Effects of Composition and Solid Solution Strengthening on the Compression Strength of Iron-Based Hardfacing Alloys

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Abstract

Three iron-based hardfacing alloys were fabricated to have a tungsten strengthened matrix with varying compositions of 10-15, 20, and 30 wt% tungsten/chrome boride content. The fourth sample was fabricated to have a molybdenum solid solution strengthened matrix with 10-15 wt% W/Cr Boride content. This project focuses on the compressive strength of iron-based hardfacing alloys. Preliminary compression tests with Scoperta iron-based hardfacing alloys showed a need for sample dimension reduction due to compressive loads that could not be met by a 50 kN maximum capacity mechanical testing system. The preliminary tests showed compressive strengths exceeding 2340 MPa. Samples of the current alloys were electro discharge machined (EDM) to cylinders with 3 mm diameters and 2.41 mm heights. Hardened 440C stainless steel platens were used to compress the samples in a compression testing setup using a 50 kN capacity mechanical testing system. The molybdenum solid solution strengthened hardfacing alloy with 10-15 wt% W/Cr Boride content showed an average compressive strength of 4346 MPa, while the tungsten strengthened matrix with the same 10-15 wt% W/Cr Boride content showed an average compressive strength of 4107 MPa. The 20 wt% W/Cr Boride content alloy showed a compressive strength of 3378 MPa, and the 30 wt% W/Cr Boride content alloy showed an average compressive strength of 2713 MPa. Each of the data sets was statistically significantly different with a 95% confidence interval.

Keywords: Iron-based Hardfacing Alloy, Compression Test, Weld Overlay, Solid Solution Strengthening, Carbide, Boride, Materials Engineering

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1 Problem Statement

Hardfacing materials are commonly used in many industrial applications to prevent wear of valuable equipment. Scoperta, Inc. (San Diego, CA) produces many hardfacing alloys for mining and oil drilling applications. The current problem is that Scoperta does not know how variations of their Vecalloy^{TM} 700 series alloy compare in compressive strength. The scarcity of available literature in this area indicates that compression testing hardfacing alloys is not a common practice. To address this problem, testing was conducted to compare the compressive strength of Scoperta's Vecalloy^{TM} 700 alloy to varying tungsten/chrome boride content and solid solution strengthening. The specific goal of the project was to test the two types of variants of the Vecalloy^{TM} series alloy as shown in **Figure 1**. Tungsten/chrome boride contents of 10-15, 20, and 30 wt% were evaluated. Tungsten and molybdenum solid solution strengthened matrices were compared to each other. The goal was to determine which variations produce statistically higher compressive strengths.

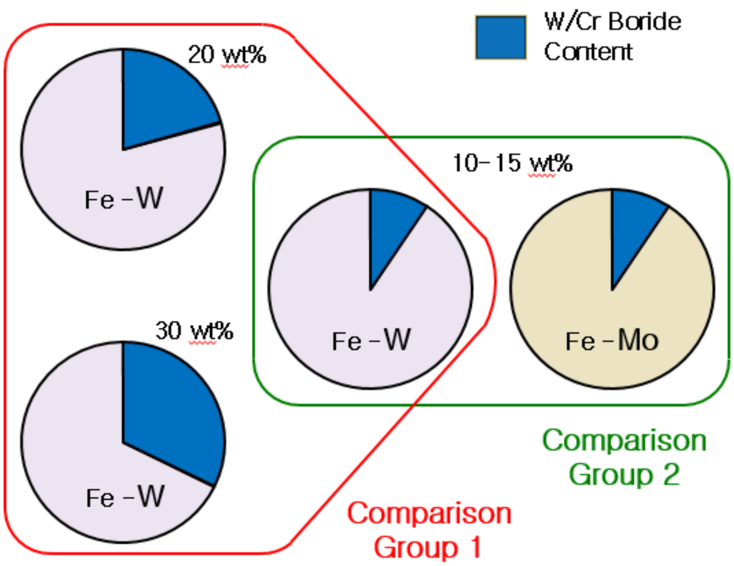

Figure 1 – The four Vecalloy^{TM} 700 alloy variations were split into two comparison groups. The compressive strengths were compared within each group to find the strongest alloy variation.

1.2 Scoperta

Scoperta produces amorphous alloys for various industrial applications including mining, marine, and power generation environments. The company uses a unique rapid alloy development (RAD) software that allows for the modeling of application-specific alloys using computational methods. The alloys Scoperta produces provide wear, cavitation, and impact resistance, as well as corrosion protection.[1] Currently, Scoperta is seeking Vecalloy 700 alloy use in Australian mining applications to protect mining equipment through the hardfacing of various parts and components.

1.3 Hardfacing

Hardfacing is the application of a wear-resistant material to surfaces of a component by a weld process to increase wear resistance and control combinations of wear and corrosion as shown in **Figure 2**.[2, 3] Categories of hardfacing alloys are largely categorized by the base material being used in the alloy. The three main types of hardfacing alloys are cobalt, nickel, and iron matrix systems. Cobalt-based alloys are almost entirely made using tungsten carbides (WC) to reinforce the cobalt matrix. The tungsten carbides primarily reside at the surface of the alloy due to processing and provide the alloy with good corrosion resistance as well as the highest hardness of all hardfacing alloys. The nickel-based alloys, however, rely on borides and carbides for their properties. The borides and carbides precipitate out of the solution during cooling producing a finely dispersed microstructure with high wear resistance. Iron-based alloys are also strengthened using carbide and boride formation, but the low cost and versatility of iron has led to its widespread use as the base material in hardfacing alloys including Scoperta's Vecalloy™ series alloys.[4]

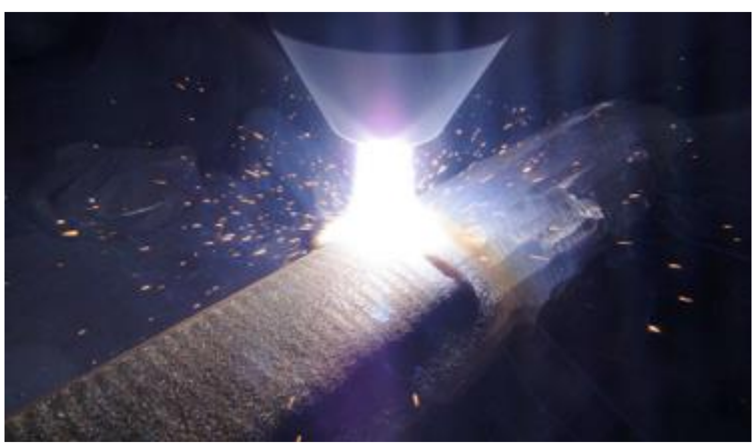

Figure 2 - The hardfacing material is deposited on to the part through a plasma transferred arc welding process.[3]

1.4 Mechanical Testing of Iron-Based Hardfacing Alloys

What sets the Vecalloy™ 700 alloy apart from WC-Co hardfacing materials is that the Vecalloy™ alloy system is iron-based, making it more cost effective than WC-Co hardfacing alloys. While there is little available literature regarding compression tests of hardfacing alloys, many other wear tests have been conducted to draw conclusions regarding strength and hardness.

Many commercial iron-based hardfacing materials are available for a range of applications.[5] Fe-Cr-C is a popular hardfacing material used for abrasive wear resistance due to its low cost.[6] The abrasion resistant properties are derived from the characteristics of the carbides in the microstructure.[6] The chrome-to-carbon ratio will determine the type of carbides that will be present.[6] A study conducted by Sabet showed the differences in abrasion resistance in hypoeutectic, eutectic, and hypereutectic Fe-Cr-C alloys with a constant Cr-to-C ratio of 6.[6] The hypereutectic Fe-Cr-C sample showed an increased hardness of 809 HV while the hypoeutectic sample was 701 HV.[6] The increased hardness was due to the increased presence of the hard $(Cr, Fe)_7C_3$ carbides, which can be seen in **Figure 3**.[6] Interestingly, **Figure 3** shows an increase in hardness for each sample after the wear test was conducted.

