AUSTRALIAN MEAT PROCESSOR CORPORATION

Butcher's Glove Technical Feasibility Report

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Table Contents

1.0 Executive Summary

The research undertaken in Stage 1 of the project indicates that the glove concept is technically feasible. A number of materials and manufacturing techniques were identified as being suitable for high, medium and low volume scale production. A range of samples were sourced and preliminary testing was completed; however further quantitative testing is recommended to verify performance.

The concept was explored with a leading Australian based glove manufacturer to identify suitable glove types, materials and construction techniques. A selection of sample gloves has been supplied for review. Various design and construction methodologies were explored to enable the integration of the scales and other specific features that contribute to overall performance. Further concept development with a glove manufacturer to source custom glove samples made to a particular specification is recommended, for the purposes of prototype validation and quantitative testing.

The bonding requirement was investigated with a worldwide adhesive industry leader to identify suitable bonding materials and techniques for our specific application. A suitable product was selected and preliminary testing was performed with positive results. Further quantitative testing in conjunction with the scale and glove samples is recommended to verify performance.

A number of scale, glove and adhesive samples have been sourced as part of Stage 2, and preliminary testing and assessment has been performed. All samples are provided for review.

The detailed contents of this report compiled as part of Stage 3 provide a summary of the research, basic principles and substantiation of recommendations.

Milestone	Achievement criteria	Status
1	AGE 1: Materials and Processes Research:	Complete
	1.1 Protective Exterior Physical Barrier ‘Scales’	
	1.2 Glove ‘Membrane’ Manufacturing Options	
	1.3 ‘Technology Bonding Techniques’	
2	STAGE 2: Material samples and testing	Complete
3	STAGE 3: Project Report	This document

All stages of the project have yielded positive results. The concept as presented as part of "**Final Report (not for public release) Butcher Glove 12 1 12.pdf**" is technically feasible from performance and manufacturing standpoints. Further stages of research, testing and development are recommended in the following areas to refine the concept:

- **Market review** – define the target market size and scope, to ensure appropriate design decisions regarding materials and manufacturing processes are made.
- **Anthropometric studies** – to review the spectrum of sizes and proportions of target users and ensure appropriate ergonomic criteria are addressed.
- **Typical injury review** – to identify high risk activities, and injury frequency, severity and location on hand or arm.
- **Scale design** – based on anthropometric and injury data, develop and test scale shape and position templates for maximum worker protection and efficiency.
- **Scale material testing** – carry out quantitative testing on the various scale material and manufacturing options to assess performance in a variety of scenarios.
- P**rototype development** – in conjunction with a suitable industry partner, develop and test suggested seamless knitted glove concepts, integrate scales and dipping process to create functional prototypes for user and performance based analysis.

2.0 Introduction

Kennovations were briefed on the details of band saw preparation of carcass primal cutting and meat portioning in 2011, including a site visit to an industry leading processor. The site visit which included an industry consultation session was used to identify typical industry operating procedures and design objectives. Kennovations then entered into a design phase in order to develop a concept for a protective glove. The resulting report; "**Final Report (not for public release) Butcher Glove 12_1_12.pdf**" for this project was submitted for review to MLA and AMPC for consideration.

Figure 1 - Protective glove concept images
*Source: "**Final Report (not for public release) Butcher Glove 12_1_12.pdf**"*

The protective glove (see Figure 1) concepts are comprised of an innovative protective exterior physical barrier and incorporate user or wearer features to promote comfort and compliance. The success of the glove concepts will be largely dependent on the capacity of the two core material technologies to deliver key benefits. Primarily the glove wearer is provided increased safety by the cut resistance of the metallic polymer 'scales' and maintains productivity by the provision of flexibility through a silicon or polyurethane 'membrane'.

3.0 Project Objectives & Methodology

The design concepts from the previous Report were preliminary only and a range of research and development activities must be undertaken to verify the design methodologies and to provide confidence the design can deliver the intended overall functionality should it be developed further. It was agreed that a three stage review be completed on the proposed core technologies to further this research.

STAGE 1: Materials and Processes Research:

3.1 Protective Exterior Physical Barrier 'Scales'

The 'scales' are considered the principal technology in this design. The general design, including material choices and potential manufacturing processes for these components will be the initial and most significant component of this research stage. Research may include (but not be limited to):

- Cutting blade type definition
- 'Scale' material selections (metallic and non-metallic options / alloys / hardness /
- durability / corrosion resistance)
- Manufacturing techniques (3D printing / sintering / stamping / forging)
- Material Treatment options (heat treating / coating / other techniques)
- Costs for development and manufacture
- Other issues of interest

3.2 Glove 'Membrane' Manufacturing Options

The glove 'membrane' components are considered a second level technology in this design. The general design, material choices, and manufacturing processes for these components will be the second focus area of this research stage. Research may include (but not be limited to):

- Material selections (durability / flexibility / repairs / maintenance)
- Anthropometrics (sizing / design versatility)
- Manufacturing methods
- Costs for development and manufacture
- Industry partnership opportunities

3.3 ‘Technology Bonding Techniques’

The method for bonding the ‘scale’ and ‘membrane’ is considered a third tier technology in this design. The general design, material choices, and manufacturing processes for this component will be the final focus of this research stage. Research may include (but not be limited to):

- Bonding materials and processes (tapes/glues/fusion techniques/co-molding)

*Some items are expected to be explored during discussions on Item 1.2

STAGE 2: Material samples and testing

Kennovations are to design, obtain and/or develop a range of product samples to assist with assessment of the design concepts. The capacity for producing samples of ‘Scales’,

‘Membranes’ and ‘Technology Bonding Techniques’ will be assessed during Stage 1 and where applicable suitable preliminary testing may be arranged. This stage does not include the development of a full working model as it is expected that a significant additional body of work is required prior to this being achievable. The required body of work may form part of further research and development.

STAGE 3: Project Report

A report is to be developed summarising findings from Stages 1 and 2. The report will identify limitations and opportunities for the research and will also contain a proposal for further development.

4.0 Project Outcomes

4.1. Protective Exterior Physical Barrier ‘Scales’ – Detailed Research

4.1.1 Band Saw Blades

There are a number of band saw blade manufacturers that supply specific meat cutting blades. Well-known brands include:

- Munkfors
- Kasco
- Starret
- Simmons

Dimensions and tooth design vary between models. Selections are based on whether bone is present, the size of the machine, the type of cut e.g. splitting, portioning, etc.

- Blade thicknesses range from 0.4mm to 0.8mm
- Blade widths range from 10.5 to 25mm
- Tooth pitch is always constant per blade, and range from 3 to 10 TPI (Tooth Per Inch)
- Tooth design is either a hook or scallop
- Tooth set is either straight or alternate

Blade speed and tension settings vary between machines. Typical speeds range from 1200-2000 metres per minute. Tension is typically pre-set by the manufacturer.

Blades are available in either high carbon steel or stainless steel. High carbon steel blades are preferred in the industry due to longer life and sharpness, although stainless blades have better resistance to the chemicals used during machine cleaning.

The high carbon steel blades are typically 1095 steel with an induction heating and quenching heat treatment process applied to the teeth of the blade to achieve high material hardness. Stainless steel blades are typically grade 420 with teeth ground sharp. The % weight chemical composition of each metal is shown below:

	Iron	Carbon	Manganese	Phosphorus	Sulphur	Silicon	Chromium
1095	Balance	0.9 - 1.03	0.3 - 0.5	0.04 max	0.05 max	-	-
420 s/s	Balance	0.15 - 0.35	1.0 max	0.04 max	0.03 max	1.0 max	12 - 14

4.1.2 Blade Hardness Testing

A range of carbon steel band saw blade samples were sourced from Thompson Meat Machinery (developer of the 'Blade Stop' technology). Six sample pieces (see Figure 8) were sent to LMATS, an independent engineering testing laboratory with NATA accreditation. The samples were mounted in epoxy resin, and one of the induction hardened teeth per sample was tested to ascertain material hardness.

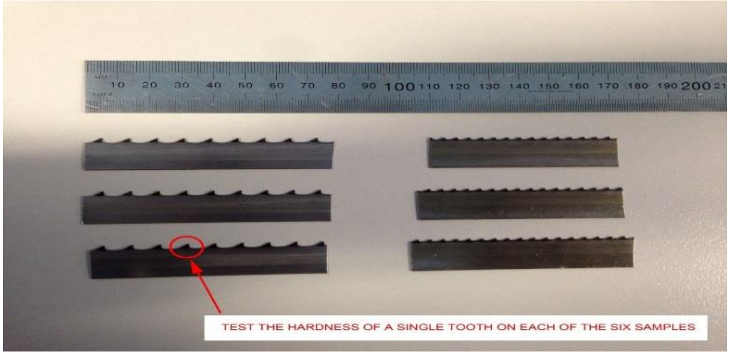


Figure 8 - Six sample blade pieces (source: Kennovations photo)

Results[1]

Identification / test location	Average Vickers hardness (HV/5)	Converted HRC[2]
MK6 Senior 3TPI	709	60
MK6 Senior 3TPI	689	60
MK6 Senior 3TPI	681	59
MK6 Senior 6TPI	655	58
MK6 Senior 6TPI	701	60
MK6 Senior 6TPI	670	59

- Refer to the appendix for full test report.
- Converted Rockwell C value is estimated as per AS 5016-2004 as an approximation for indicative purposes only.

4.1.3 Protective scale

In order to provide the band saw user with suitable protection from the rotating band saw blade, the proposed protective scale must be made of a suitable material. The ideal scale would not be damaged by the blade in any way.

Although the scale could potentially sustain damage from the blade and still protect the user, a damaged scale may be rendered inherently weak as a result, and susceptible to further damage or catastrophic failure, thus endangering the user. Furthermore, when a scale is damaged, chips or particles from the damaged scale may also contaminate the meat.

The goal is to identify one or a number of possible materials of which to make the protective scale, which are primarily harder, tougher and more wear resistant than the blade material. Additionally, in the event of damage or failure, any particles must be able to be identified through existing x-ray methods.

In order to identify a suitable material for the scale, we investigated a wide range of metals and their properties. The main characteristics we require are:

- Hardness
- Toughness
- Wear resistance
- Corrosion resistance
- Manufacturability

The properties of a material is reflected its microstructure. Microstructures are controlled by the composition of the material and how it is processed. The following section of the report includes summaries of the main factors that comprise and influence a material’s microstructure and corresponding characteristics.

4.1.4 Scale Materials

4.1.4.1 Ferrous vs Non-Ferrous Metals

All metals may be classified as ferrous or non-ferrous. A ferrous metal has iron as its main element. In its pure form iron is relatively soft, but it can be significantly hardened and strengthened by creating alloys with other elements. Iron is commonly alloyed with carbon to produce steel and cast iron; however it is susceptible to corrosion without suitable surface treatment.

Non-ferrous metals do not contain iron. Typical desirable properties include low weight, high conductivity, non-magnetic and resistance to corrosion. They are generally more expensive than ferrous metals. Common non-ferrous metals include:

- Aluminium
- Copper
- Nickel
- Zinc
- Lead
- Titanium

Non-ferrous metals can also be alloyed with steel to create metals with specific characteristics. These alloys commonly use more rare and exotic non-ferrous metals such as:

- Chromium
- Molybdenum
- Manganese
- Cobalt
- Tungsten
- Vanadium

4.1.4.2 Steel

Steel is manufactured to meet a wide variety of specifications for strength, hardness, toughness, machinability and weld-ability. Carbon is a principle alloying element that affects these characteristics. As the carbon percentage content rises, steel has the ability to become stronger and harder through a number of processing methods collectively called heat treating. The increased carbon content does however make the material more brittle and difficult to weld. Steel can be broadly categorised as follows:

Low-carbon steels (approximately 0.05 - 0.3% carbon content by weight) are inherently easier to form and work in hot or cold states due to their soft and ductile nature.

Medium-carbon steels (approximately 0.3 - 0.6% carbon content by weight) are typically used for general machining and forging of parts. They can be heat treated after processing to achieve a good balance of ductility, strength, surface hardness and wear resistance.

High-carbon steels (approximately 0.6 - 1.0% carbon content by weight) are extremely strong yet more brittle. They offer better responses to heat treatment and longer service life than medium-carbon steels. This steel is used in the manufacture of drills, taps, dies, springs, and other machine tools and hand tools that are heat-treated after fabrication to develop the hard structure necessary to withstand high shear stress and wear. This steel is difficult to weld because of the hardening effect of heat at the welding joint. Band saw blades for all types of applications (e.g. cutting metal, wood, plastic and meat) are typically made from high carbon steel.

Ultra-high carbon steels (approximately 1.0 - 2.0% carbon content by weight) can be heat treated to achieve great hardness and can maintain a sharp cutting edge. This steel is used in the manufacture of punches, chisels, knives and razors. It typically has high wear resistance due to their superior surface hardness, but is difficult to weld due to the high carbon content.

If the carbon content increases above 2.14% by weight, the material is classified as cast iron.

4.1.4.3 Alloys

Alloys are a mixture of one or more elements (the solute) into a base metal (the solvent). Ferrous metals, non-ferrous metals and non-metallic materials can be combined to form alloys. When the alloying elements are mixed with the molten base metal they will be soluble, dissolving into the mixture. When it has cooled, the mechanical properties of the alloy will often be quite different from those of its individual constituents. During material processing and component manufacture, the alloy may also undergo a specific set of heat treatment processes to achieve the desired properties. Alloy elements are selected to target improvements in the following properties:

- Strength
- Hardness
- Wear resistance
- Corrosion resistance

All steels are an alloy of carbon and iron, however, the term "alloy steel" is the standard term referring to steels with other alloying elements in addition to the carbon

4.1.4.4 Stainless Steel

Stainless steel is common alloy steel that contains minimum 10.5% chromium by weight. The chromium enables the alloy to resist corrosion due to the formation of a surface passivation film of chromium oxide. The addition of other alloying elements such as manganese, molybdenum, aluminium and titanium in varying amounts gives each grade its unique characteristics.

