

- Applicable welding standards
- Base material data and thickness ranges
- Equipment and consumables
- Consumable husbandry
- Weld joint details and preparation
- Stud welding parameters
- Daily and production testing regimes
- Stud weld visual and test requirements
- Remedial instructions for non complying studs
- Approvals

STUD WELDING PROCEDURE QUALIFICATION & INSTRUCTION		WPS No	SW-0100 Rev 0	PQR No	IR-0100 Rev 0	
Code	AS/NZS:1554 Part 2 AWS D1.1	Stud material		AS:1443 Grade 1020		
Process	Drawn arc stud welding DSAW	Stud dimensions		25mm diameter		
Joint type	Stud weld	Base material		AS:1548-7-460R		
Position	Flat (0° to 10°)	Thickness range		32mm to 90mm		
THERMAL CONDITIONS		EQUIPMENT / CONSUMABLES				
Preheat	If < 10°C preheat to 50°C	Power source		Nelson 6000		
Method	LPG / Air torch	Stud gun		Nelson P-NS 20 BHD		
Check method	Calibrated pyrometer	Flux type		Aluminium 1100 H16		
Check distance	75mm from weld zone	Ferrule type		Ceramic AF-1" F		
STUD HUSBANDRY		FERRULE HUSBANDRY				
Studs shall be free from moisture rust, oils and other deleterious materials and stored in a suitable container at all times.		Ferrule shall be clean and dry. If moisture absorption is suspected, bake at 350°C for 2 hours				
JOINT DETAILS		WELD DETAIL				
						
WELDING PARAMETERS						
CURRENT		POLARITY	STICK OUT	LIFT	PLUNGE	TIME
Optimum < 5 %	1900 Amps	DCEN	4.0mm	4.0mm	6.0mm	1.2 secs
Optimum	2000 Amps					
Optimum > 5 %	2100 Amps					
STUD WELD QUALITY CONTROL REGIME						
<div>1. Prior to the commencement of every production shift, 2 studs shall be welded at 5% below and 2 studs 5% above optimum current using weld cycle time of 1.2 seconds on representative base material within + / - 25% of the production thickness.</div> <div>2. These studs shall exhibit 360° flash and pass an ambient temperature bend test at 45° from the original axis without any sign of disbondment.</div> <div>3. The above QC regime shall be repeated at the commencement of each shift and following every 250 studs welded during any production run.</div> <div>4. Production welded studs shall be welded within 10° of bottom dead centre and upon completion, 100% visually inspected to confirm 360° flash and hammer tested. Non conforming studs shall be removed using grinding methods and rewelded</div> <div>5. Stud weld locations shall be ground to bright metal, free from oxide and other deleterious material.</div>						
Approved fabricator		Release Stamp		Approved Client		Approve stamp

12 FINITE ELEMENT ANALYSIS MODELS

Autodesk Inventor Professional Stress Analysis was used to simulate the behaviour of the stud under structural loading conditions of compression, tension and bending moment. An evaluation version of ANSYS software, made available by the University of Wollongong, generated the results presented in this report. Additional information for Autodesk Inventor Professional Stress Analysis and ANSYS products is available at <http://www.ansys.com/autodesk>.

The outcomes calculated are not a sole basis to accept or reject the design based solely on the data presented in the tables below. Evaluation of the stud considers the information gathered using FEA models in conjunction with practical test data. The general approach to any engineering design usually applies engineering calculations and additional physical testing based on actual production mock ups as the final means of verifying structural integrity.

12.1 Geometry and Mesh

The relevance setting listed below controlled the fineness of the mesh used for the FEA models. For reference, a setting of -100 produces a coarse mesh, fast solutions and results that may result in significant uncertainty. A setting of +100 generates a fine mesh, longer solution times and the least uncertainty in results. Zero is the default Relevance setting and was applied in this case. Bounding box dimensions represent lengths in the global X, Y and Z directions.

Table 13 – Stud and FEA model statistics

Bounding Box Dimensions	25.0 mm , 25.0 mm, 40.0 mm
Stud Mass	0.153 kg
Stud Volume	1.949e+004 mm ³
Mesh Relevance Setting	0
Nodes	8926
Elements	1950

Stud mass and volume is inclusive of flash material incorporating a percentage of base material, and is as calculated by the ANSYS program. Stud volume and mass alone is 1.809e+004 mm³ and 0.142 kg respectively.