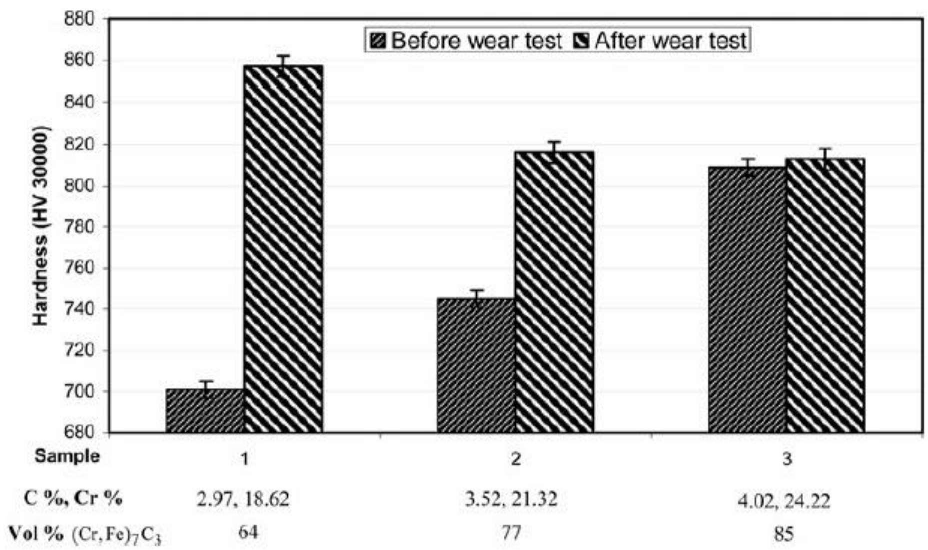

Figure 3 - Hardness values for hypoeutectic, eutectic, and hypereutectic samples of Fe-Cr-C. The lower carbon content alloys showed significantly higher hardness values after the wear testing.[6]

The increased hardness values occurred due to the work hardening that was done to the samples during the wear test which caused the austenite to transform into martensite by a stress-

induced mechanism.[6] The martensite structures can be seen in the optical microscope and SEM images of cross-sections of each sample shown in **Figure 4**.[6]

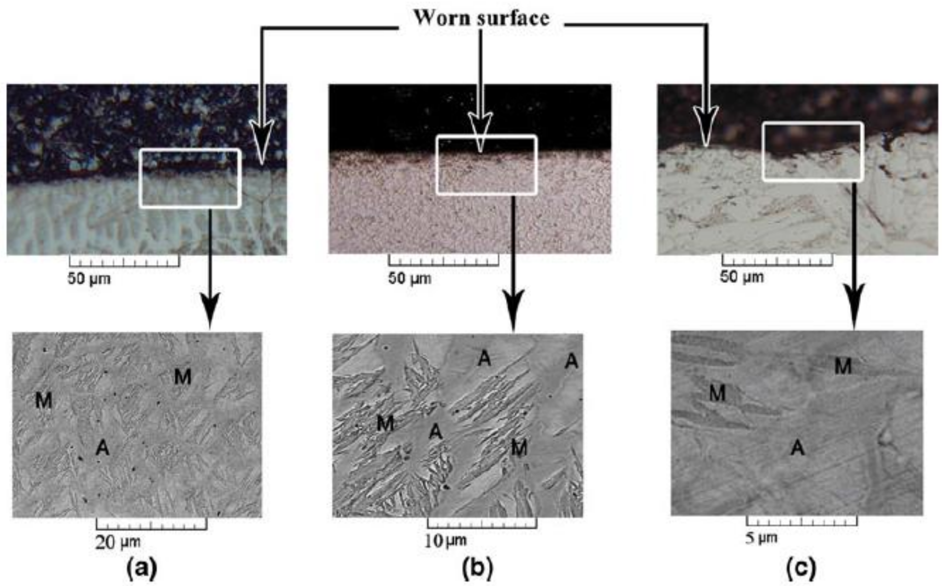

Figure 4 - Optical microscope and SEM images of worn (a) hypoeutectic, (b) eutectic, and (c) hypereutectic samples. The M refers to martensite structures and A refers to austenite regions.[6]

The study found that the abrasive wear resistance of the hardfacing alloys was dependent on the type, morphology, and amount of the hard phases, as well as the ability of the matrix to work harden.[6] Because of this, hardness alone cannot be the only parameter considered when selecting iron-based hardfacing alloys for applications in abrasive conditions.[6]

Literature concerning the effects of Mo solid solution strengthening and precipitation hardening in iron matrices shows that an increase in hardness and wear resistance can be achieved with increased Fe-Mo content.[7] The precipitation hardening is due to the presence of hard carbides (Mo_2C) dispersed in a lath martensite matrix, which effectively reduces cracking.[7] Energy-dispersive X-ray spectroscopy (EDS) testing showed that some of the Mo dissolved in the matrix and strengthened the alloy by solid solution strengthening.[7]

1.5 Welding

There are many weld processes that can be used to apply hardfacing alloys on top of steel or other substrates. The welding methods range from traditional oxyacetylene torch welding to the newer plasma-transferred arc (PTA) welding.[2] The type of welding used depends upon the desired deposition rate, the amount of allowed substrate dilution into the hardfacing alloy, and the portability of the welding equipment. Once a mode of welding is chosen, the hardfacing

material needs to be in a corresponding form for the desired welding method (**Table I**). For example, PTA welding requires the hardfacing metal to be in a powder form for proper welding overlay to occur.[2] Scoperta uses both metal inert gas (MIG) and PTA welding to apply their hardfacing alloys.

Table I - Weld Overlay Processes and Associated Consumable Forms of Hardfacing Alloys[2]

Weld Overlay Process	Consumable Form
Oxyacetylene	Bare cast or tubular rod
Shielded metal arc	Coated solid or tubular rod (stick electrode)
Gas tungsten arc (GTA)	Bare cast or tubular rod
Gas metal arc (GMA)	Tubular or solid wire
Open arc	Tubular wire (flux cored)
Submerged arc	Tubular or solid wire
Plasma-transferred arc (PTA)	Powder

1.5.1 Plasma Transferred Arc Welding

PTA welding involves the ionization of argon gas to form a plasma arc that melts the filler and base materials (**Figure 5**).[8] A non-consumable tungsten electrode and a copper nozzle form an electric arc between them that ionizes the argon.[8] The hardfacing material, in powder form, is continuously projected through the plasma arc and forms a molten layer that binds onto the base material.[8] Dilution of the base metal into the hardfacing alloy occurs in all forms of welding processes and weakens the alloy, but PTA welding has the ability to control the amount of dilution by adjusting the temperature of the arc where it reaches the base metal.[8] By reducing the temperature at the surface, less base metal will liquefy and be available for dilution.[8] Since dilution can be limited, the alloy will obtain its hardness on the first pass of the weld eliminating the need for multiple passes.[8]

