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RESEARCH ARTICLE

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Investigation of the alloying elements effect in the flux-cored wire and submerged arc welding flux combination

Erhan Ozkan[a,*]

[a]*Ege University, Mechanical Engineering Department, 35040, İzmir, Türkiye, ORCID: 0000-0002-3849-6713*

Abstract

In this study, it was aimed to investigate hardfacing weld metals' metallurgical and mechanical properties produced by flux-cored wire and submerged arc welding flux combinations. The usage of the combination for these two methods, which are generally preferred separately, distinguishes this research from other similar studies. In the first stage, the optimum production conditions and physical properties of the submerged arc welding fluxes were determined and then flux-cored wire manufacturing details have been defined. Agglomerated submerged arc welding fluxes and seamed type flux-cored welding wires samples were investigated according to the changing carbon, chromium, niobium, and wolfram ratios, while manganese and silicon values were kept constant. Five different samples have been prepared with this purpose, and the hardness test, wear test, microstructure analysis, chemical analysis, and X-Ray diffraction analysis were carried out respectively. It was observed that the increase in hardness affects the wear resistance directly. The effect of chemical analyses on the microstructure has also been determined. Moreover, while the increasing amount of chromium carbide clearly changed the microstructure, and the addition of refractory metals enabled the formation of the eutectic and dendritic structure. The problems of low efficiency in flux-cored wire and inability to alloy in submerged arc welding flux were solved with this method. Therefore, the production of hardfacing consumables via submerged flux-cored arc welding combination method was achieved firstly by using domestic raw materials, and one TUBITAK project and one PhD thesis were successfully finished with these data.
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* Corresponding author. Tel.: +90-532-509-5021; fax: +90-232-877-1715
E-mail address: erhanozkan81@icloud.com

Keywords: FCAW, SAW, Hardfacing, Wear resistance, Mechanical properties, Metallurgical properties.

1. Introduction

The process of joining or filling metallic materials by melting them using a heat source with or without pressure is called metal welding. When the history of electric arc welding is researched, it is determined that the oldest one is the Benardos welding method in 1885. Benardos created an arc between a carbon electrode and the workpiece and welded using a wire electrode, as in oxyacetylene welding. Later, in the method developed by Zerener in 1889, an electric arc was created between two carbon electrodes and the arc was blown towards the part with the help of a magnetic coil between the two electrodes. In this method, a welding wire was also required. Also in 1889, Slavianoff developed the method that forms the basis of today's electric arc welding. MMA (Manuel Metal Arc) welding is still used in many applications today [1-6].

However, due to the limited development of MMA welding, more emphasis has been given to R&D activities in MIG (Metal Inert Gas) / MAG (Metal Active Gas) [7-10], TIG (Tungsten Inert Gas) [11-13], LB (Laser Beam) welding [14], FS (Friction Stir) welding [15-17], and SAW (Submerged Arc Welding) methods [18]. MIG welding is carried out under inert gas (generally argon or helium) atmosphere. In this method, excellent melting properties can be achieved when working with high current density. The only difference between MIG and MAG welding is doing MAG method under CO_2 atmosphere instead of inert gas. In short, there is no need for additional welding equipment when welding under a CO_2 atmosphere [19]. Since the argon gas used in MIG welding is expensive, a lot of research carried out to use gases obtained at a lower cost, and it was determined that the most suitable gas was CO_2. On the other hand, the arc and molten metal are protected by a powder cover with a granular structure in the SAW method. SAW, which has high melting power, welding speed and is very suitable for welding various types of steels, is used extensively in the production of boilers, profiles, ships, pressure vessels and in fillet welding processes [20-22]. This method, like every method, is existing advantages and disadvantages. The main biggest disadvantage is that flux is applied externally and cannot penetrate directly into the weld pool. Various methods have been tried to be developed to prevent this defect and to provide advantages over MIG/MAG methods.