12.2 Material Data

The following material properties apply to this analysis:

- Linear - Stress is directly proportional to strain.
- Constant - All properties are temperature independent.
- Homogeneous - Properties do not change throughout the part.
- Isotropic - Material properties are identical in all directions.

Table 14 – Stud material statistics

Young's Modulus	2.1e+005 MPa
Poisson's Ratio	0.30
Mass Density	7.85e-006 kg/mm ³
Tensile Yield Strength	380.0 MPa
Tensile Ultimate Strength	480.0 MPa

12.3 Loads and constraints for compressive, tensile and bending forces

The following loads and constraints act on specific regions of the stud based on a 30 MPa compressive, tensile and bending load. Vector data corresponds to X, Y and Z components.

Table 15 – Load and Constraint definitions

Name	Type	Magnitude	Vector
Force	Surface force	3.e+007 N	0.00 N 0.00 N -3.e+007 N
Fixed constraint	Edge fixed constraint	0.00 mm	0.00 mm 0.00 mm 0.00 mm

Table 16 – Constraint reactions

Name	Force	Vector	Moment	Moment Vector
Fixed Constraint Compression	3.e+007 N	8.481e-003 N 3.632e-002 N 3.e+007 N	0.9375 N/mm	-0.7583 N/mm -0.4625 N/mm -0.3 N/mm
Fixed Constraint Tensile	3.e+007 N	-2.295e-002 N -3.693e-002 N -3.e+007 N	2.01 N/mm	-1.155 N/mm -1.556 N/mm -0.5353 N/mm
Fixed Constraint Bending	3.e+007 N	-0.1265 N 3.e+007 N 0.1024 N	1.14e+009 N/mm	-1.14e+009 N/mm -3.611 N/mm -0.3703 N/mm

12.4 Results

Table 16 below lists all structural results generated by the FEA analysis. Safety factor was calculated by using the maximum equivalent stress failure theory for ductile materials calculated by the ANSYS software. The stress limitation is determined by the yield and tensile strength of the material. Vector data corresponds to X, Y and Z components.

Table 17 – Analysis results - Compression

Name	Minimum	Maximum
Equivalent Stress	2980 MPa	7.767e+005 MPa
Maximum Principal Stress	-3.98e+004 MPa	1.923e+005 MPa
Minimum Principal Stress	-8.999e+005 MPa	7092 MPa
Deformation	0.00 mm	18.59 mm
Safety Factor	2.665e-004	N/A

Table 18 – Analysis results - Tensile

Name	Minimum	Maximum
Equivalent Stress	2791 MPa	9.987e+005 MPa
Maximum Principal Stress	-6467 MPa	1.159e+006 MPa
Minimum Principal Stress	-2.318e+005 MPa	5.031e+004 MPa
Deformation	0.00 mm	19.08 mm
Safety Factor	2.073e-004	N/A

Table 19 – Analysis results - Bending

Name	Minimum	Maximum
Equivalent Stress	3367 MPa	4.747e+006 MPa
Maximum Principal Stress	-1.922e+005 MPa	5.236e+006 MPa
Minimum Principal Stress	-4.782e+006 MPa	2.e+005 MPa
Deformation	0.00 mm	283.8 mm
Safety Factor	4.361e-005	N/A

12.5 FEA contour figures

The following section provides figures showing each load outcome contoured over the surface of the stud.