Nickel is another common alloy element in stainless steel, also used for corrosion resistance in combination with chromium to produce popular grades such as 304 and 316. Nickel also changes the crystalline structure of the metal from ferritic to austenitic to make the alloy more formable, weldable and tough.

Stainless steels are commonly divided into five groups, depending on the specific amounts of alloying elements, which control their crystalline structure:

- **Ferritic –** have a Body Centred Cubic (BCC) structure
- **Austenitic –** have a Face Centred Cubic (FCC) structure
- **Martensitic** – are similar to ferritic grades but contain more carbon. They are FCC at high temperatures, but transform to either BCC or Body Centred Tetragonal (BCT) martensite at lower temperatures, depending on the rate of cooling.
- **Precipitation hardening –** are similar to martensitic grades, but with higher alloying contents. They are put through an additional heating process to achieve their desired structure, which can be austenitic, semi austenitic or martensitic.
- **Duplex –** a combination of equal amounts of ferrite and austenite

4.1.4.5 Grains and Crystalline Structure

Metallic materials consist of a microstructure of small crystals called "grains" (see Figure 9). The size, composition and crystalline structure of the grain are the most effective factors that can determine the overall mechanical behaviour of the metal.

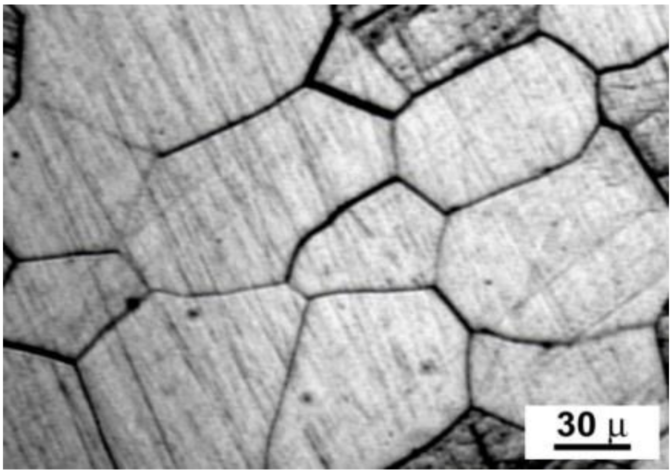


Figure 9 – A magnified photograph of piece of metal showing the grains and grain boundaries (source: http://en.wikipedia.org/wiki/Grain_boundary)

When a metal solidifies from the molten state, millions of tiny crystals start to nucleate. These grow to form the grains in the solid metal. The crystal structure of the grain consists of atoms that are grouped in a very specific arrangement, called a lattice (see Figure 10). The lattice is made up of identical unit cells, stacked in three-dimensional space.

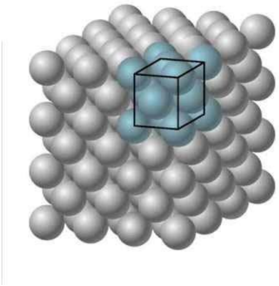
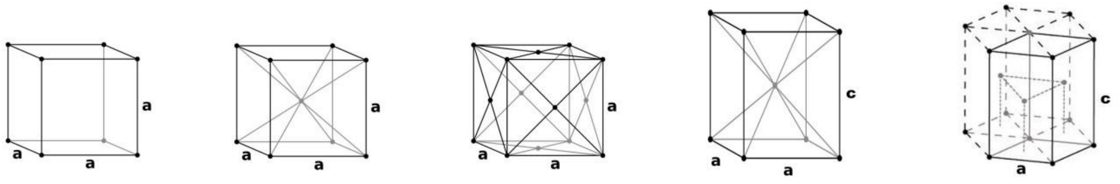


Figure 10 - An example of a lattice structure with the unit cell highlighted

(http://tex.stackexchange.com/questions/176657/drawing-3d-crystal-lattice-with-molecular-layer-in- tikz)

There are numerous possible unit cell structures with defined atom positions, edge lengths (based on the atom sizes), and edge angles. The most common for metals include (see Figure11.):

- **Simple Cubic** – atoms are positioned at the corner of the cube
- **Body Centred Cubic (BCC)** – atoms are positioned at the corner of the cube, with an additional atom in the centre of the cube
- **Face Centred Cubic (FCC)** - atoms are positioned at the corner of the cube, with additional atoms in the centre of each face of the cube
- **Body Centred Tetragonal (BCT)** – same atom layout as BCC, however the edges form a tetragonal (rectangular) shape
- **Hexagonal Close Packed (HCP)** – also known as the “close packing of equal spheres”, this structure has the highest average density of atoms



Simple Cubic

Body Centre Cubic (BCC)

Face Centre Cubic (FCC)

Body Centre Tetragonal (BCT)

Hexagonal Cubic Packed (HCP)

Figure 11 - Some of the common unit cell structures (source: http://en.wikipedia.org/wiki/Crystal_structure)

The longer the metal takes to cool from the molten state, the larger the grains will be able grow. If the material is cooled quickly it will form into many smaller grains, however, the lattice structure within even a very small grain is millions of unit cells long. Each grain has its own lattice orientation, and as the borders of each area of growth meet, they form grain boundaries (see Figure 9 and 12).

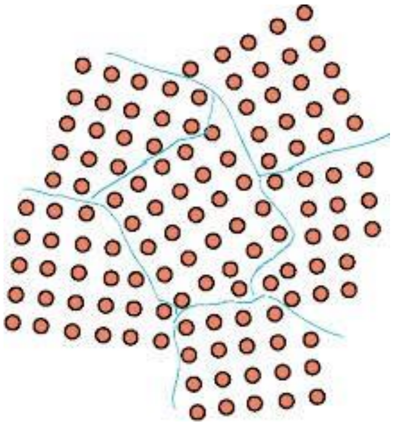


Figure 12 – A schematic illustration showing the lattice structure of grains and grain boundaries (source:http://2.bp.blogspot.com/_52ad6YS2zrs/TCLH7J79sUI/AAAAAAAAAFg/scdI1X_HvQE/s400/caf6.png)

When alloys are mixed, the atoms of the solute elements take positions in the base metal's lattice. The manipulation of atom-to-atom relationships within the lattice establishes the specific properties of the alloy.

4.1.4.6 Phase

The term "phase" can be used to describe a physically distinctive form of a substance, for example a solid, liquid or a gas. Temperature and pressure are the variables that drive these changes in form. In this usage of the term, the physical properties of the substance are essentially uniform throughout the temperature and pressure range of the phase.

However, temperature can also drive a change in the structure of a metal while it is in its solid form. Pure iron, for example, has a FCC crystal structure at low temperature but rearranges itself into a BCC structure at a higher temperature. Here, the term "phase" can be used to describe the different atomic structures of the solid metal in various temperature ranges.

In alloys, changes in phase while the metal maintains in its solid form can occur several times and at many different temperatures, depending on the various amounts and types of elements that the alloy contains. This change in structure can cause an element that will not normally dissolve into the base metal lattice in one phase to suddenly become soluble in another. When the phase change is reversed, the element may be either partially or completely insoluble (see Figure 13).

When alloying metals, a "**solid solution**" is formed when the crystal structure of the solvent remains unchanged by the addition of the solute atoms. The atoms of both elements occupy positions on the same lattice, and there is a homogeneous grain structure consisting of identical crystals. This is called a "**single phase alloy**", where the concentration of the solute element remains consistently soluble throughout the full temperature range of the solid state.

If the crystal structures of the alloyed elements are not the same, or if the materials are alloyed above a certain concentration, the metals will phase separate upon cooling. This can create a "**two phase alloy**" where the constituents become insoluble and separate, creating a heterogeneous microstructure of two or more different types of grain.

Alternatively "**intermetallic compounds**" can form along the grain boundaries. This typically occurs when the cooling process has happened very quickly, and the insoluble elements do not separate (or "**precipitate**") until after crystallisation has occurred. Intermetallic compounds can have crystal structures that are different to that of either of the alloyed elements.

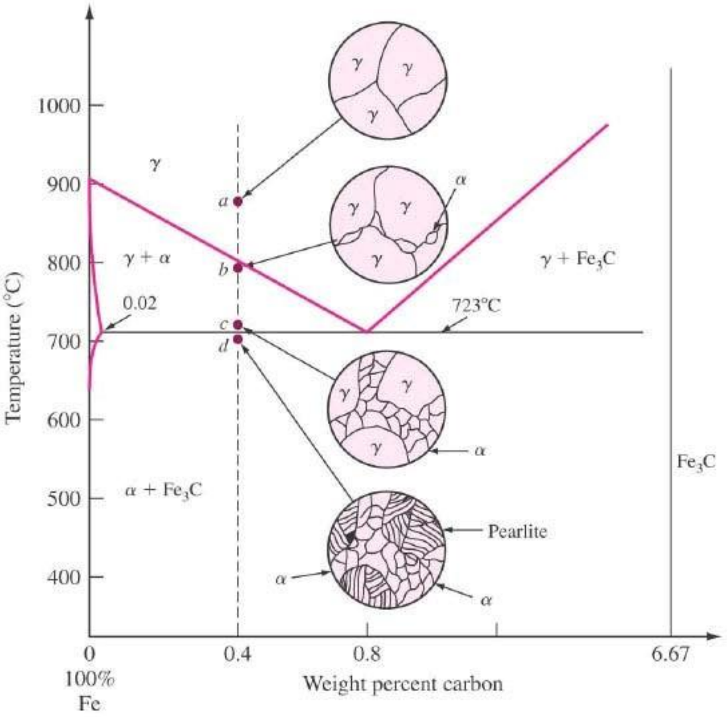


*Figure 13 – A phase diagram showing the changes in phase (α, γ and pearlite structures) of 0.4% carbon steel during a slow cooling process (source: www.ce.berkeley.edu/~paulmont/CE60New/**alloys**_steel.pdf*

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4.1.4.7 Crystal Defects

The arrangement of atoms into crystalline structures is never perfect. Crystallographic defects interrupt the regular patterns of the lattice and can be classified as follows:

- **0-dimensional defects** - or point defects, affect isolated sites in the crystal structure. An example is if an atom is missing from a position in a unit cell, or if an atom in in an unusual position which alters the crystal pattern at a single point
- **1-dimensional defects** - are called dislocations. They are lines along which the crystal pattern is broken
- **2-dimensional defects** - are surfaces, such as the external surface and the grain boundaries along which distinct crystals are joined together.
- **3-dimensional defects** - change the crystal pattern over a finite volume. They include precipitates, which are small volumes of different crystal structure, and also include large voids or inclusions of second phase particles.

Defects in the crystal structure directly influence the mechanical properties of the material. The presence of defects contributes to the strength of a material by preventing the movement of dislocations through a material.

4.1.4.8 Dislocations

When stress is applied to the metal, the atoms in the lattice will start to spread apart. As the atomic bonds stretch, the attractive forces between the atoms will oppose the applied stress, pulling the metal back into its original shape as the stress is removed. This is known as “elastic” deformation. If the force applied exceeds the threshold of the material, permanent or “plastic” deformation will occur.

Plastic deformation corresponds with the movement or dislocation of a large number of atoms. The stress will cause a number of inter-atomic bonds in the lattice to break and a set of atoms to move across a plane (referred to as a “slip plane”, see Figure 14). The atoms will re- bond themselves to the next adjoining set of atoms. This is permanent deformation, in that the atoms will not move back to their original position when the stress is removed. Dislocations re-arrange the atoms within the lattice structure, as they move though the grain.

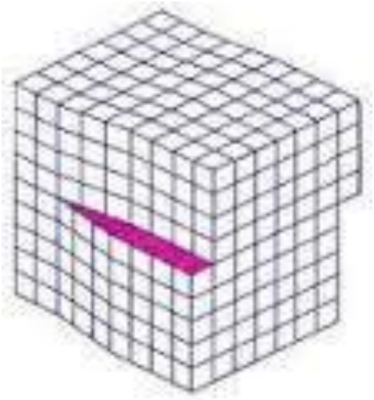

Figure 14 – Schematic illustration of a lattice, highlighting a slip plane along which a dislocation has travelled (source: http://practicalmaintenance.net/?p=1085)

The number of dislocations increases dramatically during plastic deformation. They can generate from existing dislocations, defects, grain boundaries and surface irregularities. Dislocations move more easily on specific planes and in specific directions (known as the “slip system”) depending on the crystal structure of the metal. BCC and FCC crystals have more potential slip systems than the more evenly packed HCP crystal, making them more ductile (the ability of a material to undergo plastic deformation before fracture), and the HCP more brittle. Introducing a mechanism that prohibits the movement of these dislocations is an effective method of improving a material’s mechanical properties. Strong materials are those that can slow down or stop the movement of the dislocations.

Dislocation movements are impeded by various obstacles, which are classified in the different types of crystal defects. An accumulation of dislocations create a stress field which repulses any approaching dislocation. The greater the number of dislocations in a cluster, the stronger the repulsion and opposition to dislocation movement, and the metal becomes more difficult to deform. However, there is a limit to the dislocation density in a cluster and once this number is reached; a crack nucleates at that point.

There are a number of mechanisms that can contribute to the strengthening of an alloy, that all reduce or prohibit the movement of dislocations:

- Work hardening
- Solid solution strengthening
- Precipitation strengthening
- Grain boundary strengthening
- Transformation hardening (or Martensitic transformation

4.1.4.9 Work Hardening

When the metal is forcibly deformed by “cold working” processes, for example by cold forging, stamping, or rolling; its shape is permanently or plastically deformed. These processes typically take place at room temperature, i.e. far below the metal’s recrystallization temperature (where the deformed grains would be replaced by new, underformed grain growth).