FCAW is one of these developed methods [23-26]. Academic and technical studies are continuing these products, which are obtained by filling the flux into the void area within the wire. In this method the flux, applied externally in SAW method is placed inside the wire, allowing the welding process to be carried out at higher current densities. In addition, another important effect of FCAW is that the greater penetration obtained in the MAG method and the faster and cleaner weld deposits obtained in MIG welding are provided in a single method more economically [27-31].

The most advanced applications of FCAW are hardfacings. There are still unknowns for hardfacing products, which have a wide range of usage, especially in the repair and maintenance of heavy equipment [32]. The reason for this uncertainty is the complex integration of the system and the limited database on the effect of metallurgical events on the mechanical properties of refractory metals that provide wear resistance. The main goal of this article is to evaluate the microstructure, hardness, and wear behavior in the controlled change of chromium, niobium, and tungsten elements, which increase the wear resistance in hardfacing applications. There are numerous articles in the literature in which the effect of refractory metals on welding ability was investigated by handling them in a controlled manner, but the originality of this study is being the first mechanical and metallurgically detailed investigation of the FCAW method, in which the elements were distributed homogeneously, and the SAW method, in which high-speed welding can be carried out [33-39].

In this article, details of a successfully completed TUBITAK project and a related PhD thesis were included, and it was aimed to present an original study in which the mentioned disadvantages of FCAW, due to too much spatter, and SAW methods, due to the inability to direct high amounts of alloying elements to the weld pool, were eliminated with a synergistic effect. While the amounts of iron, carbon, chromium, niobium, and wolfram were changed in a controlled manner by keeping manganese and silicon constant, wear tests were carried out according to the hardness values obtained for these variants, microstructure controls and details of the data were conveyed to the readers. As a result, it was determined that the highest hardness and best wear resistance were obtained in the material sample with dendritic structures in the eutectic phase containing 35% chromium, 7% niobium and 3% wolfram.

Nomenclature

FCAW	**F**lux-**C**ored-**A**rc-**W**elding
FS	**F**riction-**S**tir
LB	**L**aser-**B**eam
MMA	**M**anuel-**M**etal-**A**rc welding
MAG	**M**etal-**A**ctive-**G**as
MIG	**M**etal-**I**nert-**G**as
SAW	**S**ubmerged-**A**rc-**W**elding
TIG	**T**ungsten-**I**nert-**G**as

2. Material and Method

In this section, the preparation methods of welding consumables, the production of welding fluxes whose composition was determined according to different criteria, and the general conditions of flux-cored wire manufacture were included. The production of submerged arc welding fluxes was carried out in the Submerged Arc Welding Flux Production Line with a capacity of 10 tons/day within Oerlikon, and the agglomeration method was preferred in production. On this line, the dry mixtures, which can be changed according to the recipe, was prepared and mixed first, later dried at 100±10 °C for 120 minutes, and last treated at 400-850 °C, depending on the type of recipe, for 2-5 hours, again depending on the type of recipe. After the physical, chemical, and metallurgical properties of the treated products were checked and approved, they were packaged in 25 kg packages and delivered to the laboratory. The prepared SAW products fulfilled the requirements of the EN 760 SA FB 1 55 AC. These regulations describe the characteristics of the powders and mean that fully basic agglomerated SAW flux. The Fig. 1. shows the SAW specimen used for the tests.

Fig. 1. SAW flux.

The production of FCAW wires was carried out in the FCAW Production Line within Oerlikon with a capacity of 15 tons/day. The FCAW production line is given schematically in Fig. 2. In this diagram, (a) represents the state of the strip material before it takes shape, (b) shows the plastic deformation that occurs to fill the strip with flux, (c) defines filling the strip with flux, (d) represents complete closure of the strip, (e) shows joining the tips, (f) defines completing the coverage of the diameter, and (g) represents the final form by thinning the walls.

