Spall Strength Comparison of High Strength Steels

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Defining steel’s dynamic behaviour is important for armoured applications. The material characteristics dictate the appropriate application for the material. A pertinent dynamic behaviour that should be considered in impact dynamics is a material’s spall strength. Understanding how a material reacts dynamically to an impact force can aid in selecting and possibly improving steel to withstand large dynamic forces. Two different grades of armoured steel were supplied by Bisalloy®. Bisalloy ultra-high toughness (UHT) 440 and Bisalloy ultra-high-hardness (UHH) 600 are compared in spall strength and Hugoniot Elastic Limit (HEL) to determine which material is more suitable for military applications. This was done through flyer plate impact testing with 70mm high-velocity single stage light gas gun at UNSW Canberra. From impact tests and microstructural analysis, UHT440 had the higher spall strength than UHH600. Relationships between the grain sizes, ductility and effect on the spall peak gradient demonstrated a relationship for the higher spall strength. Theory suggests that higher yield stress characteristics in a material correlate to a higher HEL. In this case, UHH600 was determined to achieve a higher HEL than compared to UHT440. It was concluded that UHT440 is more resistant to high impact stresses such as blast waves, where UHH600 would be more suitable against ballistic penetration.
Nomenclature

\[ \text{Afrac}_{\text{dam}} = \text{Area fraction of damage} \]
\[ BCC = \text{Body Centred Cubic} \]
\[ c_l = \text{Longitudinal Sound Speed} \, [\text{m/s}] \]
\[ C_0 = \text{Bulk Sound Speed} \, [\text{m/s}] \]
\[ FCC = \text{Face Centred Cubic} \]
\[ FSV = \text{Free Surface Velocity} \]
\[ HEL = \text{Hugoniot Elastic Limit} \]
\[ HSS = \text{High Strength Steel} \]
\[ IPF = \text{Inverse Pulse Figure} \]
\[ IQ = \text{Image Quality} \]
\[ OM = \text{Optical microscopy} \]
\[ PDV = \text{Photonic Doppler Velocimetry} \]
\[ S = \text{Empirical parameter specific to a certain material} \]
\[ SEM = \text{Scanning Electron Microscopy} \]
\[ \Delta U_{fs} = \text{Difference in free surface velocities} \, [\text{m/s}] \]
\[ U_H = \text{Hugoniot Elastic Limit velocity} \, [\text{m/s}] \]
\[ UHH = \text{Ultra High Hardness} \]
\[ UHT = \text{Ultra High Toughness} \]
\[ U_s = \text{Shockwave velocity} \, [\text{m/s}] \]
\[ VISAR = \text{Velocity Interferometry for Any Reflector} \]
\[ Y = \text{Dynamic Yield Stress} \, [\text{GPa}] \]
\[ \sigma_f = \text{Spall Strength} \, [\text{GPa}] \]
\[ \sigma_{HEL} = \text{Hugoniot Elastic Limit Stress} \, [\text{GPa}] \]
\[ \sigma_{\text{micro spall}} = \text{New failure criterion for spall strength} \, [\text{GPa}] \]
\[ \rho_0 = \text{Density} \, [\text{kg/m}^3] \]
\[ \nu = \text{Poisson’s Ratio} \]

I. Introduction

Steel is a highly regarded metal due to its extensive range of mechanical properties and increased quality compared to other metals. (Mandal, 2015) This makes steel quite suitable for a range of applications, from military shock and ballistic armour to building materials and basic household appliances. Therefore, it is important to investigate and define the material’s performance and relate that to a specific use. Failure to do so can be catastrophic in both the material and human factors.

Steel is defined as an ‘all-rounder’ type of material with substantial and customisable material properties such as toughness, hardness and fatigue resistance. (Hazell, 2016) Steel can be categorised into two major groups due to its chemical composition, alloyed steel or plain carbon steel. The type of crystal lattice structure also characterises the steel’s properties. Steel two types, Alpha (\(\alpha\))- steel called ferrite which has a body centred cubic arrangement (BCC) and Gamma (\(\gamma\))-steel called austenite which has a face centred cubic (FCC) arrangement. (Hazell, 2016) With these as starting arrangements, the material can be subject to various metallurgical techniques to differ the mechanical properties. Such techniques include quenching, tempering and annealing. Overall, steel can be characterised by its chemical composition with alloying elements and the type of metallurgical technique applied to the material.

The focus of this project is to investigate high strength steels (HSS). As defined by the American Iron and Steel Institute (AISI), HSSs are a specific group of steels with a composition that has increased mechanical property values than standard steel. Carbon content in HSSs are lower than other types of steel and are characterised by their fine grain size and precipitation. (Leslie, 1981) HSSs are commonly desirable for military applications, especially regarding armour capability. Armour steels are typically exposed to two types of loadings: ballistic penetration and blast waves. Defence against both impacts requires a significant level of hardness and ability to absorb the energy to mitigate the consequences of high-velocity impact. Deciding which material is suitable for this type of application requires in-depth material characterisation and evaluation. An effective way to determine suitability for armour applications is through the spall strength of the material.