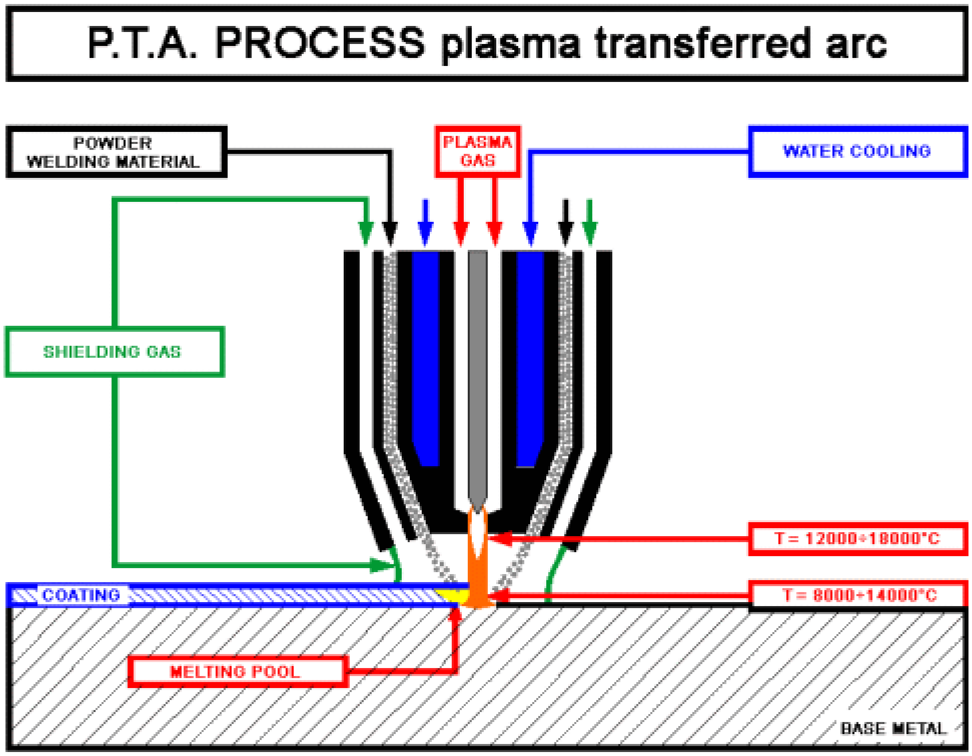

Figure 5 - A diagram of the PTA welding process for hardfacing alloys.[8]

1.5.2 Metal Inert Gas Welding

MIG welding is defined as the use of a consumable electrode that is continuously fed during arc welding while an inert gas is pumped over the weld.[9] For hardfacing, the electrode is the hardfacing alloy that is being applied. An electric current is passed through the alloy, in wire form, resulting in the alloy heating up due to its electrical resistivity.[9] The alloy becomes molten at which point a bottom portion of the wire necks off and joins the substrate material below (**Figure 6**).[9] An arc then jumps from the remaining electrode down to the molten alloy, heating up the alloy and substrate material.[9] While this is happening, inert gases are pumped over the weld area to prevent the atmospheric gases from diffusing into the liquid alloy and forming unwanted compounds.[9] The molten weld pool forms a metallic bond with the substrate material as the two cool, thereby setting the hardfacing alloy in place. Dilution during this step can be controlled by limiting the voltage of the arc.[9] Limiting the dilution during welding allows the MIG process to be performed in one pass. By only needing one pass, MIG welding takes less time and uses less material than other welding processes making it a cost and energy efficient welding method.

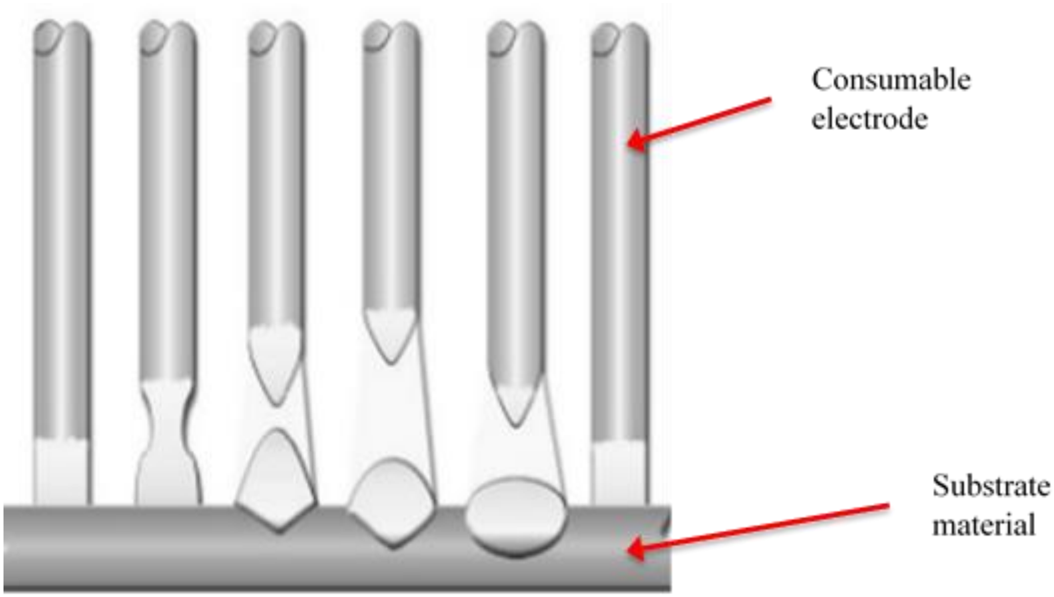

Figure 6 - A representation of the MIG welding process. The process of the electrode necking as it heats up before forming a molten weld pool on the substrate material is shown sequentially from left to right.[9]

1.6 Application: Mining

In the last decade, Australia has experienced an economic shock from the growth of mining. This shock has come from the world price of Australian mining exports that has tripled in the last ten years. This has had economic impacts in the form of real wages increasing by 6% and disposable income increasing by 13% in 2013. Furthermore, the mining boom has decreased Australian unemployment by 1.25%.[10]

Hardfacing industrial mining equipment is necessary to ensure the longevity of the various parts used to mine ore and rock from the Earth. Hardfacing alloys can be used to protect large screens that are used to sift rock (**Figure 7**). These large steel screens can deform and crack from constant use if they are not properly protected.

Figure 7 – A screen used in mining to sift various sizes of rock and earth.[11]

The steel interior of dump truck beds are hardfaced to prevent wear. Chute blocks are hardfaced to increase longevity. Stacker reclaimers, as shown in **Figure 8**, require protection to reduce wear.

Figure 8 – A stacker reclaimer machine used to scoop rock and earth in a bauxite mining operation.[12]

Ground engaging tools are used to scoop rock and ore, and can become damaged if left unprotected. These applications represent a small percentage of the various parts and machines that need to be hardfaced in mining operations.

1.7 Compression Testing

A common test used to compare mechanical properties of hardfacing materials involves wear resistance testing. This test is typically used because hardfacing materials experience wear more than compression or impact in many applications. However, many hardfacing applications such as chute blocks or dump truck beds experience impact and compression from rock and ore that is dropped from a scoop or conveyor. The impact or compression can be enough to cause the hardfacing material to chip and spall leaving the bare steel susceptible to corrosion, wear, and permanent deformation.

2. Procedure

2.1 Safety Precautions

During the steel heat treatment process, long pants, closed toed shoes, and safety glasses were worn at all times while in the heat treatment lab. Additionally, a face shield, heat resistant apron, and gloves were worn when removing the samples from the furnace.

During each compression test, a ½ inch thick piece of acrylic "safety glass" was placed in front of the Instron mechanical testing machine to ensure that fragments from the fractured samples did not cause injury to the machine operator when they were ejected from the testing area. Additionally, closed toed shoes, long pants, ear protection, and safety glasses were worn in the mechanical testing facility at all times.

2.2 Preliminary Testing

Preliminary compression testing was completed on a 50 kN maximum load mechanical testing machine using samples of Vecalloy™ 700 alloy with a 5mm diameter and 4 mm height. The samples tested were from a previous project completed by Kristi Lucas.[13] The compression testing had to be stopped before the samples fractured because the compression loading required to fracture the samples exceeded the maximum load for the mechanical testing machine. Because the samples did not fail during the preliminary testing, smaller dimension sizes were used to obtain the final results.

2.3 Alloy Compositions

Four alloys were produced for this experiment. The samples vary in composition and solid solution strengthening mechanisms. **Table II** shows the composition of each alloy.

