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INVESTIGATION OF SOFTENING IN HARDFACED LAYERS DURING WELDING

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Abstract

Hardfacing is a widely used technique to create wear-resistant layer on the base material to ensure good durability and performance under harsh operating conditions. However, despite its effectiveness in improving wear resistance, hardfaced layers can sometimes exhibit softening phenomena during welding, compromising their mechanical properties and overall performance. In this research, the effect of heat input was investigated in case of Fe-based hardfacing material with high Cr content. 4 different heat inputs were applied with gas metal arc welding and significant differences were determined in hardnesses, which can be influential to the lifetime of hardfaced parts. Hardness drop happens in the heat-affected zones between the hardfaced layers and the highest heat input causing the most significant softening (20% hardness drop).

Keywords: *hardfacing, softening, hardfaced layer, welding*

1. Introduction

Hardfacing is a specialized surface modification technique extensively employed across industries to enhance the wear resistance and lifetime of components subjected to abrasive, erosive, or corrosive environments. This method involves depositing a layer of wear-resistant material onto the surface of a base material, effectively creating a protective shield against harsh operating conditions. Commonly used in applications ranging from mining and construction to oil and gas, hardfacing has become integral to extending critical machinery and equipment's service life and performance. *Figure 1* shows a typical usage of hardfacing in demolition shears. The hardfaced layers' quality depends on the type of hardfacing consumable and the hardfacing process. The gas metal arc welding is commonly used for hardfacing, because it can ensure a good deposition rate and it can be easily automated. On the other hand, this process uses relatively high heat input, which can cause microstructural changes in the hardface layers and base materials. To reach good quality, it is important to determine a hardfacing material that fits to the loadings and environmental effects. The optimization of the welding process is also important because the heat has different effects on the different hardfacing materials.

***Figure 1**. A typical hardfaced product is a demolition shear*

Hardfacing consumables can be categorized into four groups: iron-based, cobalt-based, nickel-based, and tungsten alloys (Gerard, 2016; Garbade et al., 2021; Henderson et al., 1991; Norrish et al., 2006; Pradeep et al., 2010; Venkatesh et al., 2015; Okechukwu et al., 2018).

- Iron-Based Alloys: these are the most cost-effective group of hardfacing alloys and are used for applications including abrasion, impact, and thermal fatigue resistance. They can be further divided into two groups: iron-based with less than 20% alloying elements and iron-based with more than 20% alloying elements (Cr cast iron alloys) (Okechukwu et al., 2018; Kvidahl, 2022). There are several alloying elements in the iron-based hardfacing consumables like: C, Mn, Cr, Mo, Cu, Ni, Co, V, Ti, W, Nb, and B (Gerard, 2019; Digambar et al., 2014). Several types of microstructures formed with these alloys, including austenite, ferrite, martensite, and carbides, it basically determined by the alloying elements (Balakrishnan et al., 2012). Iron-based hardfacing alloys with high contents of Cr and Mo cause the formation of hard carbide and boride phases, which ensures their good abrasion resistance. These alloys can possess various matrix structures, including austenitic, martensitic, pearlitic, ferritic, or combination of these structures. Some iron-based alloys with high chromium carbides, may have transverse surface cracks on the hardfacing layers (Gerard, 2016; Balasubramanian et al., 2008). Despite these cracks, the deposits are suitable for many applications in the mining and earth engaging industries.
- Cobalt-Based Alloys: this group of alloys is used for those types of application where good wear, oxidation, corrosion, and heat resistance are important sometimes combined with high hot hardness. The primary composition elements of these hardfacing alloys are Co (usually 60%) and Cr (usually 30%). The most common alloys are derivatives of stellite with a nominal composition of Co-28Cr-4W-1.1C atomic weight percentage (wt%). High Cr content is important for corrosion and high-temperature resistance, Ni for good ductility, and W, Mo, and C to increase the strength and wear resistance. These alloys have better weldability and thermal fatigue resistance compared to nickel-

based alloys (Stubbington, 2021). The cobalt–chromium–tungsten alloy is one of the most expensive alloys in hardfacing industries (Balakrishnan, 2011; Rizio, 1994).