Figure 1. Atomic Crystal Structure of BCC (\(\alpha\)-grains) and FCC (\(\gamma\)-grains)
(Joshi, et al., 2010) Understanding how a material reacts to dynamic events indicates the suitability of that material; spall strength is one of many ways to ascertain this dynamic behaviour of materials. (Li, et al., 2016)

II. Project Scope

The scope of this project is to explore the difference in spall strength between two types of armoured steels, one being considered as ultra-high hardness (UHH) and the other to be ultra-high toughness (UHT). Through the application of plate impact testing, the materials will be compared in spall strength and their Hugoniot Elastic Limit (HEL) to determine whether a difference exists, why and which is more suited for military shock loading applications. Additionally, strength data will be determined and compared between the steels to ascertain whether the material’s properties have a role in affecting spall strength and the material’s measured tensile strength. The investigative methods that will be utilised throughout this project are gas gun plate-impact experiments, Vickers Hardness testing, Electron Backscatter Diffraction (EBSD) and Optical Microscopy (OM). Each of these methods will be explored in depth in this report.

III. Literature Review

A. Spall Strength and the Hugoniot Elastic Limit

Spall strength is defined as the fracture strength where spallation occurs within the material when under shock-loaded conditions. (Shtremel, 2014) Spallation is a type of dynamic tensile failure due to transient dynamic tensile stresses that exceed the strength of the material. During a planar collision, a shock wave is propagated through material upon impact. This initial wave is classified as a compressive wave. Once the shock wave hits the free-surface on the rear of the plate, it is reflected as tensile elastic waves, often called release waves. This section is under compression. When the release waves produced from the flyer and target plates interact, their superposition cause a high magnitude of internal tensile stresses and localised strain within a specific area of the material, often referred to as the spall plane. (Brown, 2015) If these stresses exceed that of the strength of the material, then spallation occurs. This is demonstrated through nucleation, growth and coalescence of voids in the material until it ultimately reaches failure. (Li, et al., 2016) Spallation has varying degrees of damage. Incipient spall is the initiation of void nucleation of the material and is usually characterised by no visible damage on the specimen. Techniques such as SEM (Scanning Electron Microscopy) and OM (Optical Microscopy) are required to determine whether spall damage is present. The voids then grow and coalesce into larger voids to produce intermediate spall. Intermediate spall is characterised by large and predominately visible voids, and cracks, with some, joined together. Eventually, all these larger voids coalesce together to form a spall fracture. Spall fracture is the separation of the material sometimes completely into two halves. This occurs when the tensile stresses that are subjected to the sample are significant. (Oscarson & Graff, 1968) Images of these types of spall are displayed in Figure 2. Achieving spallation in the middle of the target plate is desirable for analysis. This is achieved under two conditions, that the acoustic impedance of the flyer and target material are equal, and the flyer-to-target thickness ratio must be 1:2. Acoustic impedance is defined as the product of the elastic wave velocity and the density of the material. This term is a function of the composition of the material and is where the bulk speed of sound ($C_0$) and density ($\rho_0$) are of significance.

The most common method for determining spall strength of the material is through planar plate impact experiments. (Grady, 1988) The spall strength is determined through the analysis of free-surface velocities (FSVs) recorded during the impact experiment. FSVs can be calculated through a velocity interferometry system or commonly referred to as Velocity Interferometry System for Any Reflected Surface (VISAR) or Photonic Doppler Velocimetry (PDV) (Brown, 2015) From this, the maximum and minimum velocity can be acquired to find the FSV.

\[
\Delta U_{fs} = U_{max} - U_{min}
\]  

The spall strength is be determined using the following relationship:

\[
\sigma_f = \frac{1}{2} \rho_0 C_0 \Delta U_{fs}
\]

This equation is based upon the assumption that the acoustic impedance terms are kept as close to their original values. (Brown, 2015) The thickness of the flyer and target materials must be chosen with caution. If the
thicknesses of the plates are too large, the release waves from flyer and target plate surface, might not meet inside the body of the target. It is essential to conduct either an X-T diagram of the experiment or computational simulation of the impact to ensure this does not occur. (Joshi, et al., 2010) Spall strength, however, is not an intrinsic material property. While somewhat dependent on the microstructure of the material, the spall strength also depends on the loading conditions and the sample geometry. Various studies have accounted for this effect on spall strength, with factors such as peak stress, strain rate and pulse duration. (Li, et al., 2016) By determining spall strength and studying the conditions at which spall failure initiates, the material can be accurately allocated and possibly improved for specific applications.