Table II – Compositions of the Alloy Variations for Compression Testing

Alloy	Compositions wt%										
	B	**C**	**Cr**	**Mn**	**Mo**	**Nb**	**Si**	**Ti**	**V**	**W**	**Fe**
10-15% W/Cr Boride	1	1.37	5	0.2	0	5	0.5	0.5	2	9.5	Bal.
20% W/Cr Boride	1.5	1.37	4	0.2	0	5	0.5	0.5	2	9	Bal.
30% W/Cr Boride	2	1.37	2	0.2	0	5	0.5	0.5	2	6	Bal.
10-15% W/Cr Boride with Mo Strengthened Matrix	1	1.37	5	0.2	5	5	0.5	0.5	2	9.5	Bal.

2.4 Sample Dimensions and Processing

Literature regarding the compression testing of hardfacing materials is scarce. No ASTM standards exist for compression testing hardfacing alloys or advanced intermetallics. However, the ASTM E9 – 09 standard for compression testing alloys can be used for sample dimensions in this project (**Table III**).[14]

Table III – ASTM E9-09 Sample Dimensions[14]

NOTE 1—Metric units represent converted specimen dimensions close to, but not the exact conversion from inch-pound units.

Speci-mens	Diameter		Length		Approx L/D Ratio
	in.	mm	in.	mm	
Short	1.12 ± 0.01	30.0 ± 0.2	1.00 ± 0.05	25 ± 1	0.8
	0.50 ± 0.01	13.0 ± 0.2	1.00 ± 0.05	25 ± 1	2.0
Medium	0.50 ± 0.01	13.0 ± 0.2	1.50 ± 0.05	38 ± 1	3.0
	0.80 ± 0.01	20.0 ± 0.2	2.38 ± 0.12	60 ± 3	3.0
	1.00 ± 0.01	25.0 ± 0.2	3.00 ± 0.12	75 ± 3	3.0
	1.12 ± 0.01	30.0 ± 0.2	3.38 ± 0.12	85 ± 3	3.0
Long	0.80 ± 0.01	20.0 ± 0.2	6.38 ± 0.12	160 ± 3	8.0
	1.25 ± 0.01	32.0 ± 0.2	12.50 min	320 min	10.0

[A] Other length-to-diameter ratios may be used when the test is for compressive yield strength.

In accordance with ASTM standard E9-09, the height to diameter ratio of the cylindrical compression testing short sample should be 0.8. Due to the strong a brittle nature of the hardfacing alloy, the short dimension height to diameter ratio was used for this project. A diameter and height of 3 mm and 2.41 mm respectively was chosen for the sample dimensions.

An arc welding machine was used to weld wire of each alloy variation to form uniform 4” x 1” x 0.375” ingots. The arc welding process uses an argon backfill to mitigate oxidation of the material during the melting process. To produce the desired height of the samples, the ingots were surface ground to 2.41 mm thicknesses. Each surface ground small plate had 15 cylinders cut from it using electro discharge machining to for samples shown in **Figure 9**.

Figure 9 – Fifteen cylinders were cut using electro discharge machining to 3 mm diameter samples. The plate on the left side of the image is the surface ground ingot. The small cylinder on the right is one of the samples.

2.5 Compression Testing Setup

The setup for the compression test is shown in **Figure 10**. Due to the strong, hard, and brittle nature of the hardfacing alloys, precautions had to be taken in choosing what material to use for the platens that compressed the samples. 440C stainless steel was chosen for the platens due to its hardenability and strength.

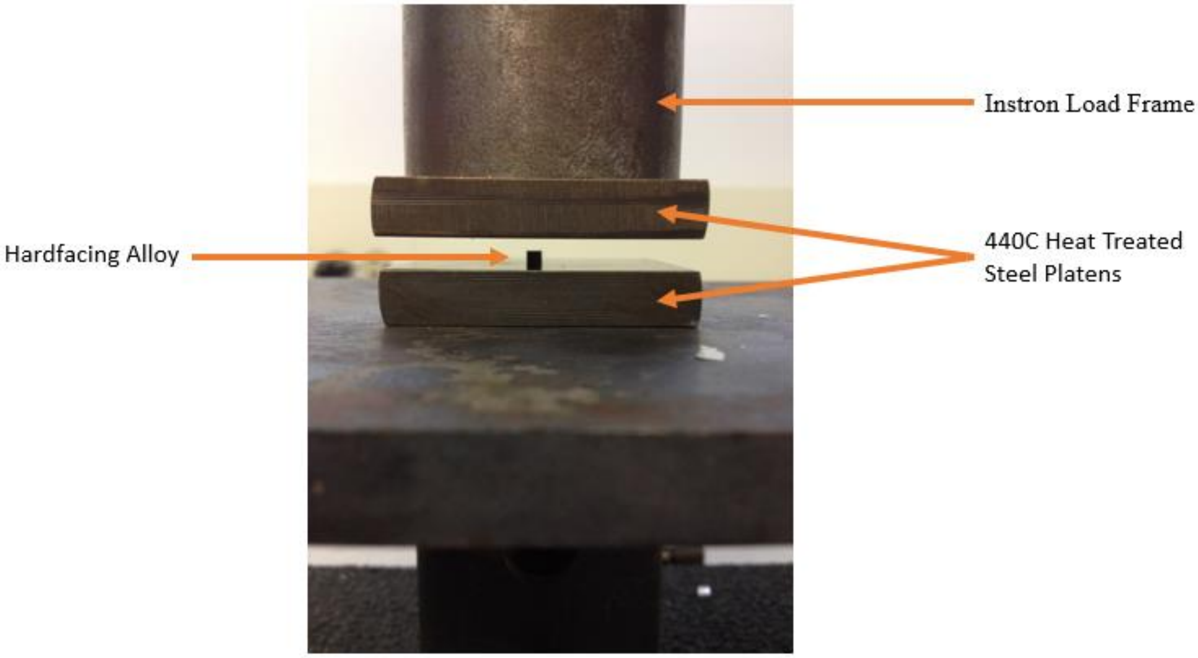

Figure 10 – Compression testing setup on a 50 kN maximum load Instron mechanical testing machine.

Ten platens were fabricated to 2″ x 2″ x 3/8″ thick plates (**Figure 11**). These plates were heat treated to increase hardness and strength. This was achieved by austenitizing the steel at 1000°C for 1 hour before oil quenching to produce a hard martensitic structure. In order to reduce oxidation of the steel, each platen was placed in a high-chromium stainless steel container during the heat treatment process. In order to mitigate the risk of the platens cracking during the compression testing, each platen was tempered to 300°C for 1 hour and water quenched. The platens were then surface ground to produce a smooth, parallel surfaces.

During the compression testing, a large amount of energy was released during the brittle fracture of the samples. This caused fragments of the samples to adhere to the platens. After each compression test, the remains of each sample were removed from the platens to ensure a smooth surface for the next sample to be tested.

Figure 11 – Hardened 440C stainless steel platen used in compression testing. The marking at the center of the surface was caused by the removal of hardfacing material after a test.

3. Results

15 samples of each alloy type were compression tested at five samples per session. The compression tests for each alloy are shown in the following figures. **Figures 12, 13, and 14** show the compression test results for the 10-15, 20, and 30 wt% W/Cr Boride content alloys with a tungsten solid solution strengthened matrix. **Figure 15** shows the compression testing results for the 10-15 wt% W/Cr Boride content alloy with a molybdenum solid solution strengthened matrix. **Figure 16** shows the compressive strengths of each alloy variation sample on the same plot. From these results, a clear distinction can be seen in the separation of each grouping.