As a result of the plastic deformation, cold working or “work hardening” increases the dislocation density (1-dimensional crystal defects) in the material. The dislocations become entangled in each other as they accumulate, preventing the further movement of dislocations. Alloys that are not responsive to heat treatments, including low-carbon steel, are often work- hardened; however, the process directly contributes to a reduction in ductility.

The effects of work hardening can be reversed by “annealing”. This is a process where the metal is heated to a temperature around where a solid phase change will occur and held there for a period of time long enough for the dislocation filled lattice to recrystallise back intostrain free grains. The existing grains are dissolved and replaced by new grain growth over a time period of about an hour. The annealing process has to be carefully controlled so that the grains do not become too large. The material is then cooled at a specific rate to maintain the refreshed grain structure. The metal becomes ductile again, but will have lost the strengthening effects of the work hardening.

4.1.4.10 Solid Solution Strengthening

Solid solution strengthening is an alloying technique that improves the strength of a pure metal. The material is heated above the recrystallization temperature and new atoms (0- dimensional crystal defects) are introduced into the lattice structure. In a diffusion process the solute atoms of the alloying element are incorporated into the solvent base metal in either of the following ways (see Figure 15):

- **Substitutionally** by replacing atoms in the lattice (when the size of the atoms of each metal does not differ by more than 15% and the crystal structures of the base elements match)
- **Interstitially** by fitting into the space between solvent atoms (this is the more effective method of solid solution strengthening)

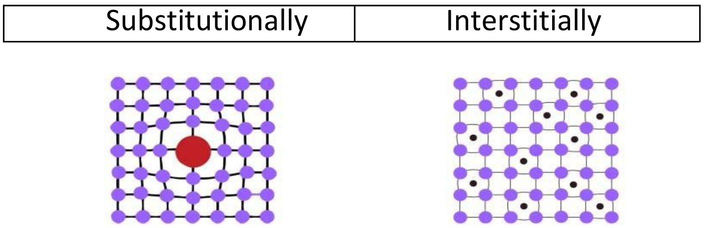

Figure 15 – Schematic illustration showing the lattice structure of grains and grain boundaries (source:http://en.wikipedia.org/wiki/Strengthening_mechanisms_of_materials)

Carbon atoms are relatively small compared to iron atoms, so carbon atoms will enter the iron crystal lattice as interstitial solute atoms. In contrast, other alloying elements such as manganese, nickel and chromium have much larger atoms, closer in size to those of iron, and consequently will enter substitutionally into the solid solution.

As the metal cools and reverses the phase change, the new atoms remain contained in the base metal lattice. In both cases, the overall homogeneous nature of the crystal structure is essentially unchanged; however the solute atoms cause distortions and strain in the lattice structure and strengthen the material by impeding the movement of dislocations.

Solutes can only be dissolved by the solvent up to a certain concentration, known as the solubility equilibrium. Additional solutes can be dissolved in the heated state but will precipitate out of the solid solution as the material cools and reverses the phase change. The excess solutes will accumulate as second phase particles at the grain boundaries, resulting in a heterogeneous two phase alloy.

4.1.4.11 Precipitation Hardening

Precipitation hardening, or age hardening, provides one of the most widely used and effective mechanisms for the strengthening of nonferrous alloys. The strength and hardness of the alloy may be enhanced by the formation of extremely small uniformly dispersed second-phase particles (3-dimensional crystal defects) within the lattice. These areas of different crystal structure within the grain are impurities that play the same role as the particle substances in particle-reinforced composite materials. The presence of these particles often causes lattice distortions and resistance to slip dislocations, and therefore strengthen the material. The process involves the following steps (see Figure 16):

Solution treatment - when the relevant alloying elements are dissolved in a solid solution in a greater concentration allowed by the solubility equilibrium.

Quenching - when the metal is rapidly cooled to form a supersaturated solid solution. Due to the speed of cooling, the excess alloy atoms do not have time to precipitate out of the solid solution and remain trapped in the lattice. The lattice is unstable as it is overly stressed by the concentration of solute atoms.

Aging - when the material is then kept at an elevated temperature for a certain time (often many hours), to allow the precipitates to form throughout the lattice. The lengthy time period is to obtain a controlled precipitation and even distribution of strengthening particles.

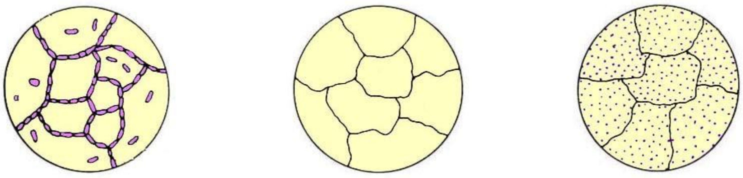

Figure 16 – Schematic illustration showing grain structure in an alloy: Left: a supersaturated alloy that has been cooled slowly, resulting in a heterogeneous two-phase structure, Middle: the same alloy that has been quenched, resulting in an unstable single phase structure, Right: the same quenched alloy that has been aged, resulting in precipitates throughout the single phase lattice (source: http://practicalmaintenance.net/?p=1255)

The aging temperature is typically between 15-25% of the temperature difference between room temperature and solution heat treatment temperature. The alloy will stop precipitating the solute atoms when it has reached the solubility equilibrium, however this results in a loss of strength and is known as "over-aging" (see Figure 17).

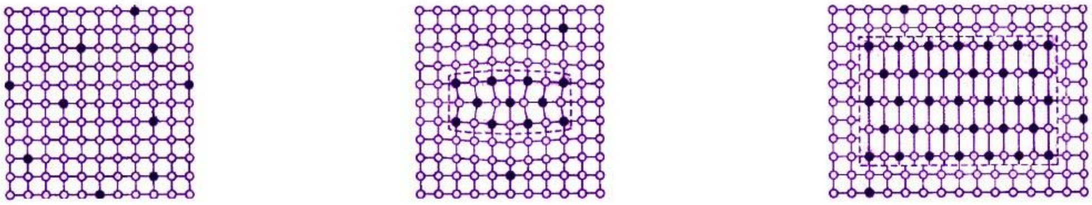

Figure 17 – Schematic illustration showing the lattice structure as the precipitate forms during ageing:

Left: solution treated and quenched lattice, supersaturated with solute atoms, Middle: precipitate particles have formed in the lattice, distorting it to hinder the movement of dislocations, Right: an over- aged situation where the solubility equilibrium of the base metal has been reached (source: http://practicalmaintenance.net/?p=1255)

4.1.4.12 Grain Boundary Strengthening

The size of the grains in a material also has an effect on the strength of the material; generally, the smaller the grain, the stronger the material. As adjacent grains have different lattice orientations, the slip planes are discontinuous between grains. The greater the difference in angle between the slip planes, the more energy is required for the dislocations to move between grains. In these ways grain boundaries (2-dimensional crystal defects) act as a barrier to dislocation movement, and they will accumulate at the grain boundary. Making the grain size smaller also increases the ratio of grain boundary to grain volume in the material, and therefore shortens the distance a dislocation can move along a given slip plane.

The size and number of grains within a material is controlled by the rate of solidification from the liquid phase. As previously mentioned; the longer the metal takes to cool, the larger the grains grow. During heat treatment processes the temperature must also be precisely controlled and closely monitored to ensure desired grain size. When heating a material up above the recrystallization temperature, grain growth can occur with further increases in temperature. Here grain growth can be inhibited by second phase particles at the grain boundaries.

Grain refinement is unique in that it is the only method of strengthening that also increases the toughness of the material and its resistance to brittle fracture. Grain size reduction does have a limit beyond which it will actually begin to weaken the material. Once the grain size is smaller than 10nm (0.00001mm) the grain boundaries will slide across each other making the material susceptible to creep (slow plastic deformation of the material when it is under constant stress).

4.1.4.13 Martensitic Transformation

Martensitic transformation is a transformation hardening mechanism specific for ferrous alloys. The achievable hardness is directly related to the carbon content of the steel. The higher the carbon content, the higher the hardness. Martensite is essentially a supersaturated solution of carbon in iron.

The steel must be heated to a temperature where the material changes phase from a BCC to FCC structure. In the FCC structure there are many more positions in the lattice for the carbon atoms to fit interstitially between the iron atoms, hence the steel can dissolve a lot more carbon. Once the carbon has been dissolved, the material is then cooled.

If the material is cooled slowly within a furnace (annealing), the metal will form a two phase solid, consisting of pearlite grains with cementite along the boundaries. Pearlite is a two phase lamellar (layered) crystal structure consisting of alternate layers ferrite and cementite (or iron carbide). In this form the steel is relatively soft and ductile, compared to the martensitic form. If the material is cooled in still air (called normalising) the cooling rate is increased, and the lamellar structure is much finer. The layers of ferrite and cementite are much thinner and closer together, making the material stronger.

To achieve a martensitic transformation the material must be cooled very quickly in a quenching process. The steel tries to return to the low temperature crystal structure BCC; however cooling at such a high rate prevents the carbon atoms from diffusing out of the crystal structure. Because of the extreme super saturation of solid solution carbon, the crystal lattice is unable to maintain its BCC structure and distorts to the BCT structure instead. This single phase is called martensite, and is extremely hard due the distorted crystal structure and the extreme solid solution strengthening, both mechanisms of which resist slip dislocation.

While it is extremely hard, martensite is also very brittle and cannot be used directly after quenching for any application. Brittleness can be reduced by applying a post-heat treatment known as “**tempering**”. Tempering is essentially an ageing process for ferrous alloy; however the process does not take as long. It consists of reheating the martensitic steels to force some carbide precipitation to the grain boundaries. It is necessary to increase ductility and toughness of martensite, however some hardness and strength is lost.

4.1.4.14 Heat Treating

Heat treating is an umbrella term to describe the processes of heating and cooling a material to achieve changes in the mechanical properties of a material. The following processes that have been previously discussed as steps in material strengthening are all forms of heat treatment:

- Annealing
- Solid solution strengthening
- Solution treatment
- Quenching
- Ageing
- Martensitic/transformation hardening
- Normalising
- Tempering

There are a number of other specialist processes that are used to alter material properties in localised areas of a material; however they all rely on the methods listed above. “Case hardening” is a common process which hardens the outer surface of the material while leaving the inner core of the material in its original composition. This process is usually performed once the metal has been formed into its final shape, and is often used for cutting blades, gears, camshafts and self-drilling screws. The hard outer surface is typically required for maintaining a sharp cutting edge and/or increased wear resistance, while the softer core retains good toughness and fracture resistance. Case hardening can be achieved using the following heat treatment processes:

- Flame or induction heating the surface only, and then quenching. This utilises the martensitic transformation mechanism.
- Diffusion hardening using Carbon (Carburizing), Nitrogen (Nitriding), Boron (Boriding) or other elements, where the density of solute atoms is increased close to the surface of the alloy. This uses the solid solution strengthening mechanism.

4.1.4.15 Other Alloys

Super Alloys

There are a vast number of alloy metals that have been developed for specialist applications. In particular a class of “superalloys” have been developed for use in high temperature environments, largely driven in conjunction with developments in jet turbine technology. They exhibit excellent mechanical strength and resistance to creep (tendency for solids to slowly move or deform under stress). They also have good corrosion and oxidization resistance, and typically find applications in the aerospace and power industries.

The base metals are typically cobalt, nickel or nickel-iron. Nickel and nickel alloys are non- ferrous metals with high strength and toughness, excellent corrosion resistance, and superior elevated temperature properties. Cobalt alloys are non-ferrous with an austenitic FCC structure at room temperature. Properties include excellent wear resistance, corrosion resistance, and retention of strength at high temperatures. Many of the properties of the alloys arise from the solid-solution-strengthening effects of chromium, tungsten, and molybdenum, and the formation of secondary phase precipitates such as carbides through precipitation strengthening. Generally the softer and tougher compositions are used for high-temperature applications while the harder grades are used for resistance to wear.

These specialist alloys families are often named and trademarked by companies:

Inconel – nickel chromium base alloys
Hastelloy – nickel based alloys
Stellite – cobalt chromium based alloys

Maraging Steels

“Maraging steels” are low carbon iron alloys containing nickel and cobalt alloying elements. The name maraging comes from the combination of “martensitic” and “aging”. The high nickel gives good strength, toughness and moderate corrosion resistance, while cobalt and other elements such as molybdenum and titanium produce intermetallic precipitates during ageing. The addition of chromium (and subsequent reduction in nickel) produces alloys known as “precipitation hardening” stainless steel.

Titanium

Titanium as a pure metal exhibits excellent corrosion resistance, low density and high strength. It is commonly alloyed with other elements to create high end sporting equipment and components for the motor racing, marine, and aerospace industries. Its durability makes it a popular choice for jewelry and watches, and its biocompatibility characteristics enable it to be used for surgical and dental implants and implements. Ti6-4 is the most common titanium alloy, containing 6% aluminium and 4% vanadium. This alloy can be heat treated, and also responds well to diffusion hardening techniques such as nitriding.

4.1.4.16 Ceramics

Ceramics are classified as inorganic and non-metallic solid materials made from compounds of a metal and a non-metal, for example Silicon Carbide (Silicon – metal, Carbide from carbon – non-metal). Typically, they will demonstrate excellent strength, hardness, corrosion and wear resistant properties; however, they are often brittle in nature. ”Traditional” ceramics are the older and more generally known types, such as porcelain, brick, earthenware, etc. The new and emerging family of “advanced” ceramics utilise highly refined materials and new forming techniques, and have found many uses in the following applications:

Electronics – the largest market for advanced ceramics which takes advantage of superior and versatile ceramic properties that can be tailored for excellent insulating or conductive purposes.

High temperature environments – used as refractory materials in furnaces and kilns, also as thermal protective barriers where operating temperatures exceed 2000o C (such as internal components of jet engines, supersonic and hypersonic flight vehicles). These components are characterised by good resistance to oxidisation and the ability to withstand thermal shock (rapid and extreme changes in temperature).