- Nickel-Based Alloys: these alloys are applied mostly for applications that require wear and corrosion resistance at higher temperatures (Balakrishnan, 2011). Nickel-based alloys usually replace cobalt-based alloys because the cobalt-based alloys are expensive. Some researchers suggest that the addition of W and Mo in nickel-based alloys increasess the hardness and high-temperature strength, the addition of C, B and Nb improves abrasion resistance, and the addition of Cr and Al gives better corrosion resistance (Stubbington, 2021; Gualco et al., 2016).
- Tungsten Alloys: these alloys are used for extreme abrasion wear resistance applications (Gerard, 2016; Balasubramanian, 2008). Tungsten carbide is one of the hardest materials in industrial applications and it is very brittle. Tungsten carbide particles do not melt during arc welding. They are directly transferred to the hardface layers, unlike carbides in iron- or cobalt-based hardfacing alloys. Usually, for hardfacing, using tungsten carbide particles gives more consistent distribution and surface coverage than using directly tungsten carbide rod as a consumable (Pradeep et al., 2010; Blombery, 1974). In this case very important to use lower heat inputs to create a uniform distribution of tungsten carbides, higher heat inputs can result in the dropping of these carbides towards the fusion line (Gerard, 2008).

High chromium iron-based alloys are the most common and economical alloys for abrasion resistance hardfacing (Venkatesh et al., 2015; Zahiri et al., 2014), while nickel-based and cobalt-based alloys are suitable for wear and corrosion resistance hardfacing at high temperatures (Gurumoorthy et al., 2007; Li et al., 2001).

The hardness of the hardfacing layer is the most important in most cases, so important to know if there are any softening in the hardfacing layers during the hardfacing process. In this research, a high chromium iron-based hardfacing layer was examined, which was welded by 4 different welding heat inputs.

2. Applied materials

For the research work, we used a high-strength steel base material S690QL produced by Azovstal. The thickness of the base material was 25 mm. In the case of hardfacing, it is often necessary to use a butter layer to obtain better joint properties (Buntoeng et al., 2019; Balakrishnana et al., 2011), especially when the material of the base material and the material of the hardfacing layer differ significantly. In the present case, the applied hardfacing layer is rather brittle, and parts of the base material may also be subject to delamination, so the use of a tough butter layer is important. The used butter layer material type is LNM19, manufactured by Lincoln Electric, with a standard grade of G CrMo1Si (ISO21952-A). This material is relatively soft, has good toughness, and is cost-effective. The hardfacing layer material is a high hardness and abrasion resistant, but rather brittle, also from Lincoln Electric: Carbofil A600, S FE8 according to EN14700 standard. It is a high Cr content hardfacing material with relatively high Si and C content.

Table 1 summarizes the chemical composition of the base material, the butter layer and the applied hardfacing layer, and *Table 2* shows the mechanical properties of the base material. The data in the tables come from the material certificates. The chemical composition of the butter layer slightly doffers from the base material (e. g. Si and Cr content), but the butter layer gives better elongation and lower sterngth properties. The hardfacing layer shows significant differences in the chemical composition, the C, Si and Cr contents are much higher than the base material and butter layer. Mechanical properties for the hardfacing layer are not reported in the material certificate nor in the official website.

Table 1. *The chemical composition of base material, butter layer and hardfacing layer (wt%)*

Material	C	Si	Mn	P	S	Cr	Cu	Mo	Ni	Fe
S690QL	0.15	0.23	1.1	0.013	0.003	0.58	0.05	0.21	0.66	rest
LNM19	0.1	0.65	0.97	0.003	0.009	1.18	0.01	0.46	0.02	rest
Carbofil A600	0.47	2.98	0.39	0.02	0.001	9.15	0.06	NA	0.17	rest

Table 2. *Mechanical properties of base material nd butter layer*

Material	Tensile strength, R_m [MPa]	Yield strength, $R_{p0,2}$ [MPa]	Elongation, A_{50} [%]	R_m*A_{50}, [MPa*%]
S690QL	777	711	18	13986
LNM19	635	530	23	14605

The R_m*A_{50} is a commonly used value in case of high strength steels, which can show the most important mechanical properties in one number. If this number is high, the mechanical properties are good. This number is good for comparison, but cannot gives accurate values.

3. Welding circumstances

The hardfacing experiments were carried out using gas metal arc welding (process 135 according to MSZ EN ISO 4063). The welding was performed using a Cloos robotic welding system, ensuring accurate positioning, uniform welding speed and thus reproducibility. The used shielding gas was a mixture of 80% Ar + 20% CO_2 in all cases. A comparison of the effect of heat input was also the aim of the series of experiments, so four different welding parameters were used, resulting in different heat inputs and $t_{8/5}$ cooling times. To ensure comparability of results, the same specimen sizes were used for all experiments. The welding parameters are summarized in *Table 3*.