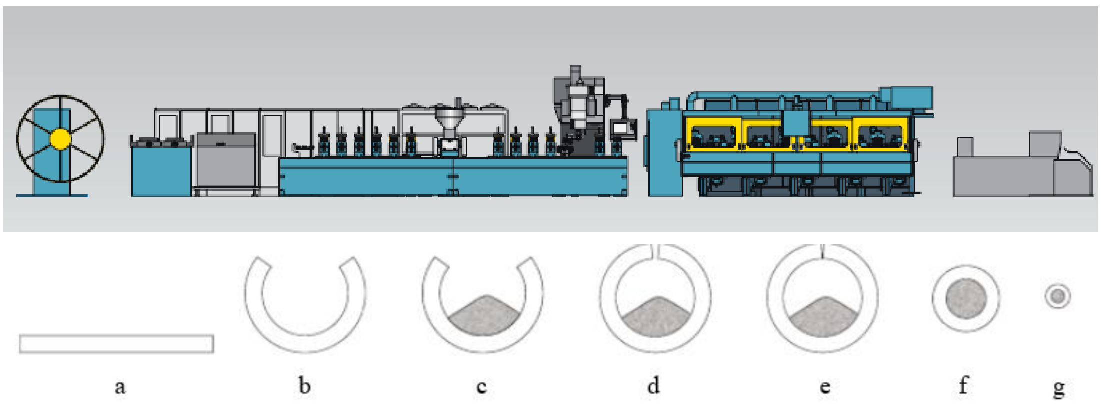

Fig. 2. Schematic representation of FCAW production line step by step.

Mechanical analyzes of FCAW and SAW combinations were carried out on S355JR (EN 10025-2) materials, and metallographic research of the parts on the same material was carried out. Welds on S355JR materials were made with Oerlikon SG100 Inverter Automatic SAW machine. The chemical composition of the weld deposits was defined by using Metavision 10008i optical emission spectrometer (Fig.3.). The microstructures of samples with varying alloys were examined with Nikon LV150NA Straight Industrial Microscope. The hardness of the samples was measured with the Presi HZ 2-4 device. Wear loss values were determined by calculating the wear losses in the substrate material and the counter friction element, as specified in the ASTM G133-05 standard. Wear amounts were determined by testing weld metal samples, 10 mm high and 40 mm in diameter, prepared for five different samples, with a TRIBOtester Brand friction wear device (Fig. 3.). Tests were carried out at 25.000, 50.000, 75.000 and 100.000 cycles under 10N load. Ø 6 mm 100Cr6 steel balls were selected as counter friction elements (abrasives) in the tests. Moreover, 3.140 meters in the 25.000 cycle stage, and 12.560 meters for 100.000 cycle stage have been covered as the total sliding distance. Before and after each test stage, the steel balls and the weld metal sample were weighed with a precision balance and the wear information was recorded. The wear images of test samples were taken with JEOL-840 A model SEM electron microscope. XRD studies have been carried out to explain the composition effect on stable carbides that give hardness to the sample. Philips Expert Pro model XRD device was used with this purpose. X-Ray diffraction patterns have been clearly obtained with the help of CuK_{α} rays (λ=0.15418 nm).

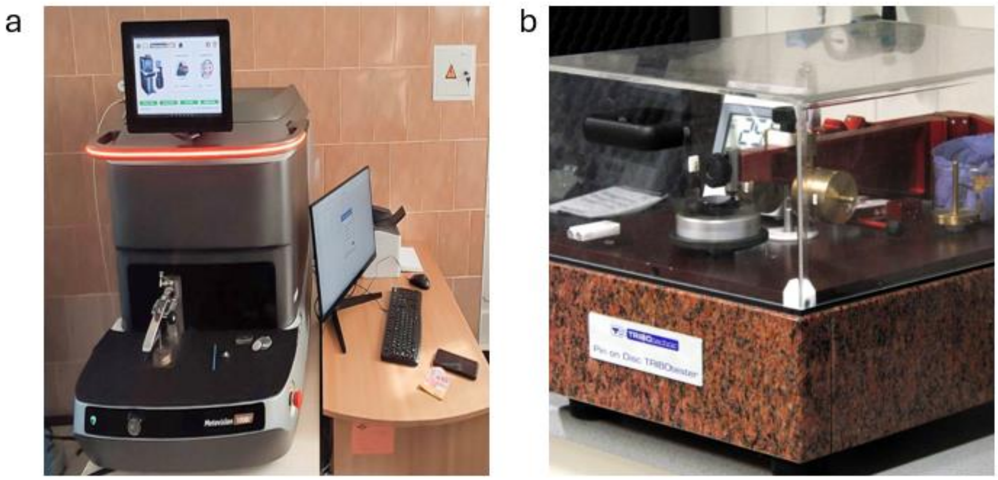

Fig. 3. (a) optical emission spectrometer; (b) wear test device.