The Hugoniot Elastic Limit (HEL) is the point where the material begins to inhibit permanent deformation. This point is defined when the shear stress ($\tau$) of the material equals the dynamic yield stress ($\tau_{\text{Y}}$). When a shock wave is produced after impact, it usually consists of a shock front, a flat top or the Hugoniot state than a release part. An elastic precursor then precedes this shock wave at specific pressure ranges, where the amplitude is equal to the Elastic Modulus of the material. Figure 3 indicates where the HEL occurs on a VISAR or PDV velocity profile after a collision. The HEL can be determined from the velocity profile using the relationship:

$$\sigma_{\text{HEL}} = \frac{1}{2} \rho c_l U_H$$

Where the $U_H$ is the free surface velocity at the HEL, and the $c_l$ is the longitudinal wave speed. Using the HEL, the dynamic yield strength of the material can also be derived:

$$Y = \sigma_{\text{HEL}} \frac{(1-2\nu)}{(1-\nu)}$$

Where $\nu$ is the Poisson ratio of the material and $Y$ is the dynamic yield strength. (Li, et al., 2016) The dynamic stress calculated from the HEL is defined as the maximum stress amplitude for an elastic wave in propagation. (Mock Jr, et al., 1976) This signifies the correlation of dynamic yield stress to the HEL. Higher yield stress is typically indicative of a higher HEL.

B. Flyer Plate Impact Test

As previously stated, planar plate impact experimentation is the most common method to determine the spall strength of a material. Plate impact testing can be categorised into two types of plate-on-plate impact tests, wave propagation experiments and thin-layer high-strain-rate experiments. The one of interest for this project is wave propagation, as this technique can determine the spall strength and HEL required for this project through a velocity profile. This analysis of wave propagation can be instrumental in quantifying and understanding the dynamic behaviour of materials. (Espinosa & Nemat-Nasser, 2000) The experiment consists of launching a flyer plate at a target at a chosen speed. The test is conducted under a one-dimensional loading condition. This ensures that the material is under uniaxial strain only and lateral strains (perpendicular to shock direction) are negligible. This is achieved through a planar and parallel impact. Another condition that must be met to attain uniaxial strain is simulating a semi-infinite body in the lateral direction. This ensures that the lateral release waves do not interfere with the longitudinal waves, decreasing the magnitude of the release waves. Targets are usually disc-shaped and with a width to thickness ratio of at least 10:1 to achieve this condition. (Brown, 2015)

Specimens are typically recovered through soft recovery to inspect the microstructure of the material and deduce if any change has occurred. Plate impact experiments are conducted with a gas gun. The experimental set-up is divided into four parts, the breech or pressure chamber, the gun barrel, the target chamber and a catcher. The breech is where the flyer plate is placed. Inside the breech, pressures up 20.7 MPa can be reached. This pressure build-up is how the flyer is accelerated down the gun barrel into the target chamber. To reduce friction, the inner surface of the gun barrel is typically polished to a high mirror finish. A keyway can be machined inside the barrel to prevent projectile rotation. (Espinosa & Nemat-Nasser, 2000) To eliminate the possibility of an air cushion between the flyer and the target, the target chamber and the gun barrel are evacuated. The velocity of the projectile is measured just before impact with the target plate, while the velocity of the target is measured with interferometry techniques. These types of systems record the data required for experimental analysis post-experiment. Usually, when designing the target sample designs, the sample has a 7-10° taper, allowing the sample to separate from the target holder without fear of “locking”. In some cases, this may not be required. (Whelchel, et al., 2013)
C. Optical Microscopy and Electron Backscatter Diffraction

OM is one of many types of microscopic techniques. This technique uses a light microscope to investigate the microstructure of the material. When analysis metals, OM can only produce a surface level analysis of the material. However, if the material is prepared correctly, substantial data can be gathered. Preparation of the specimen is often difficult in microscopy, and this aspect is elevated for OM. Due to OM utilising only the visible spectrum, the sample must be prepared adequately to gather all the important details from the material. The material is often set in epoxy, where the sample is ground and polished to a mirror-like appearance. (Callister & Rethwisch, 2014) The grinding removes any damaged surface and enables a clear view of the material’s microstructure and any damages to it. Care must be taken to ensure that way the material is ground doesn’t keep damaging the surface. (Richardson, 1973) Once completed, the specimen is ready for OM.

EBSD is a type of Scanning Electron Microscopy (SEM) technique that measures a material’s crystallographic orientation. This technique utilises an electron beam that is reflected onto a 70-degree titled sample and onto a phosphor screen to produce Kikuchi patterns. These patterns are then processed to identify a specific crystal orientation. This then creates a map of the materials crystal orientation. This type of microscopy is typically utilised in the microstructural analysis to identify grain structure, size and distribution, the grain boundary and their characteristics and deformation. Preparation for this technique is very similar to OM and care is required when preparing the sample for this type of microscopy. (Oxford Instruments NanoAnalysis, 2010)

IV. Material Characterisation

For this project, two different types of steels were manufactured and supplied by Biscalloy Steels Pty. Ltd. The first material is BISALLOY Armour Ultra High Toughness (UHT) 440 steel. This is characterised as a quenched and tempered steel armour that provides a lightweight and high resistance to shock and penetration. (Biscalloy, 2017) UHT440 is a low-carbon, ultra-high strength and toughness, low alloy steel.