Table 3. *Welding parameters*

Number	Welding current [A]	Arc voltage [V]	Welding speed [cm/min]	Heat input [kJ/mm]	$t_{8/5}$ [s]
1.	130	17.2	160	0.67	4.7
2.	170	19.2	210	0.75	5.3
3.	220	21.3	250	0.90	6.4
4.	280	26.7	280	1.28	9

By using the welding parameter combination number 1, it was possible to achieve a joint with acceptable quality with low heat input and good fusion. Welding parameter combination 4 was used to achieve a deep fusion, but cracks appeared in the hardfacing layer at higher heat input, so the upper limit of the heat input was given by this combination. The $t_{8/5}$ cooling time range is from 4.7 sec to 9 sec, the recommended $t_{8/5}$ for this base material is between 5–20 sec. Based on preliminary manufacturing experience, 120 °C was chosen as both the preheating and interlayer temperature. Welding parameter combinations were carried out on a surface of 100 mm × 150 mm; one layer of butter layer was welded and three layers of the hardfacing layer were produced.

4. Testing circumstances

Typically, the quality of the hardfacing can be checked by destructive testing. Of these, macroscopic testing and hardness measurement plays a key role. Therefore, for this series of experiments, we prepared a grinding specimen for the macro test and then tried to map the hardfacing layers and their heat-affected zone (HAZ) in detail by hardness measurement. Cross sections were first made on the specimens, taken from the centre of the 100 mm × 150 mm sections. The cut surface was first grinded and then polished; the etching was done using a 2% Nital solution, in order to clearly identify the seam lines and the zones of the heat-affected zone. After macro tests, hardness measurements were taken on each piece. Hardness measurements were not only performed along a single line, but covering a whole area, a so-called hardness map was created. In each case, the area covered the 3rd hardfaced layer and its HAZ. *Figure 2* shows precisely the locations of layers and the hardness measurings.

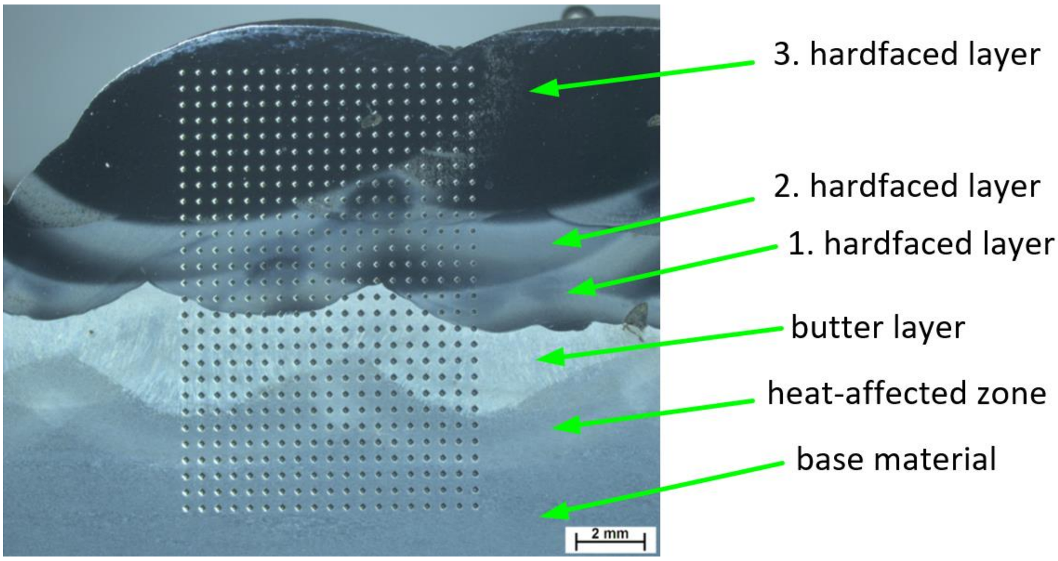

Figure 2. *Testing indents on the specimen*

Vickers hardness measurements (HV10) were made in the area, with a distance of 0.5 mm between indents in each direction. The number of indents was essentially determined by the size of the 3rd layer and its HAZ. On this basis, the number of indents varied between 420 and 480 per specimen. Indents were made automatically by the Reicherter UH250 hardness tester which was used for the tests.

5. Results and discussions

The hardness maps were made on the test specimens made the 4 different hardfacing technologies in areas where the macro sections clearly showed the heat-affected zone in the hardfacing layer. For all of these pieces, this was clearly identified.

Figure 3 shows the hardness map with the lowest heat input on the hardfacing layers.