3. Results and Discussion

The weight percentages of alloying elements can be easily controlled with the combination of FCAW and SAW. The reason for this condition is that the metals placed in the flux in elemental form were trapped in the weld seam and there was no reaction that would lead to loss of these elements due to slag formation. Table 1 includes the weld metal analysis obtained with the FCAW and SAW combination, which has different chemical analysis values, and the hardness values obtained because of these analyses.

Table 1. Hardness values of products with different chemical analysis.

Element Percentage (%)	S-1	S-2	S-3	S-4	S-5
Carbon	0.1	1.0	3.0	7.0	7.0
Manganese	0.9	0.9	0.9	0.9	0.9
Silicon	0.7	0.7	0.7	0.7	0.7
Chromium	3.0	7.0	35.0	35.0	35.0

Niobium	-	-	-	7.0	7.0
Wolfram	-	-	-	-	3.0
Iron	Rest	Rest	Rest	Rest	Rest
Hardness	S-1	S-2	S-3	S-4	S-5
HR_c	31	59	60	63	67

It has been determined that increasing the amount of chromium and carbon increases the hardness very much, but increasing chromium alone does not increase the hardness much, and added niobium does not affect the hardness as much as tungsten (wolfram), but the main purpose of adding these elements is to increase the wear resistance of the products. For this reason, in the next stage, wear tests were carried out with the products listed in Table 1.

Fig. 4. shows the friction-wear test curves of the products whose hardness and analysis values are given in Table 1. Accordingly, sample 5, which has the highest hardness value, has the highest wear resistance; It is seen that niobium in sample 4 and tungsten in product sample 5 increase the wear resistance.

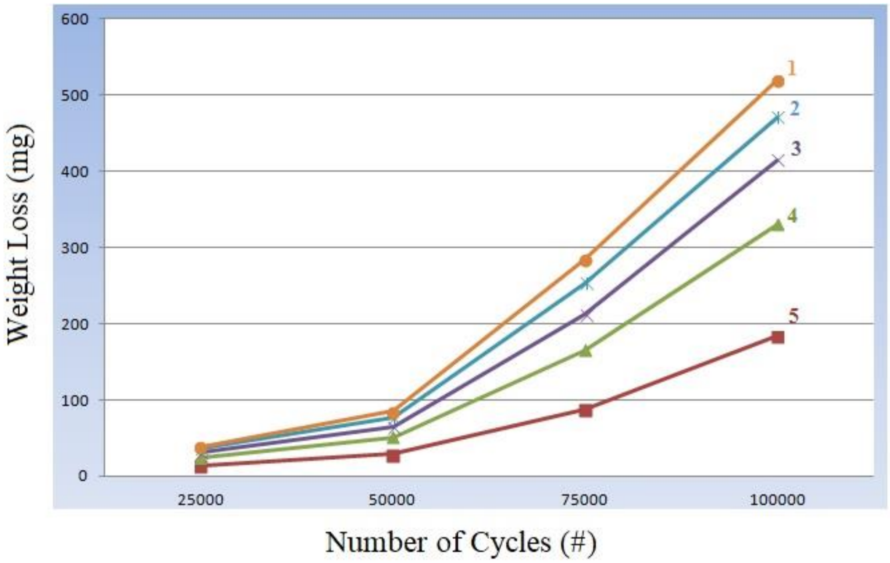

Fig. 4. Friction-wear test results in different chemical analyses.