The second material is BISALLOY Armour Ultra High Hardness (UHH) 600 steel. This steel is characterised as quenched and tempered steel that provides resistance to ballistic projectiles. (Biscalloy, 2017) UHH600 is a medium-carbon, ultra-high strength and hardness, low alloy steel. Medium carbon steels are classified to have carbon contents between 0.29 and 0.6%. (Calik, et al., 2010)

Table 1. Biscalloy UHT440 and UHH600 Mechanical Properties Comparison (Biscalloy, 2017)

<table>
<thead>
<tr>
<th>Properties</th>
<th>UHT440</th>
<th>UHH600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Stress (0.2% Proof Stress)</td>
<td>1150 MPA</td>
<td>1500 MPA</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>1450 MPA</td>
<td>2050 MPA</td>
</tr>
<tr>
<td>Elongation in 50mm gauge length</td>
<td>14%</td>
<td>8%</td>
</tr>
<tr>
<td>Hardness</td>
<td>450 HB or 47 HRC</td>
<td>600 HB or 58 HRC</td>
</tr>
</tbody>
</table>

From the data given in Table 1, UHT440 has the lower tensile strength compared to UHH600, however, has an increased elongation percentage at almost double that of UHH600. Therefore, UHT400 is considered as the more ductile steel with a lower yield and tensile strength, while UHH600 is harder steel with higher yield and tensile properties. This can be confirmed by the given hardness data from Biscalloy.

Table 2. Biscalloy UHT440 and UHH600 Chemical Composition (Biscalloy, 2017)

<table>
<thead>
<tr>
<th>Steel Grade</th>
<th>Carbon</th>
<th>P</th>
<th>Mn</th>
<th>Si</th>
<th>Sulfur</th>
<th>Nickel</th>
<th>Cr</th>
<th>Mo</th>
<th>Boron</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHT440</td>
<td>0.25</td>
<td>0.025</td>
<td>1.4</td>
<td>0.6</td>
<td>0.005</td>
<td>0.5</td>
<td>1.2</td>
<td>0.35</td>
<td>0.002</td>
</tr>
<tr>
<td>UHH600</td>
<td>0.45</td>
<td>0.02</td>
<td>0.5</td>
<td>0.35</td>
<td>0.005</td>
<td>1</td>
<td>1.2</td>
<td>0.3</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Additionally, the microhardness test was also conducted on the as-received samples to determine the difference in hardness analytically. This was done by through the micro Vickers Hardness Tester HMV-G. UHT440 microhardness images appeared less defined and with almost half of the data recorded discarded due to inaccurate readings. Examples of these images can be found in Appendix B. UHT440 microhardness Vickers reading was 491 HV while UHH600 microhardness Vickers reading was 680.8 HV.

V. Experiment Methodology

D. 70mm Single-Stage Gas Gun Experiments
A 70mm high-velocity single stage light gas gun held at UNSW Canberra was used to carry out plate impact experiments. An X-T diagram was drafted to analyse and determine whether the spall plane would occur centre of the samples geometrically for a given dimension and thickness. The shock wave velocity, the bulk sound speed and longitudinal sound speed of the material had were calculated to comprise the X-T diagram. For example, the shock wave velocity can be derived using this shock velocity and particle velocity relationship equation:

$$U_S = C_0 + S \cdot U_P$$

These values are estimates as some parameters were not available to be distributed by the manufacturer, and other similar steels were used for a benchmark. The flyer plate was chosen to be machined out of mild steel and not of the same material due to costs and machine availability. Using mild steel enabled these problems to be mitigated and still achieve symmetric impact with a relatively similar acoustic impedance. Analysis of Figure 4 concluded that the spall plane would occur approximately in the centre of the target if the flyer to target plate thickness ratio is 1:2.

![X-T Diagram of BisAlloy Steel](image)

**Figure 4. Determination of the Spall Plane for BisAlloy Steels**

Through plate impact experiments, the spall strength and Hugoniot Elastic Limit can be determined using FSV profiles that are collected through PDV probes placed at the rear of the target surface. Using a MATLAB script and other image analysis tools such as ImageJ, further analysis of these velocity profiles can be conducted with fidelity.

Appendix A illustrates the to be machined drawings for the plate impact experiment. These include the target holder, the samples and the flyer plate. The individual components are then machined and press-fitted into the target holder. The target holder assembly was then machined down to the final thickness of 4 mm. The final machined assembly has a diameter of 70 mm, and the final machined samples had a diameter of 28 mm with a 7-degree increase in diameter to a thickness of 4 mm. This angle allowed the targets to be released without the high risk of locking the samples in place when impacted. This ensures that the impact stress is the only stress affecting the material and not any orthogonal stresses due to the possibility of the samples locking into the target holder. Before the experiment, the final assembly and the flyer plate were then lapped flat and parallel to a tolerance of ±0.0020 mm. This is to ensure that the target and flyer plates achieved a planar impact during the experiment.