Medical – joint replacement components and dental implants, taking advantage of chemical inertness, biocompatibility characteristics, smooth surface finishes and high manufacturing tolerances

Magnets – ferrite magnets (ceramics containing iron oxide) are widely used as low-cost magnets in many products such as electric motors, video, radio and microwave equipment.

Cutting and machining tools – as cutting tips or teeth made from solid ceramic composites such as Tungsten Carbide, that are typically either mechanically fixed or braze welded to the cutting tool or disc, or as thin coatings applied to a base component (such as a drill bit or router cutter) to improve the quality of cut and extend the life of the cutter.

Wearing and seating surfaces – from thicker coatings applied to base components that are subject to high abrasive wear (such as drive shafts, oil/gas/tunnel drilling equipment, dragline/excavator bucket faces), to solid components such as ball bearings, and common everyday products like seating surfaces in household plumbing fittings

Protective armour – uses smaller plates for personal body protection or larger plates as protective panels in vehicles. These products protect the body or vehicle from high velocity projectile impact by utilising the high hardness characteristics of the ceramic to shatter projectiles upon impact and dissipate energy. Personal body protection plates are bonded to a plastic or composite backing plate.

4.1.4.17 Advanced Ceramic Categories

Advanced ceramics can be classified into three distinct material categories:

Oxides - consist primarily of metallic compounds such as alumina and zirconia with oxygen. Aluminium oxide is the most commonly used advanced ceramic.

Non Oxides - comprised of materials based on carbon, boron or nitrogen that form carbides, borides or nitrides, used when high wear resistance is required

Composites - consisting of ceramic particle or fibre reinforcing constituents that lie in a matrix binder. The matrix can be a ceramic or other material such as a polymer or metal, and greatly increases fracture toughness.

4.1.4.18 Ceramic Production

To ensure that ceramics achieve the specific properties they are engineered for, extremely chemically pure raw materials with the finest possible granular structure are used. The methods used for synthesis of ceramic powders include:

Mechanical methods – typically used to prepare powders from naturally occurring raw materials. Operations such as crushing, grinding and milling are used to reduce coarse, granular material into powders with particle size ranging from 0.1µm to 10µm.

Chemical methods - typically used in the synthesis of powders of advanced ceramics from synthetic materials or from naturally occurring materials with a significant chemical refinement. Many chemical methods also require a milling step to create average particle size and particle size distribution.

Generally speaking, mechanical methods are considerably cheaper than chemical methods. However, chemical methods offer better control of the powder characteristics, such as particle size and shape.

During ceramic production the chemical composition, the crystal structure and the size distribution are closely examined using x-rays.

Fine powders are difficult to handle in manufacturing environments, as the material does not flow but behaves in a manner comparable to flour. Powders are usually combined with a binder and granulated into spheres ranging in size from 50µm to 150µm, enabling thematerial to flow like sand and be dispensed automatically into moulding machines. This binder material is removed from the ceramic during the manufacturing process of the component, a process which results in ceramic parts with extremely high purity.

4.1.4.19 Ceramic Composites

A cermet is a composite material composed of ceramic (cer) and metallic (met) materials. They are engineered to combine the extremely hard properties of ceramics with the toughness of the metal, eliminating the brittle nature of the ceramic. Cermets also provide excellent wear resistance and can be used in high operating temperature environments.

The ceramic components are extremely hard carbide, oxide or boride particles with high melting temperatures (in excess of 2,500 °C). The particles are very small (between 0.5 to

50µm (microns) depending on the grade) with the content typically between 70 – 97% of the total weight of the composite. The metallic component acts as the binder, cementing the ceramic particles together. The metals are typically tough and ductile, and have the ability to undergo plastic deformation. In addition, the metals should also have high melting points; high temperature strength, and the ability to bind well to the ceramic particles. Cobalt or Cobalt-Nickel alloys with chromium and molybdenum are commonly used.

Properties of the cermet can be altered by varying the composition of the composite. The higher the percentage of binder the tougher the material will be, with better impact resistance but a reduction in hardness. A higher percentage of ceramic will harden the composite, and give it better wear resistance. The particle size of the ceramic will also influence the mechanical behaviour of the composite. Very fine particles will give the material higher hardness and better wear, while larger grains give better toughness and impact resistance. The grades with binder content in the range 10-20% by weight and ceramic particle sizes between 1 and 5 µm have high strength and toughness, combined with good wear resistance.

Tungsten Carbide/Cobalt (WC/Co) is one of the most widely used cermets. Tungsten Carbide is the hard ceramic phase, with Cobalt acting as the metallic binder. In industry it is commonly referred to as a cemented carbide, Tungsten Carbide, or just simply “carbide”. It is typically used in metal cutting tools (superseding the use of cobalt alloys such as Stellite) either as solid tools or as tips or inserts. It is also used on drill bits for the oil and gas industry, and in high wear applications such as bearing surfaces on drive shafts.

4.1.4.20 Hardness

The hardness of a material is a measure of its resistance to plastic deformation. Testing is typically performed by impacting a material with an indenter of a specific shape and force, and measuring the impression that has been formed. Two of the common standard “macro” testing methods are listed below, with each divided into a range of scales defined by a combination of indenter geometry and applied load:

Rockwell Hardness – uses different scales (HRA, HRB, HRC, etc.) with varying indenter materials, geometry and force. For example, HRC uses 150kgf load with a 120° diamond cone. The testing is performed in three stages: 1. Preload; 2. Major load; 3. Measure the difference in material thickness between stage 1 and 2, which correlates to a hardness number. A harder material gives a higher number.

Vickers Hardness – one of the widest scales that can be used across all metals. It uses a pyramid shaped diamond indenter with a square base and 136° angle. The scales (HV/1, HV/5, HV/10, etc.) are based on the amount of load, for example HV/50 use a force of 50kgf for 10-15 seconds. The test is performed by applying the load then measuring the size of the indentation. A hardness figure is the force divided by the indention size. A harder material gives a higher number.

A direct comparison between the any of the hardness methods or scales is not simple or accurate, as materials may behave differently when subjected to the various methods. However, practical conversion charts can be used as a guide (see Figure 18):

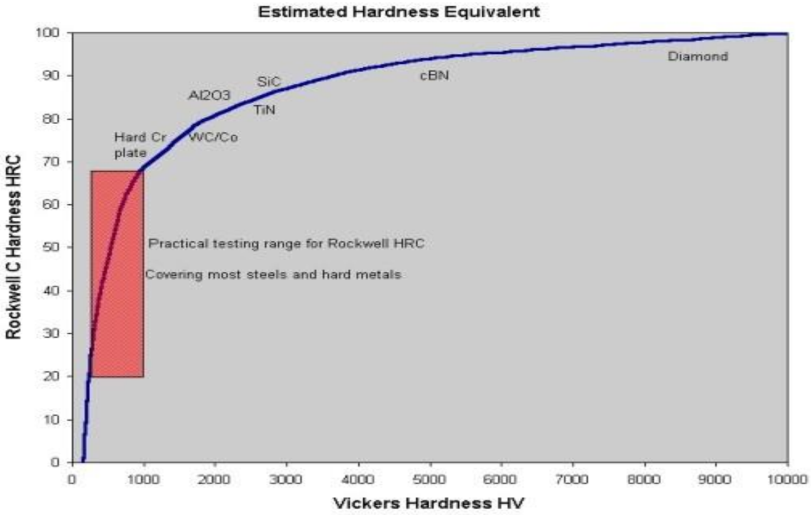

Figure 18 - Practical conversion chart for Rockwell C hardness to Vickers hardness (source: http://www.gordonengland.co.uk/hardness/ehe.htmengineering)

4.1.4.21 Hardness vs Wear

As materials increase in hardness they also tend to show improvements in resistance to abrasion, bending, scratching and cutting. However, the “macro” hardness indenter tests as described previously are not an accurate representation reflection of these other properties, in particular wear resistance. These tests are essentially measuring the average hardness of many particles, as the size of the impression left by the indenter is significantly larger than any of the individual grains or hard particles in the material.

This is especially evident when assessing cermet composites such as tungsten carbide. Each component of the material has its own “micro” hardness which then contributes to the combined “macro” hardness of the composite. The macro hardness of the cermet will vary depending on the ratio of composite. A common grade is 88/12 (88% tungsten carbide/12% cobalt), which will give a macro hardness of around 72 HRC. However, the tungsten carbide particles have a microhardness that is approximated to around 90 HRC, which will give the composite material a far greater resistance to wear than a metal or alloy with similar macro hardness.

4.1.4.22 Scale Manufacturing

The research focused on identifying suitable manufacturing processes for the production of the scale components. The viable options are listed below and detailed in the following section of the report:

- Metal pressing/stamping
- Metal or ceramic injection moulding
- Isostatic pressing
- Additive manufacturing (Rapid prototyping)
- Investment casting
- 3D scanning

Using heat treatment processes that are matched to selected scale materials has been identified as a suitable method for creating scales with performance characteristics that are suitable for the application.

Various coatings can be used to create a high hardness outer surface to a part that has been manufactured from a more commonly available and usable material. Coatings are also suitable method to provide corrosion protection to the scale component. The viable options are listed below and detailed in subsequent pages:

- Electroplating
- Physical Vapour Deposition (PVD)
- HVOF thermal spray

4.1.4.23 Metal Stamping

Metal stamping is a cold work sheet metal process generally performed on materials 0.5mm to 2mm thick, however it can be used with foils as thin as 0.2mm or plate up to around 25mm thick. Stamping presses and stamping dies are used to produce high volume sheet metal parts, capable of producing parts of a similar size and shape to the protective scales at a rate of up to 100 parts per minute.

A die set assembly consisting of a male and female tool that produces the stamped piece. The upper half of the die set, which may be either the male or female, is mounted on the press ram and delivers the stroke action. The lower half is secured to the press bed. The sheet metal is continuously fed between the die set from a coil, or individual blanks are located in position between strikes of the ram. Guide pins are used to insure alignment between the upper and lower halves of the die set. Multiple station dies are arranged so that a series of sequential operations are accomplished with each press stroke. If the size and shape of the parts are suitable, multiple components can be formed in a single die.

Metal alloys with high ductility are required for metal stamping. Lubrication is also vital for successful sheet metal forming. Lubricants range from light mineral oils to high viscosity drawing compounds. They may be oil base, water soluble or synthetic materials.

The main stamping operations include:

- Blanking - cutting flat sheet metal into a defined size and shape. Typically performed in one hit of the press, the result may be a finished part or a blank destined for further forming or processing into its final shape.
- Bending and flanging - sometimes referred to as forming, tooling bends work piece material into various angles.
- Drawing - the press essentially stretches sheet metal to a depth, often quite dramatically as is the case with products such as kitchen sinks
- Hemming - folding over of a short flange upon itself to form a smooth, rounded edge and to add thickness or facilitate the attachment of mating parts. The edges of automobile doors are usually hemmed.

Other processes the dies can perform include:

- Coining - the die forms an imprint on the work piece.
- Embossing - the material is stretched into a shallow depression. Used primarily for adding decorative pattern.
- Curling - deforming material into a tubular profile. Door hinges are a common example.
- Punching - the cutting of a slug from the sheet metal stock to produce a hole or slot.

4.1.4.24 Metal or Ceramic Injection Moulding

Injection moulding with metals or ceramics is an innovative manufacturing process in which fine metal or ceramic powders are mixed with a special thermoplastic or paraffin based binder, and then injected into a mould to form the required shape. The component is ejected from the mould, the binder is then removed and then the component is sintered, to produce a high-density metal or ceramic component.

Injection moulding is ideal for high volume, small, complex geometry, thin wall components. There are a wide range of materials available, and due to the low wastage rate it is a highly efficient process for specialist alloys, metal ceramic composites and technical ceramics. Cobalt-chrome, 17-4 PH stainless steel, tungsten carbides and alumina are commonly used. The process follows a four stage process:

Material preparation - This involves the mixing fine powdered material, typically less than 20 microns in size with a thermoplastic binder, to form a homogeneous mix. The ratio is typically 2/3 metal or ceramic to 1/3 binder. This mix is then granulated into pellets to form a feedstock which can be injected into the mould.

Injection mould - The feedstock can now be loaded into an injection moulding machine. The machines used for metal and ceramic injection moulding are very similar to those used in plastic injection moulding; however the mould cavities are deliberately larger than the required finished part dimensions to allow for the shrinkage of the part during the final sintering process. The feedstock is melted before being injected into the cavity. The component is cooled in the mould prior to being ejected then laid out in trays ready for de- binding. This step in the process takes around 30 seconds.

Debinding - After moulding the parts are in their ‘green state’. They then go through a two stage process to remove the thermoplastic binder that was required to aid the injection moulding process. The first stage is submerging the parts in a solvent to remove the primary binder, and form an open pore structure. In the second stage the parts are placed in a low temperature furnace to remove the remaining binder. The parts are now in the ‘brown state’ ready for sintering.

Sintering - The final stage is to sinter the brown components in a controlled atmosphere or vacuum furnace, close to but below the material’s melting temperature. This process causes the parts to shrink to around 80% of their moulded size while fusing the metal particles together to achieve a final density of around 96-99%.

Injection moulded parts can achieve excellent surface finishes and tolerances down to around±0.5%. Tighter tolerances can be achieved by machining the parts in their green state, before sintering. Part sizes are limited to a maximum overall dimension of 100mm and maximum weight of around 50g.

4.1.4.25 Isostatic Pressing

Isostatic pressing is a powder processing technique that uses fluid pressure to compact the part. Metal or ceramic powders are placed in a flexible container. This sealed container is the mold for the part. Fluid pressure is exerted over the entire outside surface of the container, causing the container to press and form the powder into the correct geometry.