The amounts of wear losses in milligrams depending on the number of cycles are given in Table 2 to make Fig. 4. more understandable. The difference in wear amounts between the samples increased with the increasing number of cycles. Wear rates of the samples were determined from the Table 2 for highest cycles as S-1: 4.77×10^{-6} m^3/Nm, S-2: 3.41×10^{-6} m^3/Nm, S-3: 2.39×10^{-6} m^3/Nm, S-4: 1.70×10^{-6} m^3/Nm, and S-5: 1.02×10^{-6} m^3/Nm, respectively The reason for this was the increased wear resistance of metallic wolfram and niobium due to their good mechanical properties. Similar results were also reported in the literature which clearly demonstrated the improvement of wear resistance by forming hard layers on the surface of Ni- and Co-based alloys by boriding [40-42].

Table 2. Weight loss amounts depending on the number of cycles.

Number of cycles during the friction-wear test	sample code and mass loss in milligram				
	S-1	S-2	S-3	S-4	S-5
25.000	14	10	7	5	3
50.000	88	72	54	32	18
75.000	274	241	207	166	92
100.000	514	486	415	321	188

The SEM micro images of the worn surfaces were investigated in Fig. 5. to analyze the wear behavior of the samples. It was determined that the wear marks of sample 1 were quite frequent and narrow. It was obtained that there was 14 mg wear loss under 10 N load with 3.140 m sliding distance. However, it was determined that sample 2 had wider and more spaced than sample 1 by considering the wear surfaces. On the other hand, it was observed that the wear marks of sample 3 were narrower than sample 2, and when compared to the hardness value, it was determined that this was proportional to the fact that it was much higher than sample 1. Moreover, much finer wear traces have been observed in the SEM image of sample 4. In the SEM image of sample 5, the wear marks were not quite deep, and it is seen that there was superficial wear on the material.