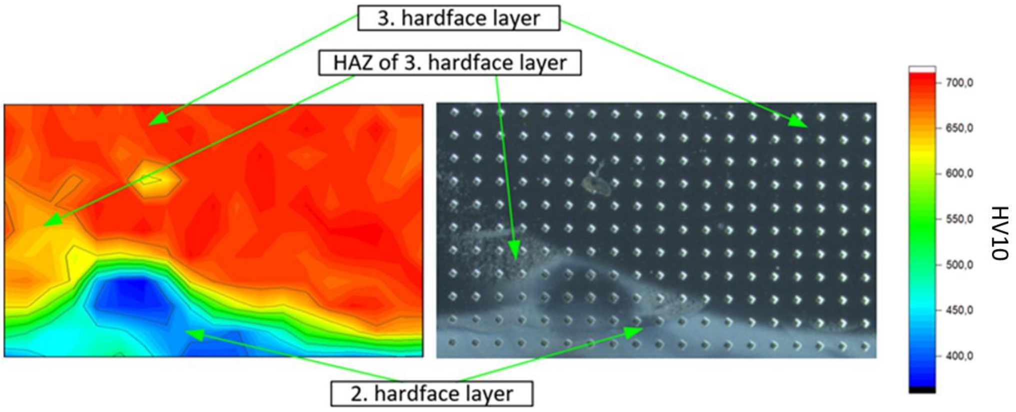

Figure 3. *Hardness map of the hardfaced area made by the lowest heat input*

The figure clearly shows that the hardness of the 3rd layer varies between 680–710 HV and the hardness, except for the heat-affected zone. The thermal effect of the rows of 3rd layer creates a HAZ, which is clearly observed in the grinding and hardness map. In this area, the hardness decrease is not so significant, typically 630–650 HV. A much more drastic hardness decrease is observed in the 2nd hardfacing layer, where the hardness drops back to 400–450 HV. This may be due to dilution, but it is more likely that the thermal effect of the 3rd layer rows is reflected in the decrease in hardness values. Further investigations are needed to clarify this.

Figure 4 shows the results of the hardness measurement of the hardfacing layers made with case 2 (higher heat input) and the lines of indents.

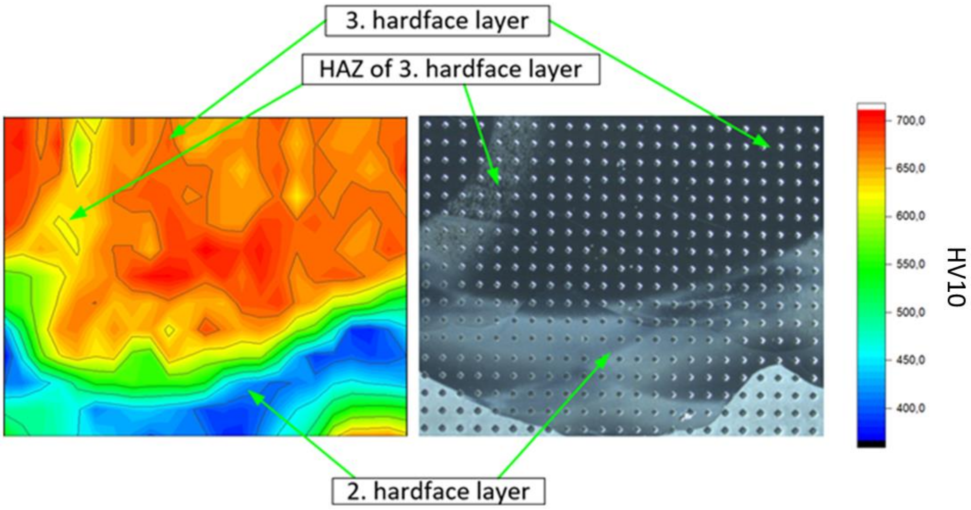

Figure 4. *Hardness map of the hardfaced area made by the 2nd case*

In case 2, a higher heat input was used. The hardness of the 3rd hardfacing layer ranges from 670 to 705 HV, which is practically the same as in the previous case. However, the heat-affected zone of layer 3 is more clearly visible in the hardness map and in the macrophotograph. In this case, the hardnesses in the

HAZ range between 600 and 630 HV, which is lower than the values measured for the previous piece. The hardnesses of the 2nd hardfacing layer are the same as the values measured for the lowest heat input.

Figure 5 shows the hardness map and indent sequence of the hardfacing layers made with case 3 (even higher heat input).