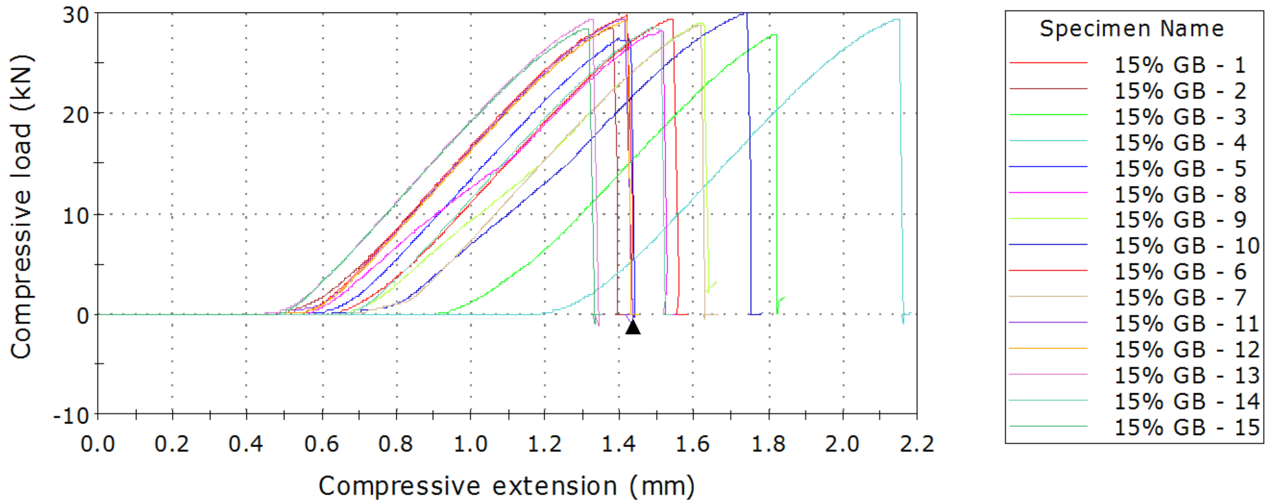

Figure 12 – Instron compression test results for the 10-15 wt% W/Cr Boride with a tungsten solid solution strengthened matrix. These samples failed with brittle fracture just before 30 kN.

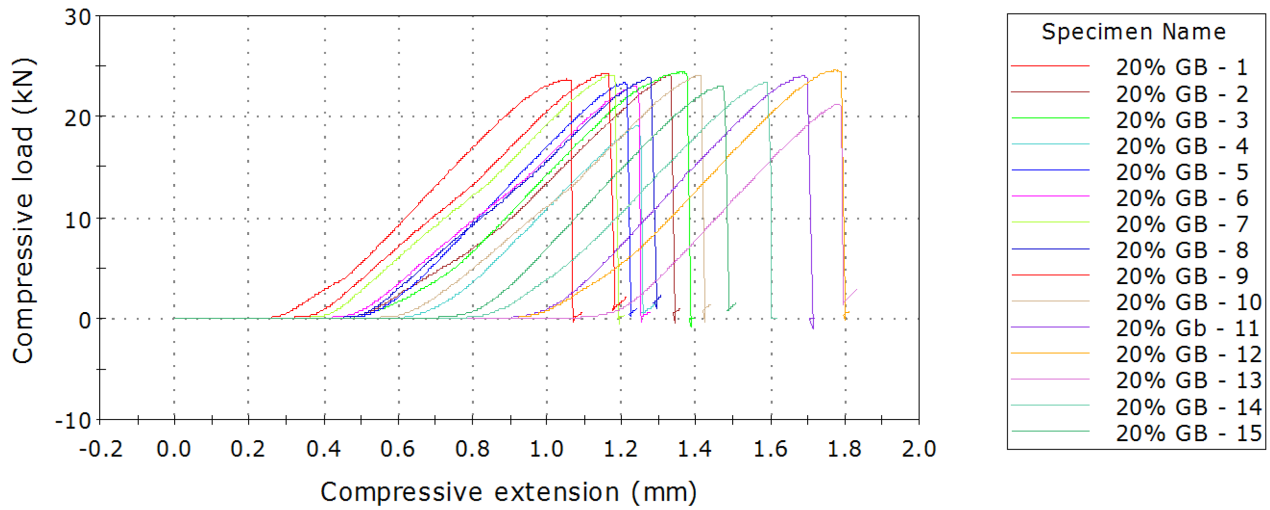

Figure 13 - Instron compression test results for the 20 wt% W/Cr Boride with a tungsten solid solution strengthened matrix. These samples did not carry as much load as the 10-15 wt% W/Cr Boride content samples and failed just below 25 kN.

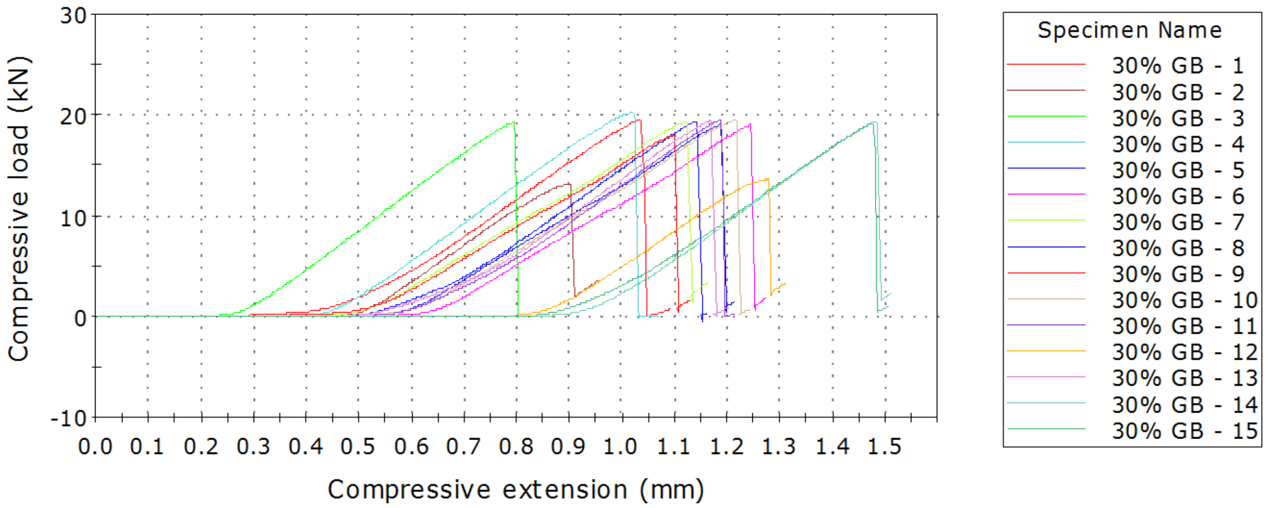

Figure 14 - Instron compression test results for the 30 wt% W/Cr Boride with a tungsten solid solution strengthened matrix. These were the weakest of Comparison Group 1, with each sample failing at or below 20 kN.

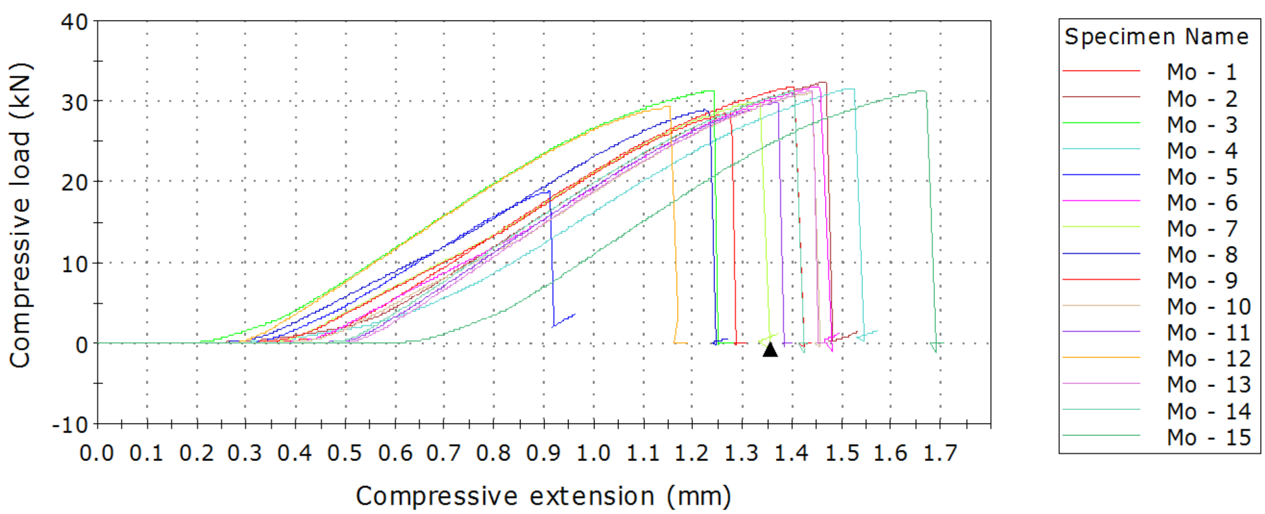

Figure 15 - Instron compression test results for the molybdenum solid solution strengthened matrix with 10-15 wt% W/Cr Boride content. These were the strongest samples failing around 30 kN.