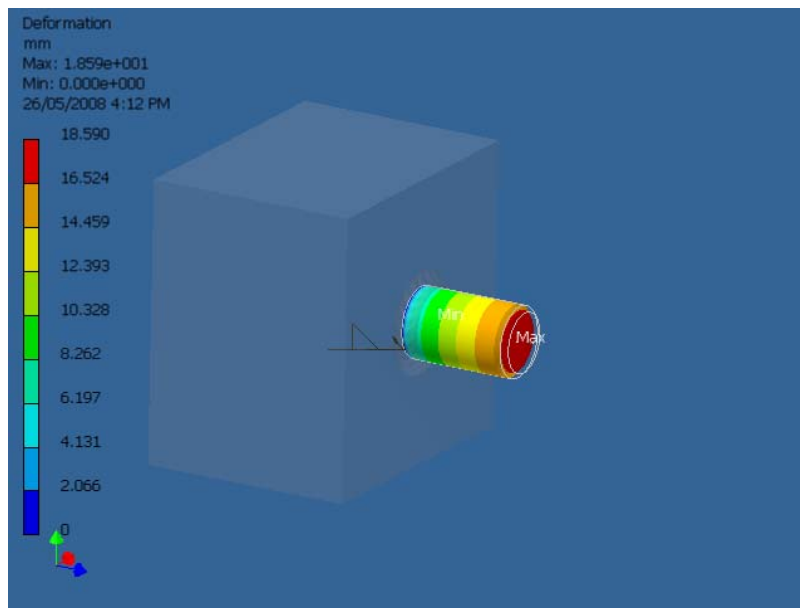


Figure 45
Deformation compression

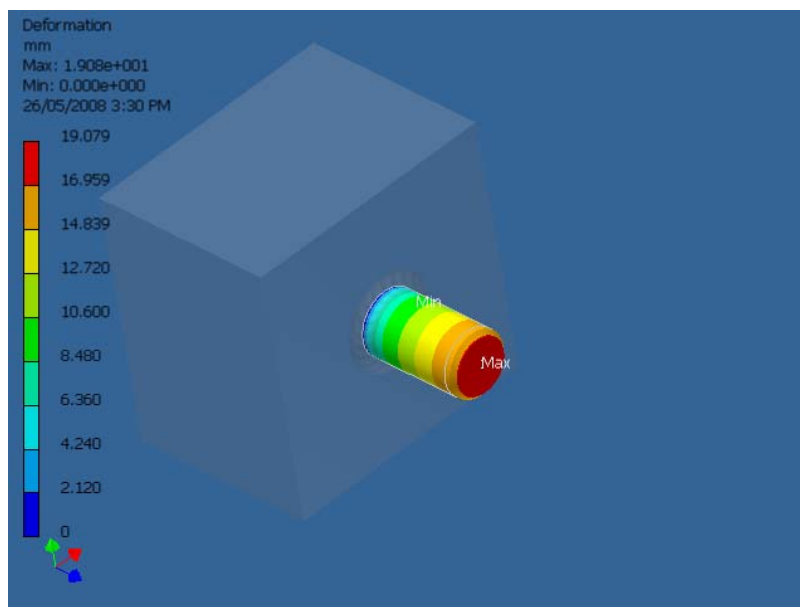


Figure 46
Deformation tension

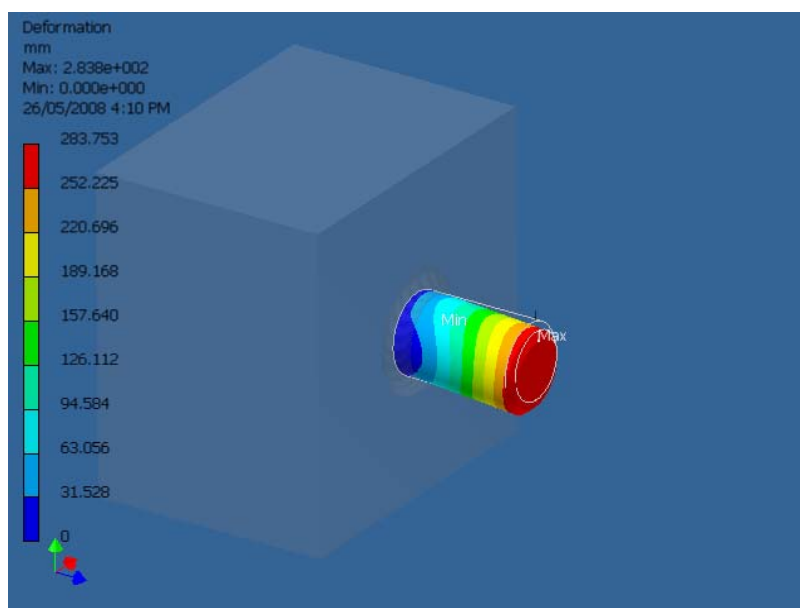


Figure 47
Deformation bending

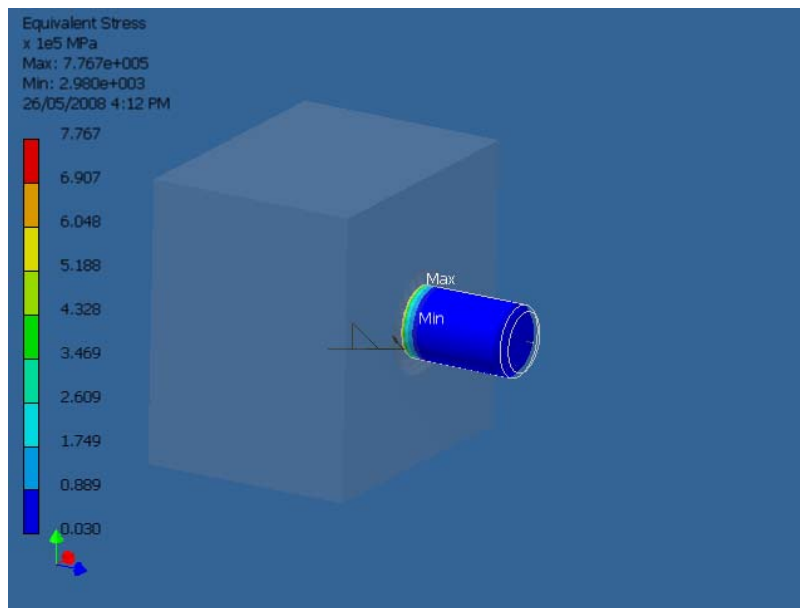


Figure 48
Equivalent stress
Compression

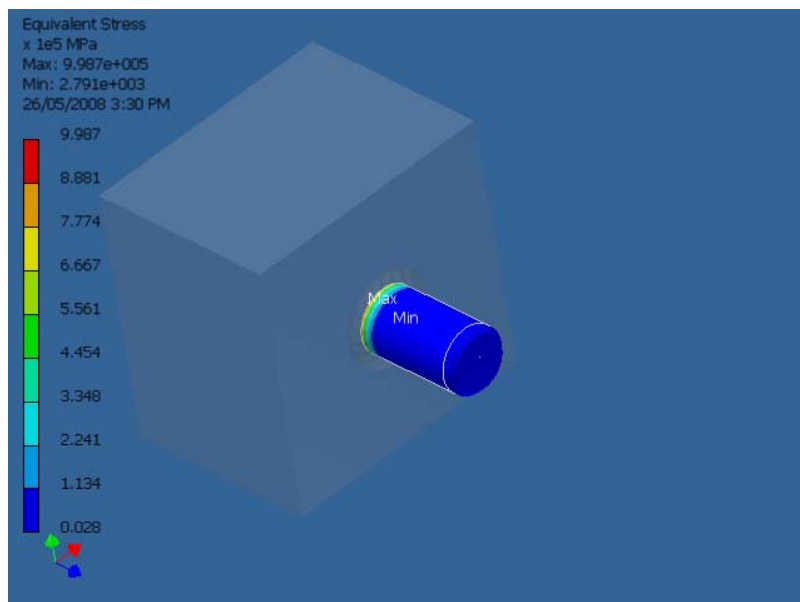


Figure 49
Equivalent stress
Tension

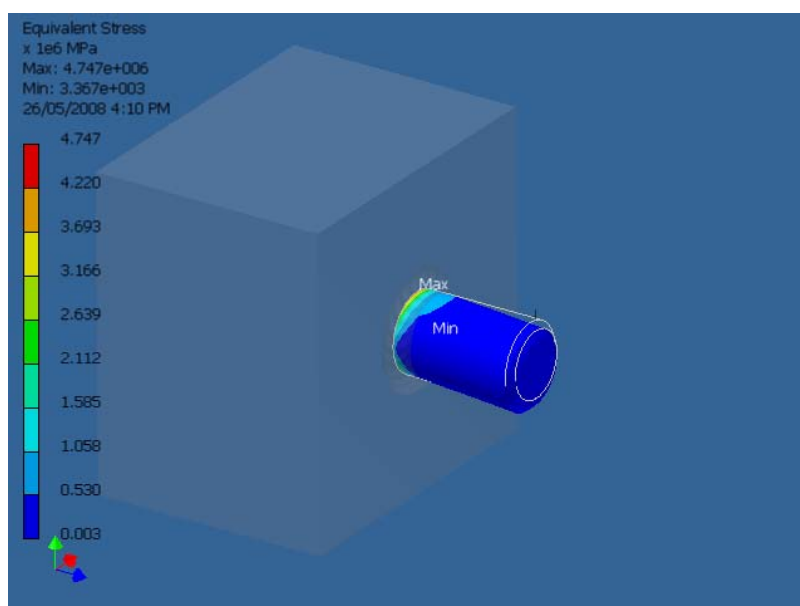


Figure 50
Equivalent stress
Bending

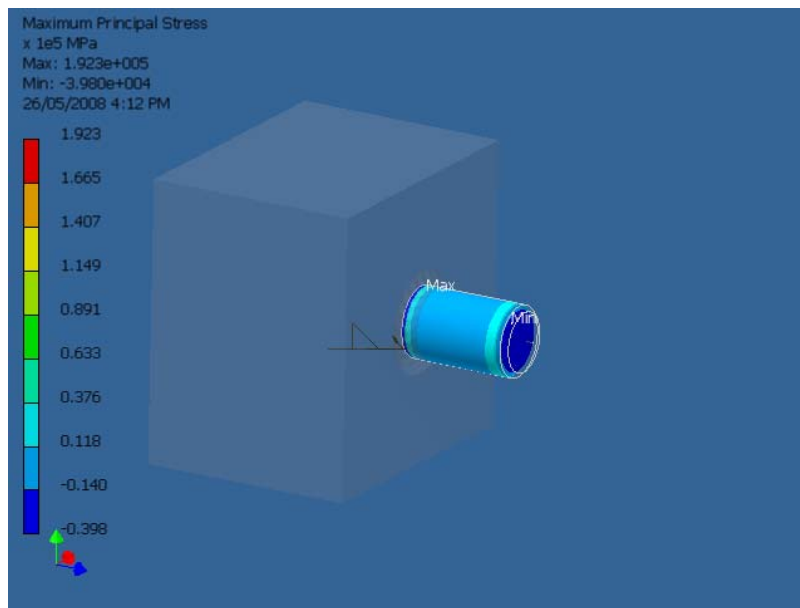


Figure 51
Maximum principle stress
Compression

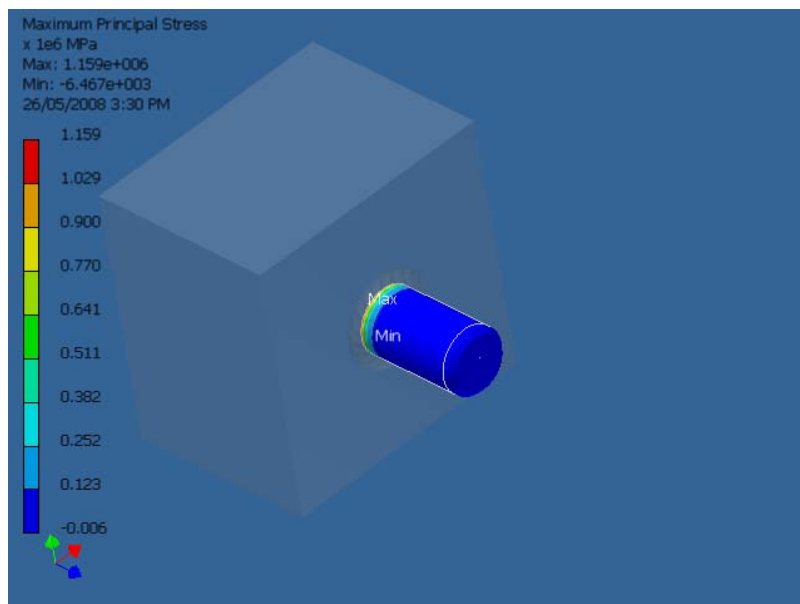


Figure 52