E. Microstructural Analysis

EBSD analysis for the as-received sample for UHT440 will be conducted to determine the materials microstructure and if there are any notable differences when compared to UHH600. A previous student has already conducted UHH600 EBSD analysis as part of their research project. Microhardness testing was also conducted on the as-received material to confirm harness values from the given material data were as stated by the manufacturer. Images of these microhardness tests will also be recorded as visual data to see how the as-received material deforms. For post-mortem analysis, OM analysis was conducted to ascertain whether spall has occurred and if so, the intensity of the spall damage recorded. This data combined with PDV FSV profiles, the spall strength and the HEL are calculated for both materials.
VI. Results and Discussion

A. Microstructural Analysis

The chemical composition of the materials as detailed in Table 2 show a notable difference between UHT440 and UHH600. One significant difference was the percentage carbon content. UHH600 had almost double the amount of carbon content than UHT440. Another distinguishable difference is the manganese content, with UHT440 containing three times more than that contained in UHH600. Carbon has a significant role in increasing hardness and decreasing the elongation of the material. Manganese has a significant effect in increasing hardenability and tensile strength of the material while countering the brittleness that is derived from sulphur content, increasing its hardness as well as ductility. (Kelderman, 2015) This is in agreement with the material characteristics of the steels as seen in Table 1. Therefore, the increased tensile strength and ductility of UHT440 can be correlated to the chemical composition, especially regarding manganese content. Ultrasonic tests were conducted on both materials using a pulse-echo technique. Through this method, the longitudinal wave speed, bulk wave speed, shear wave speed and other significant material properties were determined. Analysis of the ultrasonic tests as seen in Table 3 conclude that the mechanical properties of both materials do not differ greatly. Therefore, regarding the wave velocities of the material, the spall strength and the HEL may not show a large difference. This may change when analysing the FSV of the materials Section VI.C.

Table 3. Ultrasonic Analytical Results

<table>
<thead>
<tr>
<th></th>
<th>UHT440</th>
<th>UHH600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Wave Speed, $c_l$</td>
<td>5954.107 m/s</td>
<td>5933.036 m/s</td>
</tr>
<tr>
<td>Shear Wave Speed, $c_s$</td>
<td>3232.997 m/s</td>
<td>3203.901 m/s</td>
</tr>
<tr>
<td>Bulk Wave Speed, $c_o$</td>
<td>5954.107 m/s</td>
<td>5933.036 m/s</td>
</tr>
<tr>
<td>Young’s Modulus, E</td>
<td>211.845 GPa</td>
<td>208.569 GPa</td>
</tr>
<tr>
<td>Shear Modulus, G</td>
<td>82.050 GPa</td>
<td>80.580 GPa</td>
</tr>
<tr>
<td>Bulk Modulus, K</td>
<td>168.893 GPa</td>
<td>168.887 GPa</td>
</tr>
<tr>
<td>Lames Constant, $\lambda$</td>
<td>114.193 GPa</td>
<td>115.167 GPa</td>
</tr>
<tr>
<td>Poisson’s Ratio, $\nu$</td>
<td>0.2909</td>
<td>0.2942</td>
</tr>
</tbody>
</table>

Figure 5. Random selection of UHT440 (a) and UHH600 (b) Inverse Pulse Figures (IPF) images

The microstructure of UHT440 as seen in Figure 5a, do not show a distant texture to the material. Additionally, from this random selection, the material does not appear to have a distant orientation. UHH600 (Fig 5b) also shows similar features, with no apparent texture. Regarding UHH600 crystallographic orientation, previous studies have described the material to have preferred grain orientations of $\{101\}$ and $\{111\}$. (Kelderman, 2015) Both images are of a random selection of the surface of the material and therefore is not representative of the overall material microstructure. These observations are localised, and extensive examination of the materials through EBSD need to be taken to further the microstructural analysis. From the analysis of the IPF maps, both materials are determined to be isentropic due to no distinct orientation or texture.
The IQ maps of UHT440 (Fig 6a) and UHH600 (Fig 6b) show similar microstructures with ‘needle-like’ grains that are typically associated with the formation of martensite. Previous studies on the effect of grain sizes on spall strength indicate a correlation between smaller grain sizes with a decrease in spall strength. Smaller grain sizes are associated with an increase in grain boundaries within the material. (Brown, 2015) Qualitatively, UHT440 appears to have larger grain sizes than UHH600. However, a more quantitative analysis of the comparing actual grain sizes between the materials is required for a more definitive outcome. Previous studies have identified UHH600 as martensitic steel. Data was not able to be obtained from the analysis of UHH600. Therefore no quantitative analysis of the effect of grain sizes could be conducted. Further analysis of both materials grain size distribution is required to determine if it affects material’s spall strength. Data obtained from previous studies show that UHH600 underwent a rapid quenching process from austenite to martensite. This process turns the FCC structure of austenite into a BCC structure. Due to the similarity in material processing and IQ maps, UHT440 can also be considered as a type of martensite steel.

Post-mortem analysis of the recovered samples was carried out through bright field OM imaging taken at the midsection through the diameter of the sample. UHH600’s (Fig 7) spall damage displays cleavage and brittle-like fracturing at the spall plane. Both edges where the spall terminates also display this type of fracturing. This is indicative of brittle transgranular fracturing during spallation. Additionally, the distance from the surface and where the spall terminates is 0.319 mm and 0.239 mm right and left side respectively.

UHT440 (Fig 8) spall damage displays a pitted-like fracturing that is consistent with ductile void formation in the spall plane. This is indicative of ductile transgranular fracturing. The distance from the surface to the point of spall termination is 0.585 mm and 1.702 mm right and left respectively.