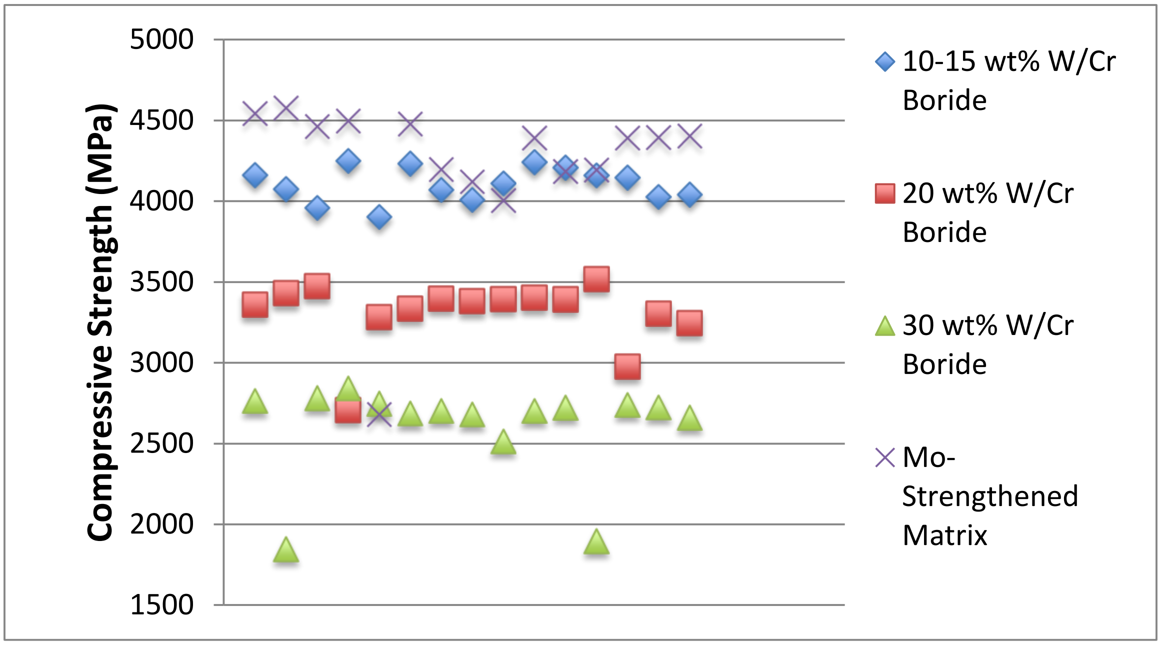

Figure 16 – Comparison of compressive strengths of individual samples, categorized by alloy variation. There is some overlap in data points but a clear grouping of each alloy variation.

Table IV shows the average compressive strength for each alloy variation. This table includes averages of all data points collected during compression testing with no omission of outliers.

Table III – Average Compressive Strength for each Hardfacing Alloy Variation

Alloy	Average Compressive Strength (MPa)	Standard Deviation (Mpa)
10-15 wt% W/Cr Boride with W-strengthened matrix	4107	102.6
20 wt% W/Cr Boride with W-strengthened matrix	3306	200.0
30 wt% W/Cr Boride with W-strengthened matrix	2601	294.2
10-15 wt% W/Cr Boride with Mo-strengthened matrix	4235	446.3

Due to the hard and brittle nature of the hardfacing alloys, some of the samples failed prematurely during compression testing. This is likely due to pre-existing flaws in the material from the ingot fabrication process. In order to provide an accurate comparison of each alloy system, the samples that had compressive strengths more than two standard deviations away

from the average were omitted. **Table V** shows adjusted average compressive strength and standard deviation values. **Figure 17** shows the compressive strengths of each alloy with the outlier data points omitted.

Table IV – Adjusted Compressive Strengths and Standard Deviations for the Hardfacing Alloys

Alloy	Average Compressive Strength (MPa)	Standard Deviation(Mpa)
10-15 wt% W/Cr Boride with W-strengthened matrix	4107	102.6
20 wt% W/Cr Boride with W-strengthened matrix	3349	124.0
30 wt% W/Cr Boride with W-strengthened matrix	2713	73.1
10-15 wt% W/Cr Boride with Mo-strengthened matrix	4345	167.9

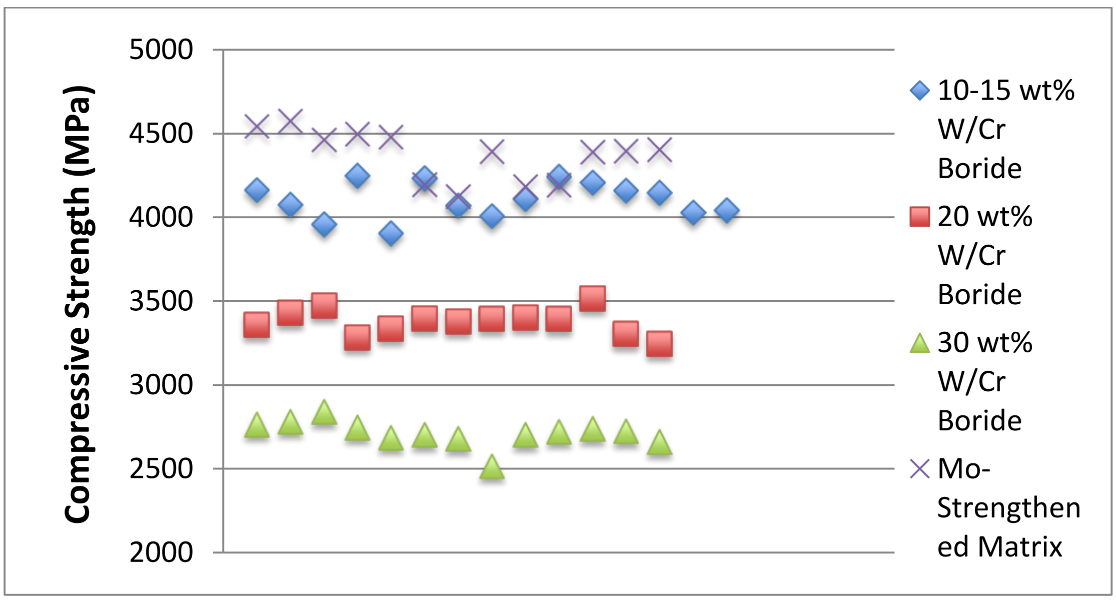

Figure 17 - Comparison of compression strengths of individual samples, categorized by alloy variation, factoring in specific sample size and omitting outliers.

In order to define a statistical significance in groupings, a Tukey pairwise comparison with a 95% confidence interval was used. The results of the statistical analysis can be seen in **Figure 18**.