The all-around pressure exerted by the fluid during isostatic pressing manufacture provides uniform compaction of the powder and uniform density within the compacted part. Isostatic pressing tends to have long cycle times and is best utilized for short production runs. This manufacturing process consists of two main categories:

Cold isostatic pressing (CIP) - is performed at room temperature and uses a mold made from an elastomer material such as urethane, rubber, or PVC. The fluid used in CIP is usually oil or water. Fluid pressure during the operation is typically between 400 MPa to 1000 MPa. A disadvantage to this manufacturing process is a low geometric accuracy because of the flexible mold. Typically the powder is compacted to a very uniform density by CIP and does not require a binding agent. After pressing, the part is sintered conventionally to produce the final product.

Hot isostatic pressing (HIP) - is performed at an elevated temperature. The mould material in HIP is usually sheet metal, which must have a high enough melting point to maintain its integrity throughout the operation. In some special cases a ceramic mould is employed. The fluid used to pressurize the mould and form the part is usually an inert gas such as argon. A common pressure and temperature for this manufacturing process is 100 MPa at 1100°C. Simultaneous application of all around pressure and temperature presses and sinters the part in one step. HIP causes an elimination of practically all porosity, producing work material that is essentially 100% true material density. In addition to the elimination of porosity, the conditions of this powder process also provide very complete bonding throughout the structure of the material. A solid uniform grain structure is established.

A component manufactured from a typical material by HIP will produce a much stronger part than the same component and material manufactured by conventional powder based moulding or casting processes. The HIP process can also be used as a secondary operation to eliminate porosity and improve the mechanical properties of parts already manufactured by other methods, such as metal and ceramic injection moulding and additive manufacturing.

4.1.4.26 Additive Manufacturing

Additive manufacturing, also known as “3D printing” is a process of building a solid object from a digital CAD file. Parts are built by building or “printing” many thin successive layers of material that correspond to the cross sections of the CAD file. The layers are fused together as they are printed to create a solid part. There are a number of 3D printing methods that allow for the creation of parts in a wide variety of materials. The most relevant for the protective scale production are:

Stereolithography (SLA) – a photopolymerization process that produces a solid part from a liquid. It works by concentrating a beam of ultraviolet light focused on the surface of a vat filled with photocurable liquid polymer. The exposed liquid hardens and once the cross section is complete the component is lowered into the vat for the next layer to be printed on top. Once complete the surrounding liquid is drained leaving the solid part, which must then be placed in a UV oven to cure. The drained liquid can be re-used in the vat for the next build. The materials that can be printed in this process include a range of plastics and elastomers. Specialist casting grade materials such as polystyrene and wax can be printed for use in the investment casting process.

Direct Metal Laser Sintering (DMLS) – uses a laser beam to sinter powdered metal, binding it together to make a solid component. The build platform is covered in a layer of powdered metal. Once the laser has sintered a cross section of the part the platform lowers, another layer of powder (around 20µm thick) is deposited across the entire bed ready for sintering. When the build is complete, the solid part is removed from the surrounding powder, which can be re-used for subsequent builds. Common materials include stainless steels, titanium, and nickel or cobalt chrome alloys.

Also of interest for ceramic parts: Fuse Deposition Modelling (FDM) – uses a filament material supplied from a coil that is heated and extruded from a nozzle. The nozzle traces a path across the full cross section of the part. Once a layer is complete the nozzle raises to continue extruding the subsequent layer. Selective Laser Sintering (SLS) – is a similar process to DMLS, however uses non metal powders. A variety of plastics can be used in the FDM and SLS, including a powdered form of the ceramic/binder feedstock used in the ceramic injection moulding process. Once the part has been built, it will then follow the same de-binding and sintering process.

The main benefit of using additive manufacturing methods is the ability to rapidly produce unique parts without the need for expensive production tooling. This also opens the opportunity to creative individually customised components for no additional cost.

A limiting factor in all 3D printing processes is size of the build bed and the resolution of the print. Build beds are typically no bigger than 300mm x 300mm x 300mm. Layer thicknesses (Z resolution) range from around 100µm to a current minimum of 16µm. X-Y resolution ranges from 100µm to 50µm. Low resolution prints result in obvious layering visible in the parts surface, while build times on high resolution parts are much longer, contributing to higher part cost. Drawbacks of 3D printed parts include structural integrity less than that of cast or formed arts, and the anisotropic characteristics of the printed parts due to the layered building method. For DMLS parts, this can be reduced or removed by appropriate heat treatment. If the parts are used as sacrificial masters in an investment casting process, this is eliminated

4.1.4.27 Investment Casting

Investment casting, also known as “lost wax casting” is a process where a sacrificial wax pattern of the required component is coated in a refractory ceramic material. Many wax patterns are assembled to a central wax sprue, to form a cluster, or tree, before it is then repeatedly dipped in a number of ceramic slurries and dried to achieve a coating thickness of around 10mm. Once this coating has hardened the ceramic mould is heated in an oven to between 100 – 200°C, which allows the wax to melt and flow out of the mould, leaving a hollow cavity to be filled with molten metal. The hollow mould is then heated to around

1000°C to burn out any residual wax and moisture, and sinter the mould. The mould is then poured with molten metal to cast the part. Once the casting has cooled, the ceramic mould is broken off and discarded, and the metal parts removed from the sprue and manually finished.

Investment casting is one of the oldest metal forming techniques, dating back over 5,000 years. It has since developed into a modern and technologically advanced process. Investment cast parts can achieve excellent dimensional tolerances and is suitable for producing parts weighing from around 5g to 5kg (although steel castings of up to 300kg have been produced). Castings can have thin walls, have an excellent surface finish that requires minimal finishing, and do not have part lines or issues with flashing that are typical to other mould based processes.

Almost all metals can be investment cast, including those with high melting temperatures, and it is a frequently used process to manufacture parts made from specialist and high performance alloys. It allows the casting of extremely complex and intricate parts that could not be manufactured easily by other methods, such as turbocharger rotors, turbine blades or other components that have hollow internal passages. The wax pattern is typically produced with an injection moulding process, and many individual wax parts can be assembled to create a complex single master pattern prior to coating in ceramic.

Investment casting is preferably used for low to medium volume production, as the process has many steps and results in long cycle times with high labour costs. The rejection rate during the manufacturing process is also quite high, up to around 10%.

4.1.4.28 3D scanning

3D scanners are devices that create a digital representation of a physical object. There are many different methods to collect 3D data, but the two most common are:

Digitizing – a contact based collection system, performed by touching a probe to various points on the surface of an object. This method collects data points of an object in space and is a very accurate way of defining the geometric form of an object as opposed to more organic shapes. Digitizing is used commonly for reverse engineering applications where precision is the most important factor.

Laser scanning – light based systems that use lasers to scan over the surface and create a "point cloud" data image of the object, defining the measured points by X, Y and Z co- ordinates. Another method uses a digital video camera device that projects a light grid pattern onto the surface of the object, while a camera at a set angle from the projection source views the grid and captures the distortion in the lines as the pattern moves across the surface (at a rate of 15 frames per second).

Post processing converts the captured data into a usable 3D CAD format such as a polygon or triangle mesh, which can then be translated into 3D surface and solid body files. Depending on the scanning method and equipment, accuracy of between 0.2mm and 0.01mm can be achieved.

Laser scanning is the most suitable method for capturing the human body. It is commonly used in the medical and dental industry, as well as for movies, TV and advertisements. It can be used to capture moving bodies for biomechanics or special effects purposes.

4.1.4.29 Scale Hardening

An overview of the hardening processes for various alloys:

440C Stainless Steel

Annealing - full anneal at 850 - 900°C, followed by slowly cooling in the furnace to around 600°C, then air cool.

Hardening - heat to 1010-1065°C, followed by quenching in warm oil or air. Oil quenching is necessary for heavy sections. Immediately temper at 150-370°C to obtain a wide variety of hardness values and mechanical properties.

Tempering - soak at 150-370°C.

Maraging Grade 350 steel

Solution treatment - heat and maintain at 802° to 829°C for one hour for each inch of thickness, air cool. In this condition the steel is readily machined and formed.

Ageing - for maximum hardness and strength, material in the solution-treated condition is heated to between 482° to 510°C and held for between 3 and 6 hours, before air cooling to room temperature.

15-5PH Stainless Steel

Solution treatment - heat and maintain at 1038°C for three minutes for each 2.5 mm of thickness, followed by cooling to room temperature. The material is usually supplied in "Condition A" (solution treated) for ease of forming.

Ageing - For maximum hardness and strength, material in the solution-treated condition is heated for one hour at 482°C and air cooled to room temperature.

Nitriding

Various nitriding techniques can be employed, depending on the composition of the base material. It is generally beneficial for the base material to first be heat treated to its maximum hardness prior to nitriding, which can the take the surface up to around a maximum of 65HRC.

4.1.4.30 Electroplating

Electroplating is a process of coating a component with a thin layer of metal by means of electrolysis. It is used to give objects a better appearance or provide protection from corrosion and wear. The electroplating material is typically a pure metal, rather than an alloy. Commonly used metals include nickel, chromium, zinc or cadmium. The component that receives the coating is usually a type of metal; however electroplating processes for plastics such as ABS and polycarbonate are now commonplace, especially in the automotive and domestic water fittings industries..

Chrome plating is generally used for either decorative or engineering purposes. "Decorative chrome" is typically applied after an initial bright nickel electroplating process. It provides a highly reflective and durable surface and is usually around .25µm thick. "Hard Chrome" is used for more functionally demanding situations. It produces a hardness of around 70 HRC on the surface of a metal to enhance wear resistance, reduce friction and improve corrosion resistance. Hard chrome plating is thicker than decorative chrome, and can range from .25µm up to 1,000µm in extreme cases. In order to achieve this thicker plating the components are left in the bath for a longer period.

The components are typically hung in the bath from cable or hooks. As the scale design has no holes it is necessary to braze on a cable. This can easily be removed after plating; however, the plating material will not cover this area. A wax like substance can also be used to mask areas where plating is not desired. It may also be necessary to finish or grind edges smooth after dipping.

While a hard chromed component presents no significant hazards, hexavalent chrome electrolyte solution is used for hard chrome plating. Hexavalent chromium is the most toxic form of chromium and is considered a carcinogen. During plating a mist of hexavalent chromium is released from the bath, which must be monitored and extracted safely. The hexavalent chromium solution is environmentally hazardous and disposal of the solution at end of life must be carried out appropriately.

4.1.4.31 Physical Vapour Deposition

Vapour Deposition is a process of coating a thin film of metal, ceramic or cermet onto a heated surface, typically carried out under a vacuum condition. The material is vaporized by either physical or chemical methods:

Physical Vapour Deposition (PVD) – uses high temperature evaporation to create the vapour, which then condenses on the part surface creating the film. The temperature within the vacuum is typically around 400°C.

Chemical Vapour Deposition (CVD) – introduces a number of gasses into the chamber that chemically react with each other or the part surface, creating a solid material that is the film.

PVD coatings are the most suitable for the scale application, and include extremely hard materials such as titanium nitride, zirconium nitride and titanium aluminium nitride. The coatings are typically used on cutting tools to maintain a sharp edge and prolong the life of the tool. The hardness of these materials is "off" the HRC scale (although estimated at around 85 HRC), and the coating thickness typically between .25µm and 5µm.

4.1.4.32 Thermal Spray

Thermal spraying consists of melting a consumable feedstock (most often powder or wire) and spraying it as molten particles onto the substrate. Upon impact with the substrate, the molten particle will flatten and solidify very rapidly. Heating is achieved by electrical (plasma or arc) or chemical (combustion flame) means.

All thermal spraying processes are "line-of-sight" processes, only the parts of the component which are directly in the line of the spray are coated. The adhesion of the coating depends on the cleanliness of the substrate surface (a high surface roughness is desirable for good adhesion), and on the velocity of the particles.

There are a number of thermal spray methods that use various types of equipment:

- Plasma Spray
- Electric Arc Spray
- Flame Spray
- High Velocity Oxygen Fuel (HVOF) Spray
- Cold Spray

The HVOF method has been identified as the most suitable of the thermal spray options for coating the scale. It is most commonly used to produce very wear resistant coatings using tungsten-carbide cobalt and other cermet feed stocks. It commonly used as a hard chrome replacement as the coating typically display higher coating hardness and greater wear resistance, as well as being a more environmentally friendly solution[3]. The HVOF system can also spray nickel and cobalt alloys such as Stellite, Inconel, stainless steels and ceramics.

Typical HVOF devices spray at hypersonic velocities, i.e. greater than MACH 5. The extreme velocities provide kinetic energy which help produce coatings that are very dense (porosity levels typically less than 0.5%) and very well adhered to the substrate (bond strength >50MPa). Due to the speed, the scales will have to be held tightly in a jig, to prevent them being blown away by the spray. The spray will also have to be applied in a controlled manner, to avoid the relatively thin scale becoming overheated.

The scales must be media blasted immediately prior to spraying, in order to clean and roughen the surface to promote good adhesion. The coating thickness is approximately 5µm per pass with the HVOF gun. Two passes must be made, the first at 45° to the surface and the second at 135° in order to achieve full coverage on the rough surface. Thicker coatings are possible but the coating will become more susceptible to cracking and chipping.

There is however potential health risks involved in the production of tungsten carbide powders; the inhalation of dust can lead to fibrosis. Tungsten carbide is also reasonably anticipated to be a human carcinogen by the US National Toxicology Program, based on limited evidence from studies. (source: http://ntp.niehs.nih.gov/pubhealth/roc/roc12/index.html)

4.1.5 Glove ‘Membrane’ Manufacturing Options – Detailed Research

4.1.5.1 Glove Manufacturers

A number of glove companies have been identified who could supply suitable products and potentially become manufacturers or industry partners:

- **Ansell -** www.ppe.ansell.com.au - Australian company that manufactures a range of medical and industrial gloves. Based in Melbourne, Australia with a strong global presence, especially throughout Europe and North America.
- **Showa Best -** www.showabestglove.com – American based company with over 1800 individual glove choices in their range. Strong global presence with Australian sales representatives.
- **Elliotts -** www.elliottaustralia.com – Australian company with a range of protective clothing and safety equipment, including gloves. Based in Brisbane, Queensland with distribution centres in Melbourne and Perth.
- **ProChoice -** www.prochoice.com.au – Australian based company with a range of protective clothing and safety equipment, including gloves. Based in Brisbane, Queensland with offices and distribution centres in Sydney, Melbourne, Adelaide and Perth.