Maximum principle stress
Tension

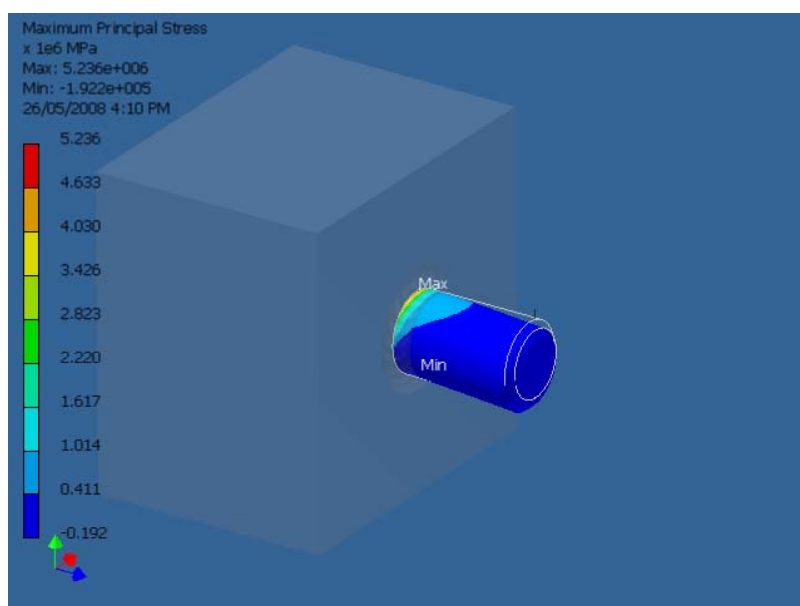


Figure 53
Maximum principle stress
Bending

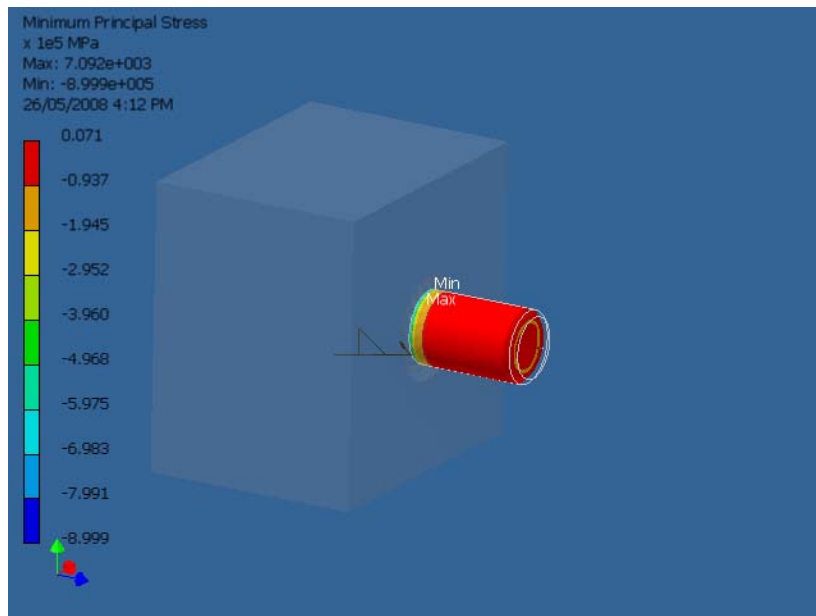


Figure 54
Minimum principle stress
Compression

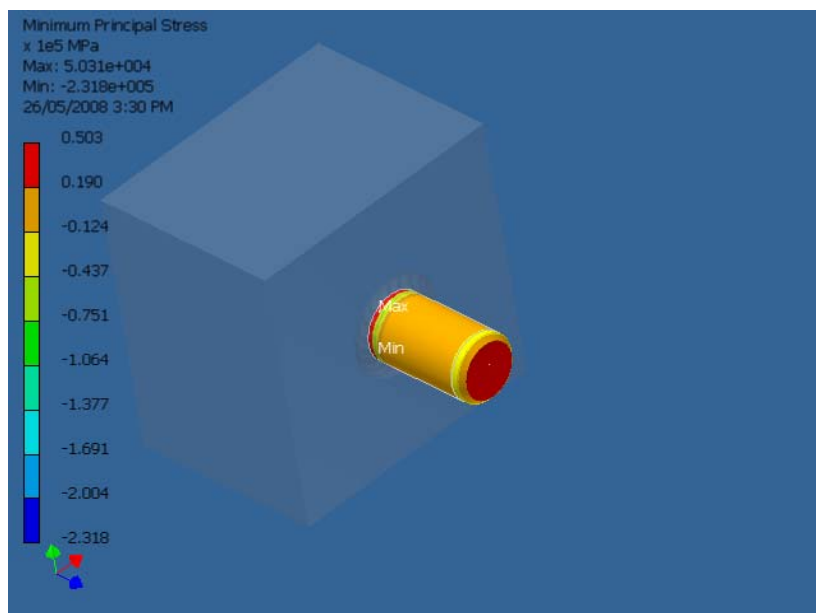


Figure 55
Minimum principle stress
Tension

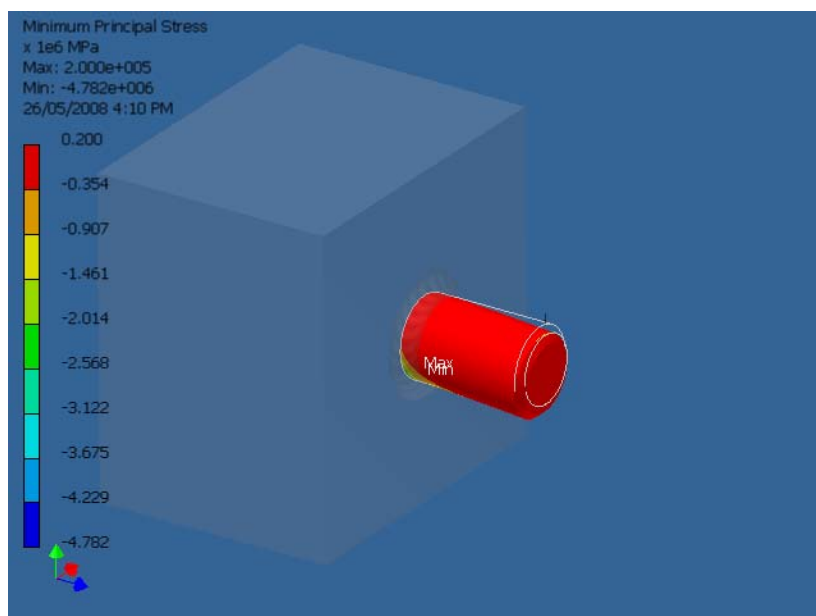


Figure 56
Minimum principle stress
Bending

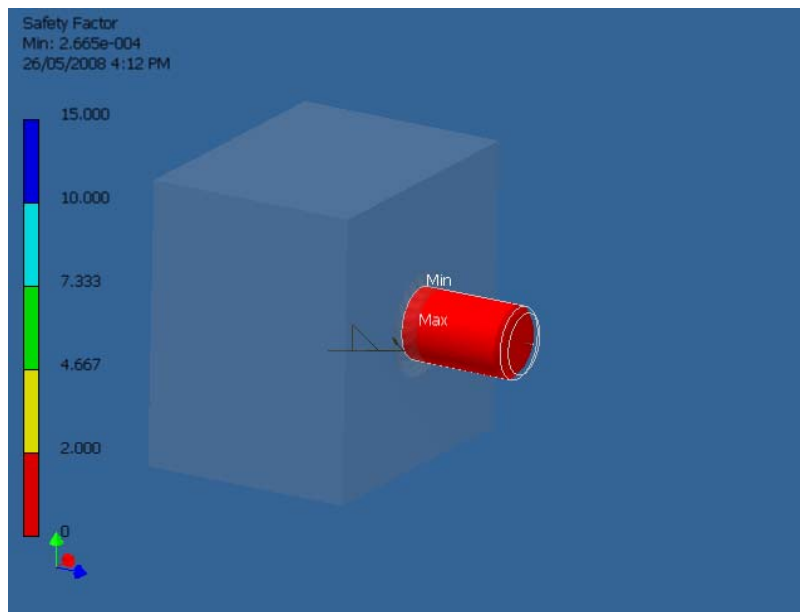


Figure 57
Safety factor
Compression

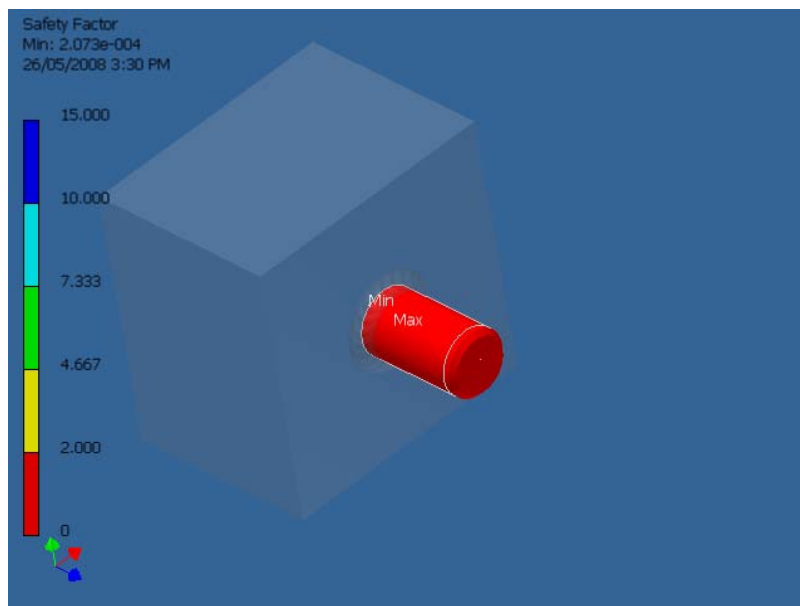


Figure 58
Safety factor
Tension

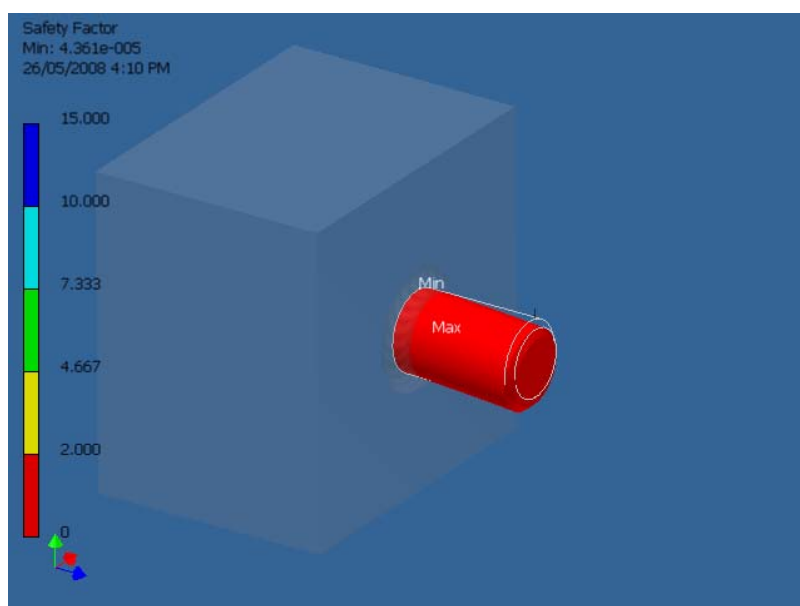


Figure 59
Safety factor