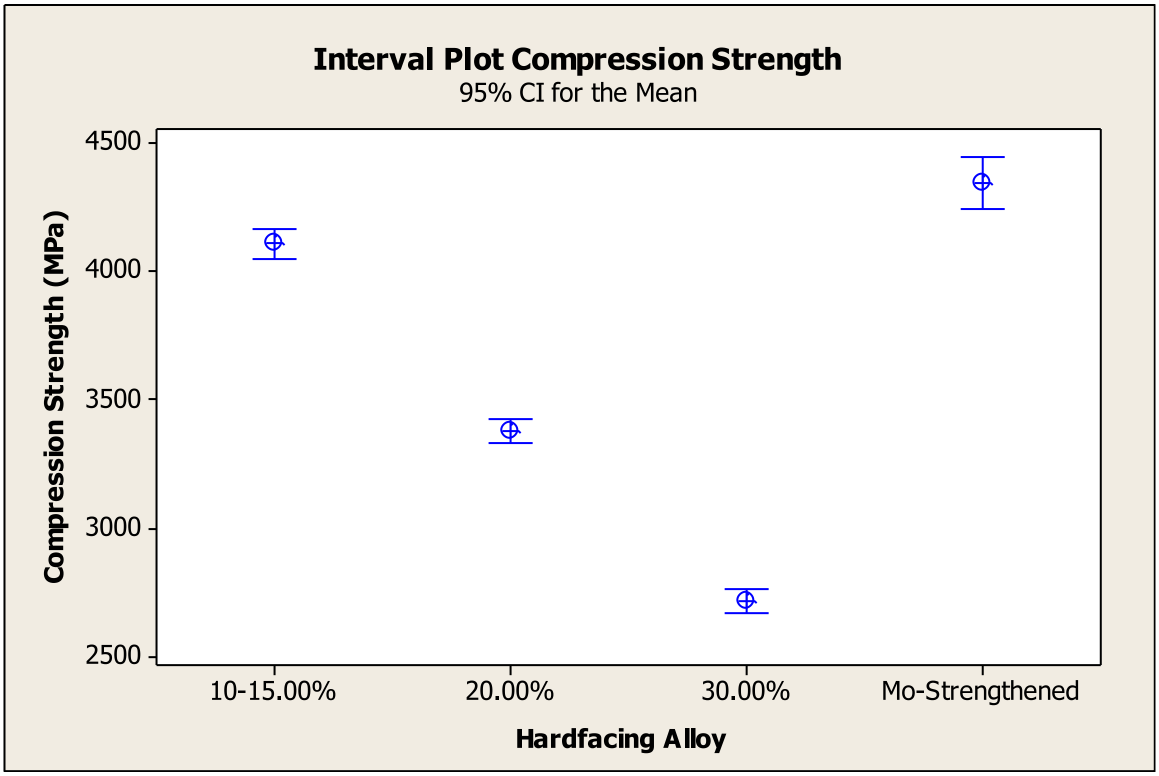

Figure 18 – Interval plot based on the Tukey pairwise comparison test. The 10-15 wt%, 20 wt%, and 30 wt% samples all have an error range of 104 while the molybdenum strengthened sample has an error range of 117.

The Tukey pairwise comparison test concluded that there was a statistically significant difference between all of the variations of the hardfacing alloys. Additionally, analysis was completed to determine if the testing session that each sample was tested on had an effect on the differences between strengths. The results of this analysis can be seen in **Figure 19**.

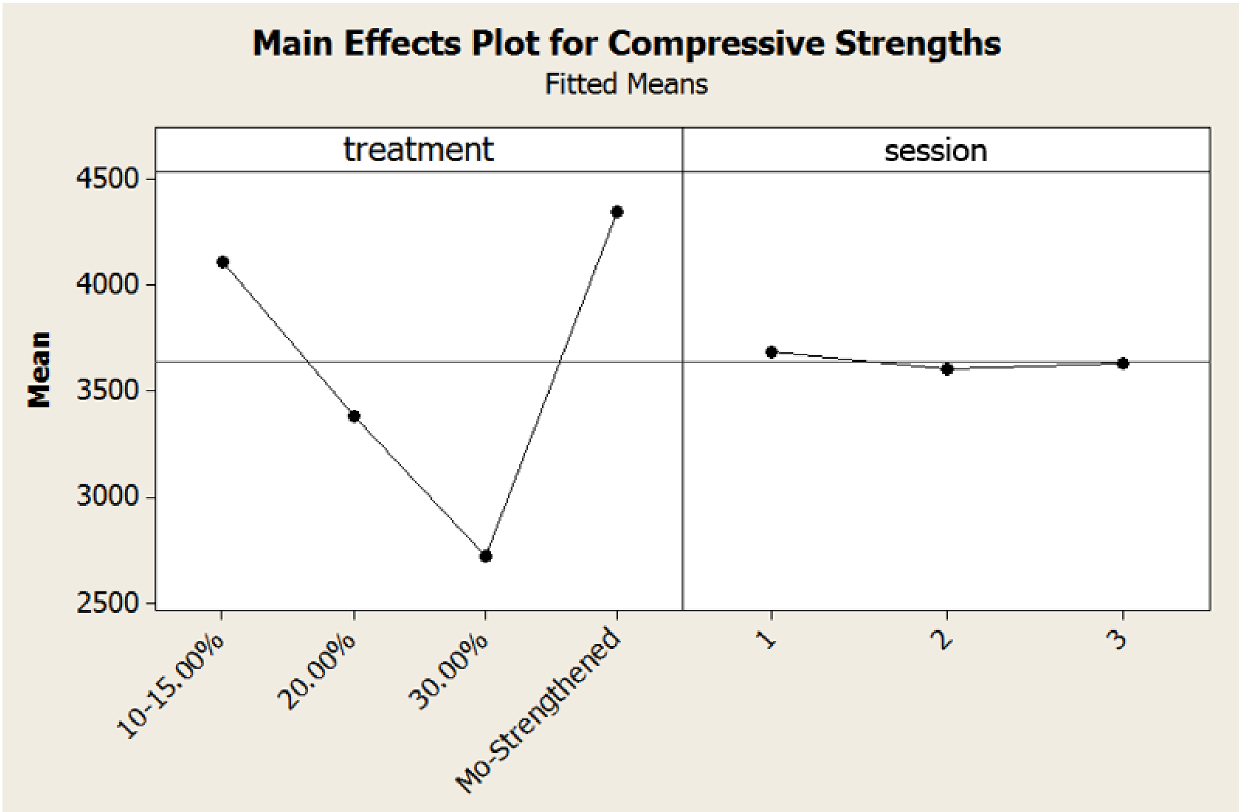

Figure 19 – Plot comparing the effect that sample type had on the compressive strengths versus the effect that the session had on the compressive strengths.

Figure 19 shows that the particular session the testing took place had a negligible effect on the total average compressive strength of each alloy variation. Therefore, it can be determined that the differences in the compressive strengths of the alloy variations were caused by the variations alone, and had nothing to do with the particular testing session.

4. Discussion

For Comparison Group 1, increasing the amount of W/Cr Boride content decreased the compressive strength of the alloy (**Figure 20**). As W/Cr Boride content increased, a new phase was introduced other than the iron matrix, borides, and carbides typically present in the alloys.[15] The new phase is $M_{23}(B,C)_6$, or $(Fe,W,Cr)_{23}(B,C)_6$, and drastically increases in amount as W/Cr Boride content increases.[15] The 10-15 wt% W/Cr Boride alloy, 20 wt% W/Cr Boride alloy, and 30 wt% W/Cr Boride alloys had approximately 14 wt%, 17 wt%, and 38 wt% $M_{23}(B,C)_6$, respectively.[15] The $M_{23}(B,C)_6$ phase is significantly softer than the matrix material as well as the

borides and carbides in the alloy.[15] As the amount of $M_{23}(B,C)_6$ increases, the alloy becomes weaker, thereby lowering the compressive strength of the alloy.

As shown earlier in **Table III**, the 10-15 wt% W/Cr Boride content alloy has the highest tungsten and chrome contents at 9.5 and 5 wt%, respectively. The 20 wt% W/Cr Boride alloy has 9 and 4 wt% tungsten and chrome respectively, and the 30 wt% W/Cr Boride content alloy has 6 and 2 wt% tungsten and chrome respectively. The decrease in compressive strength with increasing W/Cr Boride content may be due to a lack of available tungsten for solid solution strengthening. As more W/Cr Boride formation is initiated with increasing boron content, more tungsten and chrome needs to be used. However, there is less tungsten and chrome available in the higher W/Cr Boride content variations. This would lead to a dearth of tungsten available for solid solution strengthening thereby decreasing the strength of the higher W/Cr Boride content alloys.