All companies were approached for discussions under a Confidentiality Agreement. Most success was achieved with Prochoice, and progress continued exclusively with this company due to their enthusiasm and willingness to be involved in an R+D project of this nature. ProChoice is the brand name for the gloves produced by the parent company Paramount Safety products. A selection of gloves from their range was reviewed, focusing on the following features:

- Construction type
- Liner materials
- Dip materials
- Other notable features

4.1.5.2 Construction Type

The gloves that were reviewed can be classified by their method of construction:

- **Rubber dip** - A porcelain ceramic hand form is dipped in a bath of liquid material. The hand form is removed from the bath and rotated until all excess material has dripped off, leaving an even coating of material over the hand form. The hand form is then typically placed through an oven to vulcanise the material. Multiple dipping processes or layering processes can occur, with each layer adding to the overall thickness. The glove is essentially made inside out; the first dip material forms the outer layer of the glove. The finished glove is removed by stripping it off the hand form.

  Rubber dip video: http://www.youtube.com/watch?v=h-sLHYvqT7I
  Rubber dip gloves are available in thin walled form fitting styles (e.g. disposable surgical gloves) and thicker walled looser fitting styles (e.g. typical 'washing up' and industrial type chemical proof gloves)
- **Seamless knit and dip -** automated knitting machines are able to produce seam free gloves at a rate of around one glove every two minutes. The machines can be programmed to knit various glove sizes and configurations (eg. 5 finger, 4 finger, fingerless etc.), with changes in stitch densities and pattern for the cuff, finger tips and high stretch areas. Specialist yarns can be used such as high strength cut proof fibres (eg. Kevlar, Dyneema, Spectra) and conductive yarns to enable the use of touch screens. The gloves are then put onto hand forms and dipped (partly or entirely) in a bath of liquid material (e.g. latex, nitrile, polyurethane) to provide increased grip, abrasion resistance

  Knitting video: http://www.youtube.com/watch?v=TxjlYusLxHA Dipping video: http://www.youtube.com/watch?v=Fi9nhCLaIGE

  Knit gloves are typically tight fitting with elastic characteristics. The fabric can be thin for good dexterity or thicker to provide warmth. Different stich patterns in particular areas give better stretch

- **Cut and sew** - glove components are die cut from pieces of leather or fabric. The pieces are sewn together to form the glove. Panels with extra padding, different types of fabric, rubberised protective panels, etc. can be stitched into the final glove.

  Cut and sew video: http://www.youtube.com/watch?v=tQgMauVuxxE

4.1.5.3 Liner Materials

The liners of the knit and dip gloves supplied by ProChoice have been made from various types of fabric. The materials include:

- Wool
- Nylon
- Nylon/acrylic blend
- Nylon/lycra blend

All materials have suitable stretch and flexibility. There is variation in the fabric thickness and insulating capability, however thicker fabric contributes to a loss of dexterity and tactile perception.

4.1.5.4 Dip Materials

The seamless knit and dip gloves supplied by ProChoice have been dipped in various materials, including:

Latex – can be derived from natural or synthetic sources. It has high elasticity, excellent grip especially in wet conditions, can withstand extreme temperatures and has good tear resistance. The dip material can be foamed for a lighter and softer coating, which in the case of the LFN glove makes it waterproof. A range of textures can be achieved. Note - Natural latex gloves may cause or lead to the development of allergies for wearers, due to specific proteins in the material. Selected protein free latex materials are available.

Nitrile – is a co-polymer of acrylonitrile and butadiene. It is a synthetic version of latex but lacks the superior stretch and grip characteristics. It is very strong and resistant to tearing and puncturing, and has good resistance to oil. Nitrile can be foamed and used as a dip material where it will become porous and allow good breathability, and improve grip while maintaining excellent protection.

Polyurethane (PU) - is a thermoplastic polymer with good stretch, strength, and softness. It has good grip without being tacky. The low-particulate shed makes it a good choice for work with electronics and in cleanrooms. It has excellent chemical and oil resistance, but has poor resistance to heat.

Polyvinyl Chloride (PVC) – is a synthetic thermoplastic polymer of vinyl chloride, and an inexpensive material, making it one of the more common coatings for coated work gloves. It offers good abrasion resistance, though it may be susceptible to punctures, cuts, and snags. The material stays flexible at low temperatures, but typically does not provide the tactile sensitivity associated with rubber products.

4.1.5.5 Other Notable Features

Cut Proof Gloves

Many glove manufacturers offer cut proof gloves as a part of their product range. These gloves protect the users hand from cuts from sharp edges and penetration form pointy objects. They are typically targeted at specific industries such as metal handling, glass handling, waste handling, police and military and the meat and fish industry. They are typically made from the following materials:

Metal chain mail: uses interlocking stainless steel rings to form a mesh.

Metal fibre: multifilament steel yarn, or a combination of filaments with natural or synthetic fibres. These materials can be used in the production of seamless knitted gloves.

Synthetic fibres: engineered polymers that can be used in the production of seamless knitted gloves. They often are more commonly known by their trade names:

- **Para Aramid** – Kevlar, Twaron, Nomex
- **Ultra High Molecular Weight Polyethylene (UHMWPE)** – Dyneema, Spectra
- **Liquid Crystal Polymer** - Vectran

Protective Panels

Many glove manufacturers supply gloves with protective panels. These can be classified as:

Fabric panels – pieces of specialist fabric stitched into local areas to target an improvement in performance. This can include leather or other tough materials in high stress areas, padded panels for comfort, specialized fabrics for cut protection or coated fabrics for grip.

Non fabric panels – such as rubber or rigid plastic plates for knuckle and finger protection, typically stitched into place on the glove. These features are usually added for protection against impact and abrasion.

Conductive Yarns

The development of conductive yarns and their usage in gloves has largely been driven by shielding requirements in the electronics industry. Typically they are silver, copper or nickel coated fibres, although stainless steel metal fibre yarns are also used. These fabrics have also found a new market in the touch screen arena, allowing gloved fingers to operate touch screens that function by detecting changes in electric currents (e.g. IPhones, IPads, etc). Polymer coatings can also conduct sufficient current for this purpose, including Polyaniline, Polypyrrole and Polyacetylene.

4.1.5.6 Alternate Manufacturers - Notable Technologies

The research also identified a number of gloves and associated features of interest from the other identified manufactures. Gloves of interest are noted below:

Ansell

- Activarmor 97-002 HVAC – Intercept technology – stainless steel/kevlar weave liner, foam nitrile dipped
- Hyflex 11-101 – conductive yarn (suitable for use with touch screens)
- Hyflex 11-200 – sleeve
- Hyflex 11-800 – Zonz variable knit pattern in high stretch areas of the glove
- Hyflex 11-840 – highly breathable and durable

Repeated sample requests for the above gloves models were placed, however to date these have not arrived.

ShowaBest

- 281 Temres – waterproof and breathable glove. Double layer polyurethane. Seamless knit
- 282 Temres – Same features as 281 with extra insulation to resist cold
- S-TEX 541 – Hagane Coil fibre technology. Stainless steel/polyester weave liner, Polyurethane dipped

Elliots

- G-Flex Roustabout C5 IMPACT – double dipped, foam nitrile (T-Touch) over nitrile
- Dynamax C5 - sleeve

4.1.6 Glove Standards

The following Australian and International standards regarding gloves have been identified:

AS/NZS 2161.X:1998 Occupational protective glove standard – in particular:

- **AS/NZS 2161.2 / EN420** - General requirements – glove sizing chart

- **AS/NZS 2161.3 / EN388** - Protection against mechanical risks. This standard specifies the performance requirements for protective gloves with regard to abrasion, blade cut, puncture, tear and impact cut. Protection against mechanical hazards is expressed by a pictogram followed by four numbers (performance levels), each representing test performance against a specific hazard.

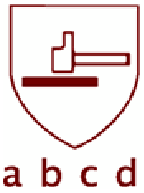

Figure 19 - The mechanical risks pictogram
(source: http://www.ansell.eu/industrial/index.cfm?pages=eu_standards_en388&lang=DA)

The mechanical risks pictogram is accompanied by a 4-digit code (see Figure 19):

a. **Resistance to abrasion:** based on the number of cycles required to abrade through the sample glove.
b. **Blade cut resistance:** based on the number of cycles required to cut through the sample at a constant speed.
c. **Tear resistance:** based on the amount of force required to tear the sample.
d. **Puncture resistance:** based on the amount of force required to pierce the sample with a standard sized point.

For all categories 0 indicates the lowest performance, 5 the highest.

- **AS/NZS 2161.5 / EN 511: 1994** - Protection from cold. This standard applies to any gloves to protect the hands against convective and contact cold down to –50 °C. Protection against cold is expressed by a pictogram followed by a series of 3 performance levels, relating to specific protective qualities.

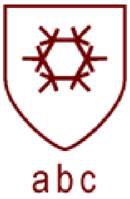

Figure 20 - The cold hazard pictogram (source:
http://www.ansell.eu/industrial/index.cfm?pages=eu_standards_en511&lang=DA)

The cold hazard pictogram is accompanied by a 3-digit number (see Figure 20):

a. **Resistance to convective cold** based on the thermal insulation properties of the glove which are obtained by measuring the transfer of cold via convection. 0 indicates the lowest performance, 4 the highest.
b. **b. Resistance to contact cold** based on the thermal resistance of the glove material when exposed to contact with a cold object. 0 indicates the lowest performance, 4 the highest.
c. **c. Permeability by water** 0 = water penetration after 30 minutes of exposure; 1 = no water penetration

All gloves must achieve at least Performance level 1 for abrasion and tear.

Other area of interest:

- **AS 4461-1997** - Hygienic production of meat for human consumption

  Light coloured gloves are recommended.

- **FDA Code of Federal Regulations, Title 21, Part 177** – Indirect food additives: Polymers

  Subpart C - Substances for Use Only as Components of Articles Intended for Repeated Use

  More detail: http://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?CFRPart=177

- **PPE Directive 89/686/EEC – risk categories** – to determine whether the glove requires independent testing by a notified body, and the relevant display of the CE mark.

  Refer to the appendix for further information regarding glove standards

4.2 Technology Bonding Techniques

4.2.1 Adhesives

The resources of worldwide adhesive industry leader 3M were utilised to identify suitable bonding materials and techniques that are suitable for the butcher’s band saw glove application. Their product range covers a variety of adhesive types. The following categories were explored with 3M engineers:

Spray Adhesives - Available in bulk cylinder form for use with a spray gun applicator, or in 500g aerosol cans. The most suitable option in this range is the “Rubber and Vinyl 80” product.

Adhesive Transfer Tape - Double sided adhesive tape available on rolls, this product can also be die cut to match the shape of the scale. The most suitable product in this range is the “9485PC”.

Industrial Adhesive – liquid or plastic adhesives supplied in tubes or in bulk form. The most suitable product in this range is the “4475”.

Polyurethane Reactive (PUR) – a moisture curing hot melt adhesive system. Available in 300ml canisters, dispensed with an applicator gun and sets in around 30 seconds. Also available in bulk, a suitable product in this range is the TE040

4.2.2 Polyurethane Reactive (PUR) Adhesive System

The moisture curing hot melt polyurethane (PUR) adhesive system was identified as the most suitable to the butcher's band saw glove application and preliminary testing was performed using the TE040 variant product. The applicator's heating chamber heats the adhesive, then compressed air is used to assist the delivery of glue through the nozzle. The TE040 product is classified as a flexible adhesive (shore hardness of 35D) and bonds very well to either a smooth or textured metal surface. Successful bonding results were achieved with a number of different fabric types (see Table 1, page 71). We observed that the adhesive impregnated and encapsulated the fibres of the fabric, creating a strong bond. Bonding tests were also performed on to the glove dip materials, (latex, nitrile, polyurethane etc.) with poor results.

In addition to the good adhesive performance, the PUR system also has processing benefits that suit the glove manufacture process.

- The adhesive sets quickly (provides a 2 minute open time, then sets in around 30 seconds)
- Once set, it can withstand temperatures of up to 135°C without re-activating
- It has a low VOC formulation that eliminates the need for drying and ventilation equipment
- Can be applied using a CNC nozzle for thin and accurate bond line deposition, with minimal waste

See the appendix for the TE040 technical data sheet.

3M demonstration video of CNC deposition: https://www.youtube.com/watch?v=GI9PL-9zKlQ

4.3 Bonding tests

A selection of the ProChoice supplied glove samples were tested with the 3M PUR TE040 product. As 3M have a policy of not signing Confidentiality Agreements, 316 stainless steel washers instead of scale samples in order to protect the concept.

The washers were tested in two conditions, smooth or abraded. The abraded samples were rubbed with 180 grit sandpaper prior to bonding. Both sample types were cleaned with isopropyl prior to bonding.

The washers were bonded to both the liner material and the dip material of each glove, to compare performance.

The adhesive was applied directly to the glove (particularly to allow impregnation through the liner fibres), before the washers were placed in position and held with light pressure for a few seconds. The gloves were then left for the adhesive to set.

Preliminary testing was performed by simply attempting to remove the washers from the glove manually. Test results are shown in Table 1.

5.0 Overall progress

The project is complete, and has been delivered to the agreed scope and budget.

A delay to the schedule was experienced as a result of a process of legal clarification regarding Confidentiality Agreement; however, this did not adversely affect any outcomes.