The distance of the surface edge to the point of spall termination is considerably larger for UHT440 compared to UHH600 with a maximum difference of 1.464 mm on the left side. Therefore, an assumption can be made that if the impact velocity were to increase, UHH600 may exhibit complete spall characteristics, while UHT440 may still exhibit intermediate spall characteristics. For this test, both samples displayed intermediate spall at the spall plane. However, UHT440 displays more incipient spall characteristics on the left side of the sample. Qualitative inspection of the materials concludes that the UHH600 is more susceptible to these tensile stresses produced by a planar impact and is hypothesised to have the weaker spall strength compared to UHT440.
B. Flyer Plate Impact Test

Two tests were conducted for this experiment. The first test was to be shot at a speed of approximately 450 m/s. A simulation was run to determine the correct actuating gas pressure to achieve the desired impact velocity. The FSV was recorded using a PDV probe positioned at the rear face of each material, at a distance of 1.0 mm. However, there was no PDV history or impact velocity recorded due to a fault in the detection of the FSV. From this test, two samples were recovered, with UHT440 released from the holder while UHH600 was stuck in the holder. UHH600 had experienced complete spall with separation into two halves. After OM analysis of UHT440, it was found to exhibit intermediate spall characteristics, with similar ductile fracturing at the spall plane.

A second test was run at an intended impact velocity of approximately 300-350 m/s. The impact velocity was lowered to achieve at least incipient spall in both materials to analyse the spall damage and compare them. Another simulation was able to determine the correct actuating gas pressure to achieve the desired velocity. The PDV probe positioned at the rear face of each material, at a distance of 1.3 mm. From this test, FSVs for both materials were recorded and are shown in Figure 9. Although the impact velocity for the second test could not be determined due to faulty readings, Figure 9 shows that both materials reached a peak velocity of approximately 321.1 m/s. Significant details of the velocity profile of both materials are displayed in Table 5. Both data sets were converted into FSV profiles using a MATLAB code and plotting and analysis of these profiles through ImageJ.

![Figure 9. PDV Velocity Profile of Second Test at approximately 320 m/s](image)

C. Spall Strength and Hugoniot Elastic Limit

From the velocity profiles shown in Figure 9, the material’s spall strength, HEL and the dynamic yield stress can be calculated using Equations 2, 3, 4 respectively. The spall strength and the HEL determined using these equations for both materials are found in Table 5. From these equations, it was determined that UHT440 had the higher spall strength when compared to UHH600, with a difference of approximately 0.378 GPa. UHH600 was calculated to have the higher HEL than UHT400 with a difference of approximately 1.211 GPa. Using the technical data in Table 1, the expected HEL can be calculated with the measured Poisson’s ratio found during ultrasonic testing and using the relationship in Equation 4. The expected HEL for the materials are 1949.94 GPa and 2572.16 GPa for UHT440 and UHH600 respectively.
Figure 10. Velocity profile after the pull-back minimum

Figure 10 shows the rate of velocity increase after the pull-back minima for both materials; this is indicated by the dotted red rectangle in Figure 9. The time and velocities were shifted so that the minimum of both profiles was set at the origin of the plot to determine the difference in the acceleration rate of the different steels. The acceleration rate from the minimum to the spall signal can be quantified using the gradients of the profiles. The acceleration rates are 23652.18 m/s\(^2\) and 24473.11 m/s\(^2\) for UHT440 and UHH600 respectively. From the qualitative analysis of the grain sizes in Figure 6, the magnitude of the acceleration increases with the increase of grain size. Additionally, both profiles indicate a change in slope after the pull-back minimum.

Table 5. Spall Strength and Hugoniot Elastic Limit Comparison from Spectrogram Image J analysis

<table>
<thead>
<tr>
<th>Material</th>
<th>HEL Velocity (m/s)</th>
<th>Umax (m/s)</th>
<th>Umin (m/s)</th>
<th>ΔU(_{ls}) (m/s)</th>
<th>Spall Strength (GPa)</th>
<th>HEL (GPa)</th>
<th>Dynamic Yield Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHT440</td>
<td>91.071</td>
<td>321.429</td>
<td>132.143</td>
<td>189.286</td>
<td>4.424</td>
<td>2.128</td>
<td>1241.282</td>
</tr>
</tbody>
</table>

Figure 11. Processed Images UHT440 (a) and UHH600 (b)

Determining the spall strength using FSV data via PDV measurements is only indicative of the stress required to create enough ‘free surfaces’ within the material for the stress wave to reflect off to change the velocity occurring over time. However, this method does not consider the actual damage caused by these stresses in the material. An additional method to determine the spallation response of a material can be done by using an area analysis technique. (Fensin, et al., 2018) This method utilises an image processing software such as ImageJ, to quantify the area fraction that the spall damage exhibits on the surface of the material. Ideally, a volume fraction would be more precise in determining this new failure criterion. However, this requires extensive sample preparation to quantify the damage in 3D. The area fraction method should not differ greatly from the volume fraction method, Figure 11 shows the images processed through ImageJ by converting to 8 bit, binarized and then cleaned to show the total damage in the materials clearly. The voids can be distinguished by red voids against the grey background. From these images, the area damage fraction can be quantified and used in this following equation:

\[
\sigma_{micro\ spall} = \frac{\sigma_f}{A_{frac\ dam}}
\]  