Bending

Bibliography and list of references

The following Australian and international standards were referenced and researched to assist with the development of this dissertation. Table numbers within these standards are referenced in the dissertation table headings.

AS:1443 – 2004: Carbon and carbon manganese steel – Cold finished bars

AS/NZS:1554: 1: 2004: Structural steel welding – Welding of steel structures

AS/NZS:1554: 2: 2003: Structural steel welding Part 2: Stud welding (steel studs to steel)

AWS D1.1: 2006 – Structural welding code – steel

AS: 1210: 97 – Pressure vessels

AS/NZS:3679-1:1996 – Structural steel - Hot-rolled bars and sections

AS: 1548 – 2008: Fine grain weldable steel plates for pressure equipment

AS: 4100: 1998 – Steel structures

The following test laboratories assisted in compiling mechanical test values and metallurgical data:

The Marine Inspection service – Mr Jeff Cook

Exceed Consulting – Mr Jeff Dunning

Amdel Testing – Mr Monty Luke

Software used to generate FEA models:

ANSYS evaluation software supplied by The University of Wollongong

Websites researched to assist with stud welding technology:

American Welding Society – www.aws.org

The Welding Institute – www.twi.co.uk

Welding Technology Institute of Australia – www.wtia.com.au

Appendix 1 – Stress range and load capacity calculations

Calculations used for design stress ranges at 10^6 cycles:

$f_{rs} = 90$ MPa from figure 11.6.2 and category 80 joint design.

$\beta_{tf} = 1.0 \leq 25$ mm thickness.

$\beta_{tf} = \left(\frac{25}{tp} \right)^{0.25}$ for > 25 mm thickness.

$f_{rsc} = \beta_{tf} \times f_{rs} \rightarrow 1.0 \times 90 = 90$ MPa for ≤ 25 mm thickness.

$f_{rsc} = \beta_{tf} \times f_{rs} \rightarrow 0.98 \times 90 = 88.2$ MPa for 27mm stud.

$f_{rsc} = \beta_{tf} \times f_{rs} \rightarrow 0.95 \times 90 = 85.5$ MPa for 30mm stud.

$\frac{f^*}{\Phi f_{rsc}} \leq 1.0 \rightarrow 1.0 \times 0.7 \times 90 = 63$ MPa at 10^6 cycles ≤ 25 mm thickness.

$\frac{f^*}{\Phi f_{rsc}} \leq 1.0 \rightarrow 1.0 \times 0.7 \times 88.2 = 61.75$ MPa at 10^6 cycles for 27mm stud.

$\frac{f^*}{\Phi f_{rsc}} \leq 1.0 \rightarrow 1.0 \times 0.7 \times 85.5 = 59.85$ MPa at 10^6 cycles for 30mm stud.

Calculations used to determine load capacity:

$F = 63$ MPa

$A =$ fillet throat x length for fillet welds in mm^2 .

$A =$ stud weld / base material interface in mm^2 .

$\sigma = \frac{F}{A} \rightarrow F = \sigma \times A$