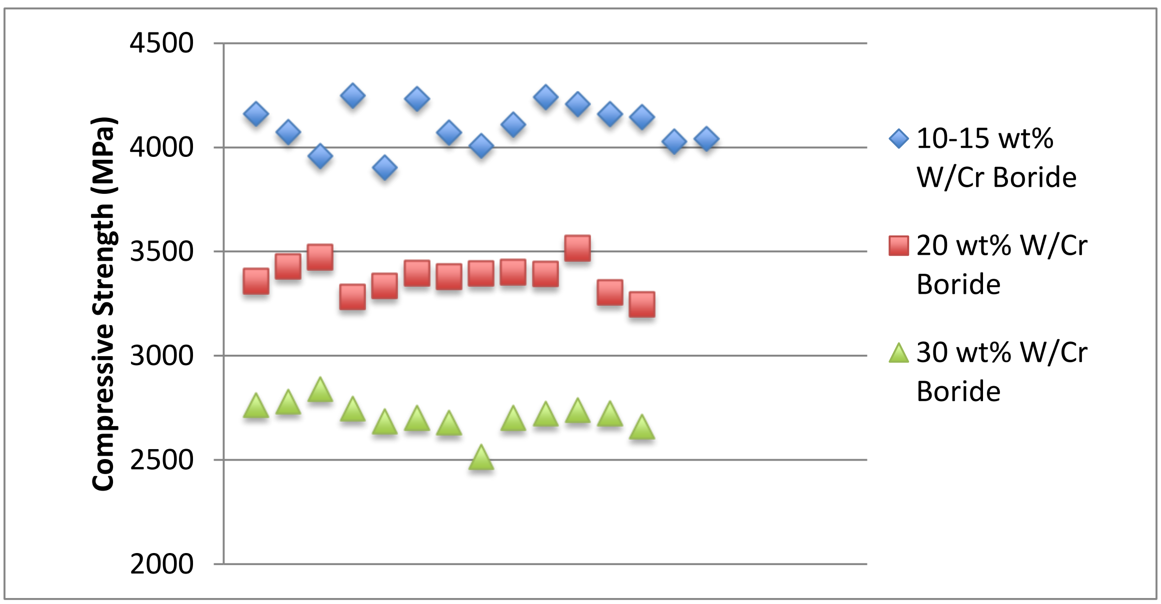

Figure 20 – Plot of the compressive strengths of Comparison Group 1 alloy variations. There is a distinct grouping between the alloy variations with no crossover of compressive strengths.

For Comparison Group 2, the molybdenum solid solution strengthened matrix gave a higher compressive strength than the tungsten solid solution strengthened matrix (**Figure 21**). The molybdenum solid solution strengthened matrix alloy did not have any of the $M_{23}(B,C)_6$ phase while the tungsten solid solution strengthened matrix alloy had approximately 14 wt%

$M_{23}(B,C)_6$.[15] The lack of the weaker $M_{23}(B,C)_6$ phase likely gave the Mo strengthened alloy a higher compressive strength.

Another possible reason for the increase in compressive strength may be due to the changes in composition of the two variations. According to **Table III**, the molybdenum strengthened alloy and the tungsten strengthened alloy have identical compositions other than the addition of 5 wt% Mo at the cost of iron in the molybdenum strengthened sample. The molybdenum strengthened sample potentially has the same amount of tungsten solid solution strengthening with additional molybdenum solid solution strengthening giving it higher strength. The molybdenum solid solution strengthened alloy may have increased strength due to it being a more heavily alloyed variation.

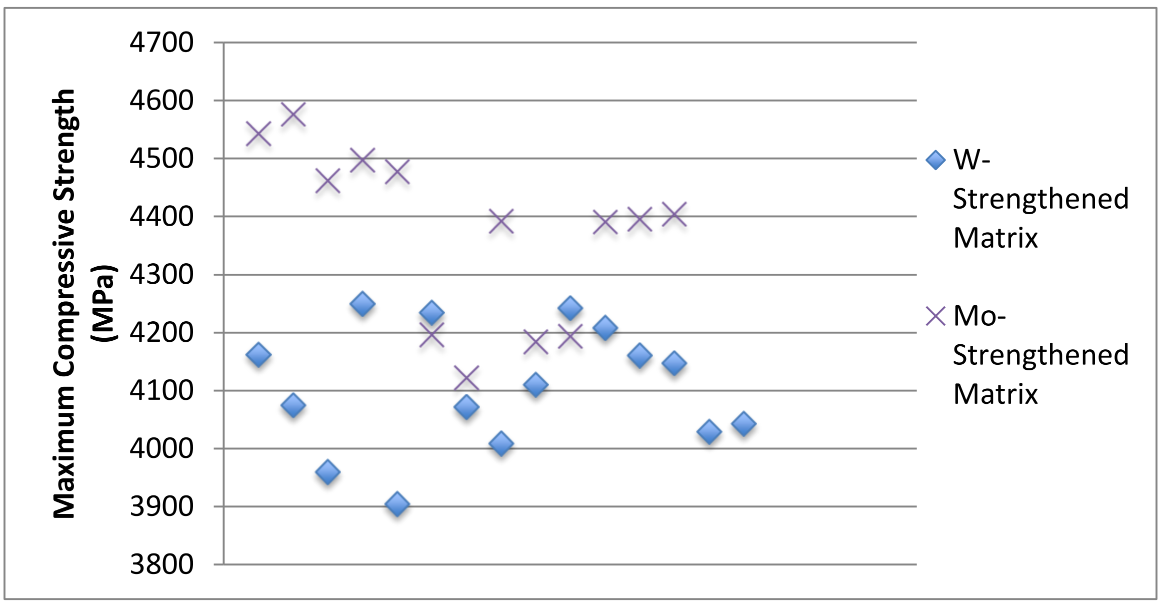

Figure 21 – Plot of the compressive strengths of Comparison Group 2 alloy variations.

Increasing $M_{23}(B,C)_6$ content also decreases other desirable properties for hardfacing alloys in addition to negatively affecting compressive strength. The impact resistance of the alloys was much higher in those that had the least amount of the $M_{23}(B,C)_6$.[15] Impact resistance is important for hardfacing alloys as it increases longevity by preventing sudden failure. Furthermore, the wear resistance of the alloys with higher $M_{23}(B,C)_6$ content decreased sharply.[15] Alloys with the most $M_{23}(B,C)_6$ phase lost more material during G65 abrasion resistance testing.[15] Higher material loss rate will lead to an earlier failure. Overall, increasing $M_{23}CB_6$ content is associated with negatively impacting Vecalloy™ series iron-based hardfacing

alloys by decreasing compressive strength, impact resistance, and abrasion resistance. The alloy variations best suited for use as hardfacing materials are the ones with little to no amount of the $M_{23}(B,C)_6$ phase such as the molybdenum solid solution strengthened matrix with 10-15 wt% W/Cr Boride content and the tungsten solid solution strengthened matrix with 10-15 wt% W/Cr Boride content.

5. Conclusions

1. With the iron-based tungsten strengthened matrix remaining constant, the 10-15 wt% W/Cr Boride content alloy is the strongest in compression of Comparison Group 1 with an average compressive strength of 4107 MPa. The second strongest is the 20 wt% W/Cr Boride content at 3349 MPa. The weakest is the 30 wt% W/Cr Boride content alloy with a compressive strength of 2713 MPa.
2. Keeping the W/Cr Boride content equal at 10-15 wt%, the Mo-strengthened matrix is the strongest in compression with an average compressive strength of 4345 MPa.

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