6.0 Discussion

6.1 Stage 1: Materials and Process Research

6.1.1 Scales

6.1.1.2 Materials

The research focused on identifying a range of suitable materials to meet performance requirements. It was assumed that in order for the scale to not be damaged by the blade, it must possess an equivalent or superior combination of material hardness, toughness and wear resistance. Testing performed on a range of band saw blades ascertained a material hardness of 58 – 60 HRC. Preliminary assessments of the scale samples have been made, but whether the performance of these material types is suitable to the application is subject to further quantitative testing.

Utilizing a corrosion resistant alloy such as stainless steel as a base metal for the scale is a logical choice, given its suitability to the food preparation environment. The 300 series stainless steels are the most common type of stainless steel (including the popular 304 and

316 grades), accounting for up to 70% of all stainless steel production. The 300 series are readily formable with good toughness and impact resistance. They also perform well at low (subzero) temperatures and are virtually non-magnetic, however they are relatively soft compared to the band saw blade and are easily damaged. The 300 series stainless steels austenitic in structure due to their nickel content and cannot be hardened by heat treatment. They can, however, have a harder surface coating applied that exceeds the hardness of the blade to provide a good overall solution. Options include electroplating a layer of chromium, known as “Hard chrome plating” or employing the advanced characteristics of technical ceramics and ceramic composites. Thermal spraying the scales with a tungsten carbide composite using a High Velocity Oxygen Fuel (HVOF) system will provide a hard and resilient coating, while the Physical Vapour Deposition (PVD) process can deposit thin films of extremely hard ceramic materials such as titanium aluminium nitride.

Particular grades of stainless steel can be heat treated to achieve a material hardness close to that of the teeth of the band saw blade. These include the 400 series and the 17-4PH and 15-5PH grades from the 600 series. Other corrosion resistant alloys such as Grade 350 maraging steel, Stellite and Grade 5 Titanium 6-4 alloy can also be heat treated to achieve desirable mechanical performance characteristics. Ageing, quench and temper techniques, as well as surface heat treatment processes such as nitriding are used to provide the increase in hardness. The research indicates that these heat treatable material options may provide the most suitable combination of performance, ease of manufacture and price.

The martensitic stainless steels in the 400 series are a popular choice for knife blade makers and the manufacture of cutlery. Stainless steel band saw blades are typically made from 420 grade. The 400 series are known as “straight chromium” stainless steels and contain little nickel. The high chromium and carbon content enable good strength, hardness and wear resistance characteristics due to the formation of chromium carbide particles during heat treatment; this does however reduce their relative corrosion resistance. Grade 440C contains the highest amount of carbon of the 400 series stainless steels, and can achieve the highest hardness through heat treatment (up to 59 HRC). Research indicates that scales made from the 440 B and C grades would be suitable for use with the appropriate heat treatment.

Maraging steels are low carbon iron alloys containing nickel and cobalt alloying elements. The high nickel gives good strength, toughness and moderate corrosion resistance, while cobalt and other elements such as molybdenum and titanium produce intermetallic precipitates during ageing. The 350 grade material can achieve a hardness of around 58 HRC. The research indicates that scales made of this material would be suitable for use. The addition of chromium (and subsequent reduction in nickel) increases corrosion resistance and produces alloys known as “precipitation hardening” stainless steel.

Precipitation-hardening martensitic stainless steels have corrosion resistance comparable to austenitic varieties, but can be precipitation hardened to even higher strengths than the other martensitic grades (with the exception of the 440 A, B and C grades). The most common, 17- 4PH, uses 17% chromium and 4% nickel. Also known as 630 grade stainless steel, the corrosion resistance of 17-4PH is comparable to 304 stainless steel in most environments, and is generally superior to the 400 series stainless steels. It is used in applications where the combination of moderate corrosion resistance and high strength are required. 15-5PH grade has similar corrosion resistance qualities to 17-4PH, but with better toughness. Scales made from 15-5PH may be suitable for use with the appropriate ageing process, where hardness of around 45HRC can be achieved.

Titanium as a pure metal exhibits excellent corrosion resistance, low density and high strength. It is commonly alloyed with other elements to create high end sporting equipment and components for the motor racing, marine, and aerospace industries. Its durability makes it a popular choice for jewellery and watches, and its biocompatibility characteristics enable it to be used for surgical and dental implants and implements. Ti6-4 is the most common titanium alloy, containing 6% aluminium and 4% vanadium. This alloy can be heat treated, however typically exhibits poor wear resistance. The alloy responds very well to diffusion hardening techniques such as nitriding and can achieve surface hardness approaching 65HRC, significantly improve this characteristic and making it suitable for use.

The Stellite family of cobalt-chromium alloys have been designed for wear resistance. Other properties include high hardness and toughness, and being non-magnetic and corrosion resistant. Stellite alloys are typically used for casting parts, as well as hardfacing, coating and cladding. The addition of carbon to the alloys increases the carbide content, and in turn makes the alloys harder and more wear resistant. Stellite 3 and Stellite 20 are two of the harder alloys, capable of achieving hardness between 53 – 59 HRC. Scales could be cast from either of these materials; however the research indicates that cobalt could be more effectively used as a binder in a cemented carbide material such as tungsten carbide and applied as a coating to the scale.

Tungsten carbide is a material characterised by its high strength, toughness and hardness. It is a cermet composite material made up of ceramic tungsten carbide particles in a cobalt metal binder. A composite ratio of 88% tungsten carbide to 12% cobalt is a commonly used and readily available product, with suitable properties for the scale application. A HVOF sprayed surface will achieve a macro hardness of around 72 HRC, but with a much superior wear resistance to other materials of this hardness, such as hard chrome plating

A variety of ceramic coatings can also be applied to the scale using the PVD process. Material options include extremely hard materials such as titanium nitride, zirconium nitride and titanium aluminium nitride. These very thin coatings are typically used on cutting tools to maintain a sharp edge and prolong the life of the tool. The hardness of these materials is “off” the HRC scale (although estimated at around 85 HRC).

6.1.1.3 Manufacturing Process

A number of manufacturing methods can be used for the scale; the most suitable will be selected based on the manufacturing quantities and anthropometric factors. Economical high volume manufacture of defined and repeatable scale sizes and shapes (e.g. for small/medium/large size gloves) is achievable, however comes with a high set up cost to create production tooling. Methods such as metal pressing and investment casting are suitable processes. For lower volume manufacture alternate methods can be used. Emerging technology such as Direct Metal Laser Sintering (DMLS), also known as metal 3D printing, is ideally suited. The higher part manufacture cost of this process can be offset by the elimination of production tooling expenses.

It is also anticipated that finger and hand dimensions will vary, and not uniformly conform to small/medium/large sizes. A 3D hand scanning process could also be used to compliment DMLS, to create scales that are perfectly fitted to an individual’s hand and result in the most form fitting, comfortable and safe glove. A cost effective medium volume production process could be to 3D print scales in specific wax or plastic materials, which can then be used as sacrificial master components in the investment casting process.

We make the following classifications:

- High volume manufacture – 10,000 + units
- Medium volume manufacture – 1,000 – 10,000 units
- Low volume manufacture – 0 – 1,000 units
- Set of gloves – one left hand glove and one right hand glove
- All price estimates are based on the conceptual glove/scale design. Detailed CAD
- models of all scale components are required for accurate production costings
- Assuming a 1mm scale thickness, we estimate the weight of the scales to be approximately 250 - 300g per glove
- All price estimates are ex-GST

For high volume manufacture, metal stamping is a suitable process. The research indicates that using 0.9mm thick sheet metal would be ideal, providing a suitable combination or strength and light weight. The tooling is made for a specific scale thickness, and can then be used to produce scales from a variety of alloys. Using a heat treatable stainless steel would be the first recommendation, if the performance was deemed suitable. Note that these alloys are not commonly available in sheet format in Australia, but are available as special orders. The minimum “mill run” order quantity would be 1 ton, which we conservatively expect will make in excess of 1,000 sets of gloves. Smaller quantities are available from overseas suppliers, but the per kilogram cost and extra shipping will add expense. The metal stamping process can be used to make scales from the more readily available 304 and 316 grade stainless steels, which can then be coated to improve their performance. The tooling price will be significant (expected around $150,000 per single sized set of gloves) however the scale price will be economical (expected around $40 per set of glove scales). Metal stamping can also be used for medium and low volume production runs; however, the tooling and set up costs may be economically prohibitive and also lead to an increase in scale unit price.

While injection moulding could also be a suitable process for high volume manufacture, the scale part price would likely be significantly more expensive (expected around $300 per set of glove scales). This process will also have a significant tooling cost (expected around $150,000 per single sized set of gloves). The larger arm plates are too large for the injection moulding process, and will have to be manufactured using a different process. We also anticipate complications during the sintering process for the smaller scales. Due to the thin walled nature of the scale, it would be likely to slump or collapse without suitable support. This could be overcome by using suitable jigs; however this will add additional set up and labour costs, pushing the part price higher again. For metallic scales, metal pressing would be preferred over injection moulding.

The investment casting process could be used for low, medium or high volume production, but presents the best value for medium volume. Once tooling is made, the scales can be cast in a variety of alloys. The research indicates that using a heat treatable stainless steel would be the first recommendation, of which casting material is readily available. Other grades can be cast and coated as required. For the investment casting process a 0.9mm scale will likely require thicker channels or ribs through the scale to allow good material flow. If a consistent scale thickness is required, the scale will likely need to be a minimum of 2mm thick, adding bulk and weight to the glove. Scale production will be more labour intensive than the other processes, and the parts will need to be hand finished to remove sprue and any wax drainage or venting features that must be incorporated into the mould. The investment casting process will also potentially have a scrap rate of 5 to 10%. The wax injection moulding tooling prices will be in the region of $50,000 per single sized set of gloves, with medium volume part prices expected around $50 per set of glove scales. Tooling investment is not required when investment casting is used in conjunction with 3D printing. Wax master parts can be 3D printed, replacing the injection moulded components; however, the print resolution is important in creating a high quality surface finish on the cast part. Part prices for 3D printing are expected to be around $500 per set of glove scales, in addition to the casting costs.

Direct Metal Laser Sintering (DMLS), or metal 3D printing, would be a suitable process for low volume manufacture. Although the unit price is high (expected around $1,650 per set of glove scales, depending on the material), the cost is offset by the elimination of expensive production tooling. Drawbacks of 3D printed parts include structural integrity less than that of cast or formed arts, and the anisotropic characteristics of the printed parts due to the layered building method. However, this can be reduced or removed by a subsequent Hot Isostatic Pressing process and/or appropriate heat treatment (with additional associated cost). The current range of available materials for DMLS is somewhat limited, but selected heat treatable stainless steels such as 15-5PH are available. Grades such as 440C are in early stages of development and will require investment in bulk amounts of powders to build and verify the components (expected around $5,000 - $10,000).

Regardless of the manufacturing method, once the scale has been formed it can go through a secondary process to improve its performance. Heat treatment as the most efficient way of achieving this improvement provided the scale has been manufactured from a suitable alloy.

The heat treatment process requires minimal handling and pre/post processing activities, and is therefore very economical with costs of less than $5 per set of glove scales.

Plating or surface coating the scale is also an effective way of improving performance. Chrome plating the scales is the most economical process to achieve scale surface hardening of around

70 HRC or greater. The cost is expected to be around $150 per set of gloves for a 3 hour dip. This includes attaching and removing the hanging wire and any manual de burring that may be required. PVD coatings in extremely hard materials such as titanium nitride, zirconium nitride and titanium aluminium nitride will cost around $300 per set of gloves with no pre or post processing required, however this coating may be susceptible to failure if the scale material is too soft.

HVOF coating the scales with tungsten carbide will cost around $500 per set of scales; this includes labour to jig the parts, sandblast, then perform the HVOF spray. The cost of a suitable jig for this process is difficult to estimate before any design or testing has been completed, but may cost in excess of $10,000. We also note that the extreme hardness of the tungsten carbide material, combined with the surface roughness as a result of the sand blasting pre- treatment will potentially result in the scales scratching any 304 or 316 stainless steel work surfaces they slide across.

Using additive manufacturing (3D printing) methods in scale manufacture eliminates the need for expensive tooling and presents the opportunity to create individually customised components for no additional cost. Employing 3D scanning as a method of creating scales matched to each particular user’s hand geometry will create the most form fitting, comfortable and safe glove. It is difficult to provide any “per glove” costs for this process as the design is only in concept form, but day rates for scanning and CAD development range from $1,200 to $1,600 per day (a more detailed schedule of costs is included in the appendix).

6.1.2 Membrane

Creating a slim and form fitting glove will contribute to the retention of dexterity and tactile perception, while a bulky glove can potentially result in a false sense of proprioception and increase the risk of inadvertent physical interaction with the band saw blade. Therefore, a tight and stretchy membrane is recommended as opposed to a loose fitting one.

Tight fitting ‘rubber’ type gloves are typically disposable, and can usually only be removed by stripping them off the hand, turning then inside out. Often the gloves are destroyed in this process. As the concept has rigid scales applied to the body of the glove, a tight fitting rubber type glove will be difficult to remove and be susceptible to damage. Tight fitting knitted gloves are an ideal solution, given their ability to slide on and off the hand easily.

There are many ‘cut proof’ tight and stretchy knitted fabric gloves in the marketplace. However, these are designed to protect against sharp edges such as knife blades, glass and sheet metal, as opposed to a fast moving serrated saw blade. These gloves are made from high performance synthetic yarns, that would likely catch on the serrations and drag the user’s hand into the band saw rather than being cut cleanly by the blade.

A number of knitted glove fabrics have been identified that provide suitable stretch characteristics, minimal resistance to cutting and ease of removal. The suitability of each these fabrics can be explored further in prototype development and quantitative testing. The knitting manufacture process is very cost effective (less than $5 RRP for a set) and allows for variable knit pattern for high stretch or tighter areas. Arm length gloves can also be manufactured using current machinery.

Many knitted gloves are also dip coated with a layer of material such as latex, nitrile or polyurethane. These dip coatings improve grip and wear characteristics, and prevent the fabric from catching and snagging. Additional benefits of this style of glove for the butcher’s application include the ability to seal the fabric from liquid contamination and insulate the user’s hand.