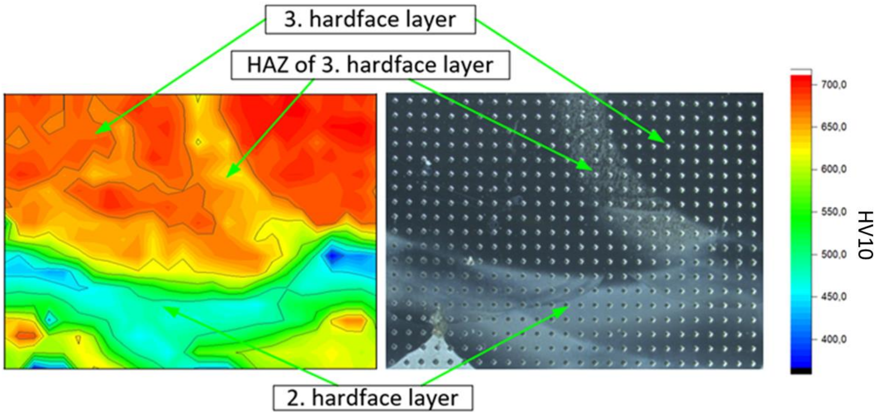

Figure 5. *Hardness map of the hardfaced area made by the 3rd case*

Analysing the figure, it can be seen that the hardness values of layer 3 are practically similar to the previous two cases. The thermal zone is clearly visible in both the macrophotograph and the hardness map. Its hardness ranges from 610 to 630 HV, which is also practically identical to the previous result. Interestingly, the hardness of the 2nd hardfacing layer is slightly higher than in the previous cases, ranging from 430 to 470 HV.

The hardness maps and indent sequences of the hardfacing layers with the highest heat input case are shown in *Figure 6*.

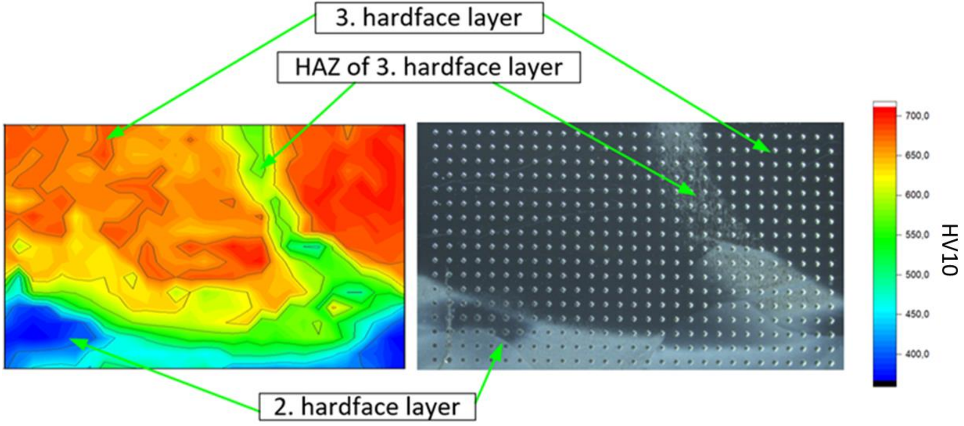

Figure 6. *Hardness map of the hardfaced area made by the lowest heat input*

Based on the hardness map, it can be stated that the hardness of the 3rd applied layer ranges from 650 to 690 HV, which is less than in the previous cases. The heat-affected zone is most clearly visible in this case both in the hardness map and in the macro photo. The hardness values in this case range from 530–580 HV, which is 110–120 HV less than the hardness values of the 3rd applied layer. The

2nd applied layer also shows lower hardness values than in the previous cases, typically 380–450 HV. This result clearly shows that the higher heat input causes significant softening in the heat-affected zone in this hardfacing layer. *Table 4* summarize the hardness results.

Table 4. *Summary of hardness results*

Case number	3rd hardfaced layer, HV	HAZ of 3rd hardfaced layer HV	Difference between 3rd layer and its HAZ, HV	2nd hardfaced layer, HV	Difference between 3rd and 2nd layer, HV
1	680–710	630–650	50–60	400–450	260–280
2	670–705	600–630	70–75	400–450	255–270
3	670–705	610–630	60–75	430–470	235–240
4	650–690	530–580	110–120	380–450	240–270

6. Conclusions

The following conclusions can be drawn from the results of the investigation:

- the hardness of layer 3 varies only slightly depending on the heat input, only the highest heat input resulted slightly smaller hardness values.
- The thermal effect of the rows in the 3rd layer reduces the hardness of the 3rd layer with an average difference of 10% in the heat-affected zone. For the case with the highest heat input, the hardness of the heat-affected zone was 20% less than the average hardness of the 3rd layer. It clearly shows that lower heat input is preferable instead of high heat input.
- The hardness values of the 2nd hardfacing layer are significantly lower than the 3rd hardfacing layer (235–280 HV difference), which is either due to thermal annealing or possibly due to dilution with the butter layer. Further investigation is needed to determine the reason. In addition, these low hardness values raise the need for a 1st and 2nd layer.

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