(5)

This equation signifies a new failure criterion for the sample. This failure criterion indicates the stress required to create the area damage within the material. Smaller area damage, the stronger the material to withstand damage. This is particularly useful when distinguishing the weaker material if they both exhibit a similar spall strength. Although the materials may be determined to have similar spall strengths, the amount of damage created by the impact would indicate that the material with larger voids would be weaker or more susceptible to damage. From this relationship, it is determined that the failure criterion is lower for UHH600,
due to the smaller spall strength and the larger area damage fraction. The calculations in Table 6 show that the measured spall strength is consistent with the area damage that is exhibited within the samples.

### Table 6. Spall Strength and normalised Failure Criterion for UHT440 and UHH600

<table>
<thead>
<tr>
<th>Material</th>
<th>Area Fraction Damage (%)</th>
<th>Spall Strength from PDV (GPa)</th>
<th>Failure Criterion (GPa)</th>
<th>Spall Strength from ImageJ (GPa)</th>
<th>Failure Criterion (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHT440</td>
<td>2.751</td>
<td>4.347</td>
<td>1.580</td>
<td>4.478</td>
<td>1.622</td>
</tr>
<tr>
<td>UHH600</td>
<td>3.031</td>
<td>3.970</td>
<td>1.315</td>
<td>3.873</td>
<td>1.284</td>
</tr>
</tbody>
</table>

From the qualitative analysis the of the IQ maps and the area damage fraction, there is an indication that smaller grain sizes correlate to a larger void area within the material. When damaged, voids and damage preferentially tend to nucleate at grain boundaries or other imperfections in the material. Therefore, in an area with a larger grain boundary density, it is assumed to exhibit larger voids. This phenomenon can be attributed to how voids begin to grow and coalesce. At the nucleation phase, voids appear at these grain boundaries or imperfections within the microstructure of the material. Those with smaller grain sizes can exhibit more void per unit area than compared to materials with larger grain sizes. Due to the larger void density in smaller grain sizes, as the voids grow, they are more likely to coalesce into larger voids because of the small proximity to another void nucleation sites. On the other hand, materials with larger grain sizes, the voids will grow, but since the distance between the void nucleation sites is larger, they will tend to be isolated and require more void growth before coalescence into larger voids. This is evident in Figure 11 and the area damage fraction in Table 6. Using the relationship of larger area damage and smaller grain sizes, a correlation can be made to the effect on the spall strength of the material. Large void nucleation site density indicates a lower spall strength. These observations in grain size are qualitative only, and quantitative analysis of the grain sizes is required for a conclusive relationship.

### Table 7. Comparison of expected and calculated values for Yield Stress and HEL

<table>
<thead>
<tr>
<th>Material</th>
<th>Given Yield Stress</th>
<th>Calculate Yield Stress</th>
<th>Expected HEL</th>
<th>Calculated HEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHT440</td>
<td>1150 MPa</td>
<td>1241.282 MPa</td>
<td>1.949 GPa</td>
<td>2.128 GPa</td>
</tr>
<tr>
<td>UHH600</td>
<td>1500 MPa</td>
<td>1947.117 MPa</td>
<td>2.572 GPa</td>
<td>3.339 GPa</td>
</tr>
</tbody>
</table>

Using the FSV measurements, the analysis concluded that UHH600 exhibited the higher HEL than UHT440. This agreed with the expected HEL values calculated from the technical data from the manufacturer and the results from the ultrasonic tests and the known quantitative relationship between the yield stress and the HEL. The comparison between the expected and calculated values for the HEL and yield stress agreed for UHT440. However, for UHH600, the calculated values for the yield stress and HEL were higher than what was expected. More shots are required to determine if this is an anomaly for this test or if it is indicative of something else in the material. Additionally, from the FSV UHT440 exhibited the higher spall strength than UHH600. This also correlates to the area damage calculation where UHT440 was determined to withstand higher stress with a lower damage area. Previous studies have determined a relationship between the grain sizes and spall strength. In this case, from the qualitative analysis of the microstructure, the smaller grain size correlates to a lower spall strength. Both materials were exposed to the same conditions and were of the same geometry. Therefore the effects these can have on the spall strength, as previously mentioned, can be negligible. The nature of the growth of voids within the material can be attributed to the rate of acceleration post the pull-back minimum. Analysis of this gradient shows that UHH600 had a higher acceleration rate the UHT440, which is correlated to the area damage fraction in the materials. In order words, the higher the acceleration rate, the larger voids in coalescence than in growth due to the proximity of the void nucleation sites. As previously mentioned, this can also be correlated to the grain size of the material, which UHH600 qualitatively exhibits smaller grain sizes.