Gloves with good breathability features are recommended when gloves are to be used for extended periods, as exposure to sweat inside the gloves for a long period can cause dermatitis or other skin reactions. However, integrating breathability features into gloves for the butcher’s application will typically make the gloves susceptible to liquid contamination. In hot environments gloves can be changed frequently or workers can use interchangeable absorbent liners.

Due to the refrigerated environment; extreme cold may be more of an issue than excessive heat. Insulated gloves may be beneficial, and could potentially even use conductive fibre technology for integrated heating. Conductive fibres could also be used as a complimentary feature to the current sensing Blade-Stop technology as developed by Thompson Machinery

If a glove dip material is used, it potentially may be specified to compliment the camera sensing equipment that is also being integrated into these machines.

ProChoice is a leading Australian glove manufacturer their product range and factory contacts were used as a resource to explore design and manufacture options. Research indicates that a knitted glove can be manufactures to the following specification (see Figure 2):

- Fingertip to elbow length for protective coverage
- Variable knit pattern for high stretch or tighter areas
- Full length complete glove dip (if appropriate)

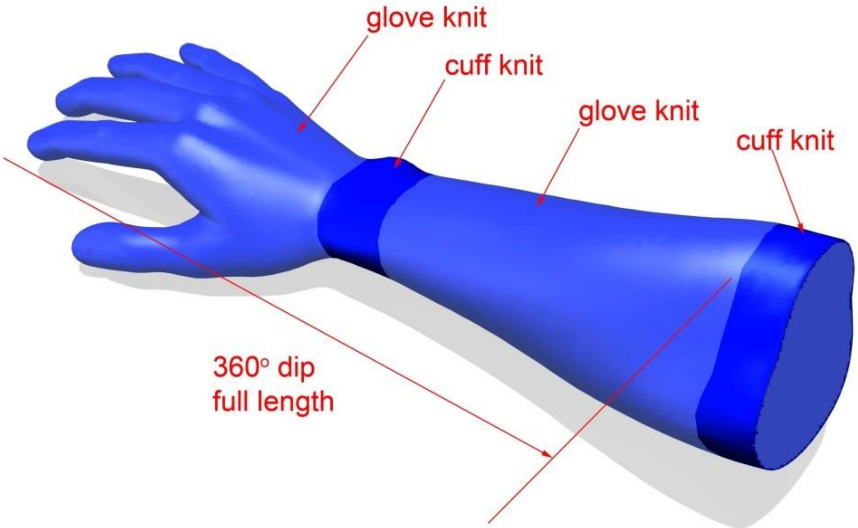

Figure 2 - Conceptual design for a knitted glove (source: Kennovations)

Feedback from ProChoice indicates that the process of bonding the scales to the glove can easily be integrated into the manufacturing process, either before or after the dipping process.

The bonding of the scales will eliminate stretch in the glove in the area that they are positioned, and care must be taken to ensure there is sufficient “scale fee” area to allow a suitable range of motion and endure the gloves to be put on and removed comfortably. Note that the areas between the scales designed to promote movement and flexibility in the glove will expose these areas of the hand to injury from the band saw blade.

6.1.3 Bonding

The resources of worldwide adhesive industry leader 3M were utilised to identify suitable bonding materials and techniques for our specific application. Various adhesive systems were assessed in conjunction with 3M engineers, including: sprays; tapes; industrial liquid and plastic adhesives; and hot melt systems.

The moisture curing hot melt polyurethane (PUR) adhesive system was identified as the most suitable to the butcher's band saw glove application and preliminary testing was performed using the TE040 product variant. It is classified as a flexible adhesive (shore hardness of 35D) and bonds very effectively to either a smooth or textured metal surface. Successful bonding results were achieved with a number of different fabric types (see Table 1 on page 72). We observed that the adhesive impregnated and encapsulated the fibres of the fabric of knitted gloves, creating a strong bond. Bonding tests were also performed on to the glove dip materials, (latex, nitrile, polyurethane etc.) with poor results, reinforcing the recommendation to use a knitted liner.

In addition to the suitable adhesive performance, the PUR system also has a number processing benefits that are beneficial to the glove manufacture process:

- The adhesive sets quickly (provides a 2 minute open time, then sets in around 30 seconds)
- Once set, it can withstand temperatures of up to 135°C with re-activating
- It has a low VOC formulation that eliminates the need for drying and ventilation equipment
- Can be applied using a CNC nozzle for thin and accurate bond line deposition, with minimal waste

6.1.3.1 Advanced Design Concept

The scale size and position is purely conceptual at this time; once anthropometric data has been considered the scale designs can be further developed. Sydney based 3D scanning company WYSIWYG 3D was consulted to explore the opportunity of using 3D scanning in the development process for the scale and glove design gloves. Their services can be used in the following ways:

Anthropometric data collection – WYSIWYG 3D can use their portable Artec (www.artec- group.com) scanner to perform site visits and scan the hands and arms of a selection of band saw users. This data can be used to ascertain the size range variations and assist with suitable scale design.

Personalized glove design – if deemed suitable, WYSIWYG can scan every individual band saw user's hand and arms and use this data to create scale designs tailored to that person's unique body geometry. A generic scale template design can be created, which can then be adjusted in a CAD program to suit the scan data from each user. Identification data can be added to the individual scale components during the CAD design process to assist in the order management and production process (see Figures 3 to 7).

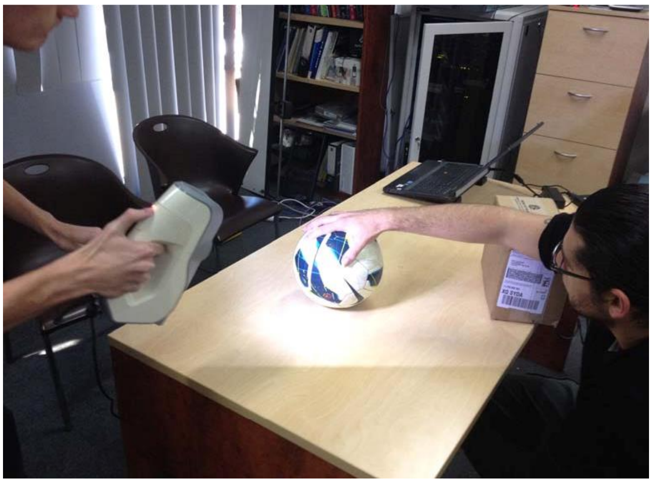

Figure 3 - Using the portable 3D scanning equipment to record a user's hand and arm geometry. Positioning the hand on a ball or similar purpose built jig spreads the fingers to enable a complete scan of the finger geometry and ensures stability during the scanning process (source: WYSIWYG photo)

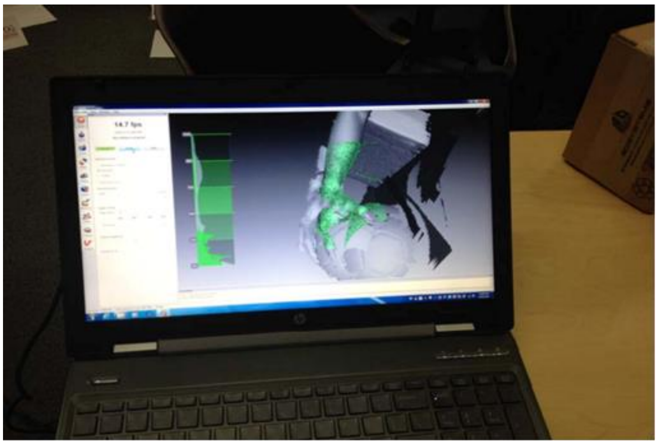

Figure 4 - The captured data is processed to create a 3D CAD model (source: WYSIWYG photo)

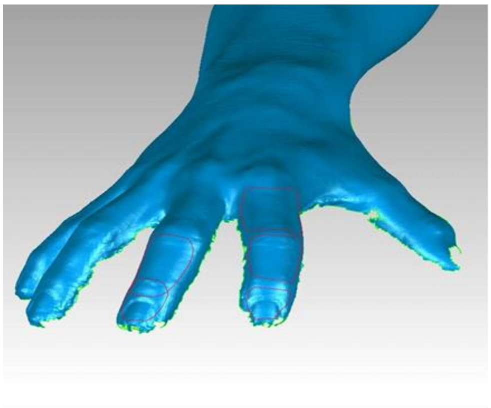

Figure 5 - Using commands in the CAD software the hand surface is offset to allow for the thickness of the glove material, and the scale outlines are defined (source: WYSIWYG photo)

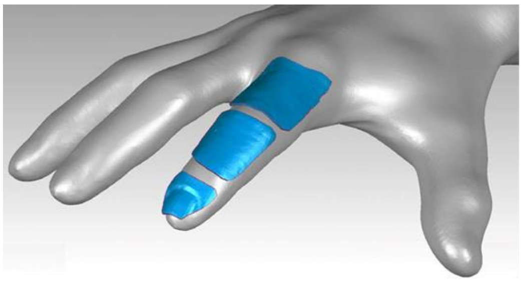

Figure 6 - The scale pieces are thickened. Surface detail can be smoothed out at this point (source: WYSIWYG photo)

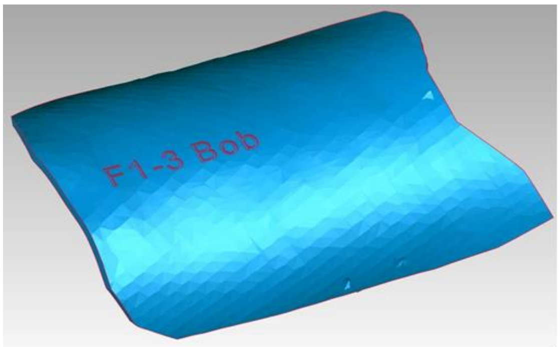

Figure 7 - Unique markings can be applied to each scale to identify the user and the scale location on the glove. The parts are then saved in a 3D CAD format that can be read by a 3D printing machine (source: WYSIWYG photo

6.2 Stage 2: Materials Samples and testing

6.2.1 Scale

Material	Thickness	Grade	Process	Coating/treatment	Notes
Stainless steel	1.5mm	316	sheet metal	-	
Stainless steel	1.2mm	304	sheet metal	-	
Stainless steel	0.9mm	316	sheet metal	-	
Stainless steel	0.9mm	316	sheet metal	hard chrome plate	1.5 hour dip
Stainless steel	0.9mm	316	sheet metal	hard chrome plate	3 hour dip
Stainless steel	0.9mm	316	sheet metal	PVD titanium nitride (TiN)	
Stainless steel	0.9mm	316	sheet metal	PVD titanium aluminium nitride (TiAlN)	
Stainless steel	0.9mm	316	sheet metal	PVD TiN/TiAlN multilayer	
Stainless steel	0.9mm	316	sheet metal	PVD zirconium nitride	
Stainless steel	0.9mm	316	sheet metal	HVOF tungsten carbide	88/12
Polycarbonate	1mm	-	MJM 3D print	-	29µm
Stainless steel	1mm	15-5PH	3D print (DMLS)	-	20µm
Titanium	1mm	6-4	3D print (DMLS)	gas nitride	20µm
Bronze – white phosphor	1mm	-	3D print wax / investment cast	-	16µm
Bronze – white phosphor	1.5mm	-	3D print wax / investment cast	-	16µm
Bronze – white phosphor	2mm	-	3D print wax / investment cast	-	16µm
Silicon carbide	4mm	-	hot pressed	-	
Aluminium oxide	1.2mm	99%	tape cast	-	

6.2.2 Membrane

The following samples are provided for review:

ProChoice Gloves				
Product name	**Construction type**	**Liner material**	**Dip material**	**RRP (ex GST)**
Arctic Pro	knit and dip 270°	Wool	Latex	$9.04
Black Panther	knit and dip 270°	Nylon	Latex	$3.67
LFN	knit and dip 270°	Nylon	Foam latex	$4.35
Dexifrost	knit and dip 270°	Nylon/acrylic	Nitrile	$6.13
Superguard	cut, sew and dip 360°	Not confirmed	Nitrile	$3.54
Maxipro	knit and dip 270°	Nylon/lycra	PU/Nitrile	$3.43
Maxipro 360	knit and dip 360°	Nylon/lycra	PU/Nitrile	$5.10
Stinga	knit and dip 270°	Nylon	PVC	$4.31
Green heavy duty latex	cut, sew and dip 360°	Cotton	Latex crinkle	$7.21
One +	cut, sew and dip 270°,rubber back	Nylon	Nitrile	$21.74
ProFit Razorback	cut and sew, rubber back	Synthetic leather	-	$57.22

6.3 Stage 3: Report

This document is the deliverable for Stage 3.

7.0 Conclusions/Recommendations

All stages of the project have yielded positive results. The concept as presented as part of "**Final Report (not for public release) Butcher Glove 12 1 12.pdf**" is technically feasible from performance and manufacturing standpoints. Further stages of research, testing and development are recommended in the following areas to refine the concept:

- **Market review** – define the target market size and scope, to ensure appropriate design decisions regarding.
- **Anthropometric studies** – to review the spectrum of sizes and proportions of target users and ensure appropriate ergonomic criteria are addressed.
- **Typical injury review** – to identify high risk activities, and injury frequency, severity and location on hand or arm.
- **Scale design** – based on anthropometric and injury data, develop and test scale shape and position templates for maximum worker protection and efficiency.
- **Scale material testing** – carry out quantitative testing on the various scale material and manufacturing options to assess performance in a variety of scenarios.
- **Prototype development** – in conjunction with a suitable industry partner, develop and test suggested seamless knitted glove concepts, integrate scales and dipping process to create functional prototypes for user and performance based analysis.

8.0 Bibliography

The author should include all references used in the report or referred to for background information. This must be done using the Harvard Referencing Style Guide.

Reference Contact List

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