From the FSV profiles, UHH600 is determined to have a smaller spall peak than UHT440. Previous studies suggest the ratio between the peak velocity and the spall peak velocity can determine the amount of area damage exhibited in the material. Therefore, a lower magnitude in the spall peak indicates a larger void area fraction or damage exhibited by the material. This relationship agrees with the profiles shown in Figure 10. Additionally, the difference in the fracture mechanics as a function of the mechanical and chemical characteristics of the material is determined to exhibit an effect on the spall strength. The difference in the chemical composition indicates the UHT440 is a ductile material and is exhibited by ductile fracturing at the spall plane, whereas UHH600 is a brittle material in comparison. Ductility is often referred to as a measure of the material’s ability to experience plastic deformation before failure or fracturing. Therefore, a correlation can be made between the material’s ductility and the spall strength. In this case, ductile characteristics present in the material, which can be regarding the fracturing mechanics or the failure strain, increases the spall strength of the material.
VII. Conclusion

Comparison of the UHH600 and UHT440 was conducted through flyer plate impact tests and the FSV analysis, OM and EBSD analysis. EBSD and ultrasonic measurement analysis yielded no discernible difference regarding material characteristics on the as-received specimens. However, when comparing the OM images of the spalled samples, the materials differed in the fracturing mechanics. UHT400 displayed a ductile transgranular fracturing, while UHH600 showed a brittle transgranular fracturing. Using the FSV profiles, the spall strength and the HEL was determined with UHT440 exhibiting the higher spall strength than UHH600 and UHH600 exhibiting the higher HEL than UHT440. Regarding the HEL, UHH600 displayed a higher yield strength as per the technical data from the manufacturer which correlated to the higher HEL. Previous studies also concluded on the relationship of the yield stress of the material to the HEL. Spall strength of the material was seen to be attributed to the grain size and the pull-back signal from the FSV profile. Smaller grain sizes in UHH600 correlated to the lower spall strength when compared, and the higher acceleration rate and lower spall peak stress demonstrated a relationship of void area damage in the material. This project concluded that UHT400, with the higher spall strength, to be more resistant to high impact stresses such as blast waves, than UHH600.

VIII. Recommendations

Throughout this project, a few problems were encountered the limited further analysis. Recommendations include more impact tests to increase the fidelity of the results that were recorded using the PDV probe. Additional tests at different velocities can also assist in determine the spall strength more quantifiable and determine if the peak velocities have an influence on spall strength for this material. Due to the lack of data from the previous students work, it was difficult to determine the average grain size and grain size distribution of the materials. This data could be used to ascertain if the grain boundary density had a significant effect on the difference in spall strengths and HEL. EBSD analysis on the spalled samples could also investigate the fracture mechanics of the materials further and determine how the material is fracturing in reference to grain size and grain boundaries. Additional investigations would be beneficial regarding the relationship of ductility and spall strength of a material. Possible studies could look at comparing materials of very similar mechanical properties with the only significant variable to be the ductility or failure strain of the material and determine their spall strengths or compare materials of the same ductility and determine if tensile stress has an effect on the spall strength.

Acknowledgements

I would like to acknowledge my thesis supervisor, Professor Paul Hazell for his mentorship and guidance through this thesis project. I would also like to thank Dr Juan Pablo Escobedo-Diaz and Mr Ali Ameri for their assistance and guidance on EBSD and OM imaging, preparation and analysis. I would also like to thank Mr Hongxu Wang and Mr Zongjun Li for their advice and assistance conducting and analysing the flyer plate impact tests, ultrasonic testing and microhardness testing. I would also like to thank Lieutenant Elizabeth Kelderman (ARA) for her previous work on the steel UHH600 and her EBSD analysis. Finally, I would like to thank Justin Suwart from Bisalloy for answering all material related questions and more importantly providing all the sample material to conduct this project.

References


Tsai, L., 2006. Shock Wave Structure and Spall Strength of Layered Heterogenous Glass/Polymer Composite, s.l.: Department of Mechanical and Aerospace Engineering.


Appendix A1 — Flyer To Be Machined Drawings
Sample V3

Sample Pieces for Spall Experiment
4 pieces out of UHT440, 4 pieces out of UHH600
= Total of 8 pieces
Appendix A3 – Target to Be Machined Drawings
Appendix B1 – Micro-Vickers Harness Results

UHT440

UHH600
Appendix C1 – Post Test Images

First Shot:

<table>
<thead>
<tr>
<th>Weight of Projectile (g)</th>
<th>342.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of Projectile (mm)</td>
<td>111</td>
</tr>
<tr>
<td>Actuating Gas Pressure (bar)</td>
<td>18</td>
</tr>
<tr>
<td>Muzzle Velocity (m/s)</td>
<td>449</td>
</tr>
</tbody>
</table>

Image 1. Target Holder
Image 2. Flyer embedding into Target Holder

Image 3. UHH600 Complete spall separation
Second Shot:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Weight of Projectile (g)</td>
<td>341.603</td>
</tr>
<tr>
<td>Length of Projectile (mm)</td>
<td>110.40</td>
</tr>
<tr>
<td>Actuating Gas Pressure (bar)</td>
<td>8.5</td>
</tr>
<tr>
<td>Muzzle Velocity (m/s)</td>
<td>309</td>
</tr>
</tbody>
</table>

Image 6. Target Holder (left) and flyer plate (right) UHH600 placed in right hole, UHT440 in left hole