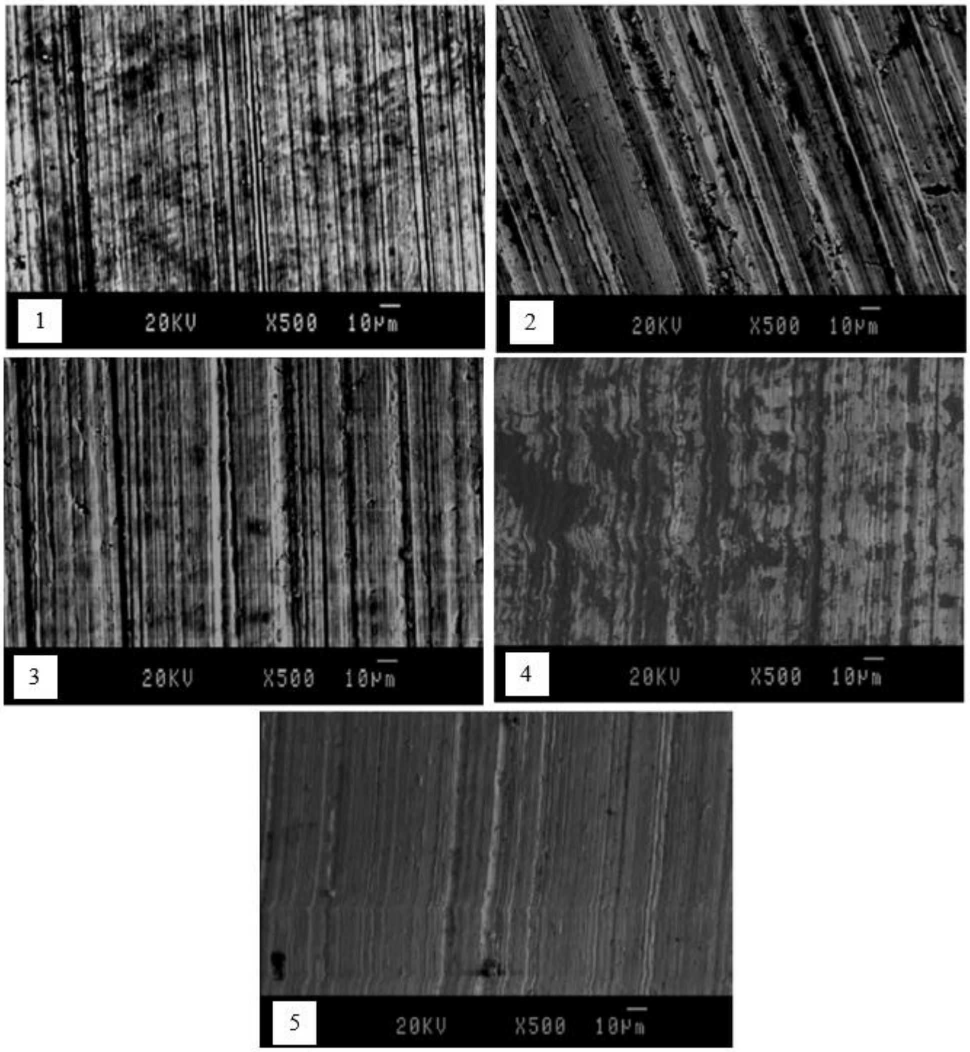

Fig. 5. SEM images of the samples after wear test.

The XRD analysis performed before and after the test to determine the effect of the phases on the wear resistance of the sample showing the highest wear resistance is shown in Fig. 6. This figure represents the XRD patterns obtained before (a) and after (b) wear test. The first striking feature in comparing the XRD patterns was the disappearance of alpha iron and chromium carbide phases after the wear test. Alpha iron is a body-centered cubic allotrope, and it can only dissolve small concentrations of carbon. For this reason, it is soft and able to quickly separate from the material surface in the wear test. The width of the chromium carbide peak provides information about the grain size of the particles. Therefore, big chromium carbide particles' separation from the material during the initial wear of the test explains the disappearance of chromium carbide peak. On the other hand, since alpha iron removed from the system and gamma iron remains in the weld deposit in a more stable state, the intensity of gamma iron's peak increased after the wear test. The niobium and wolfram carbides, which increase the hardness and especially the wear resistance of the samples, show the lowest level of the peaks, because of their less amount in the total system. They disappeared after the wear test due to fulfilling their duties on the wear and abrasion characteristics.

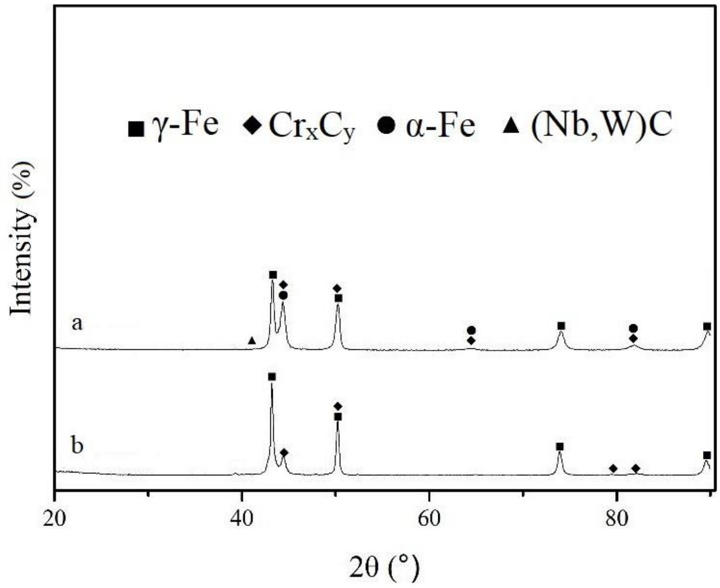

Fig. 6. XRD patterns before (a) and after (b) wear test of the sample with the highest hardness and wear resistance.

The difference in chemical analyses not only affects the mechanical properties at the macro level, but also naturally affects the structure at the micro level. For this reason, the microstructures of all products were examined, and the microstructure of sample 1 at 100x magnification is shown in Fig 7., and the martensitic structure is suited to hardfacings resistant to wear by impact, compression, and slight abrasion [43].

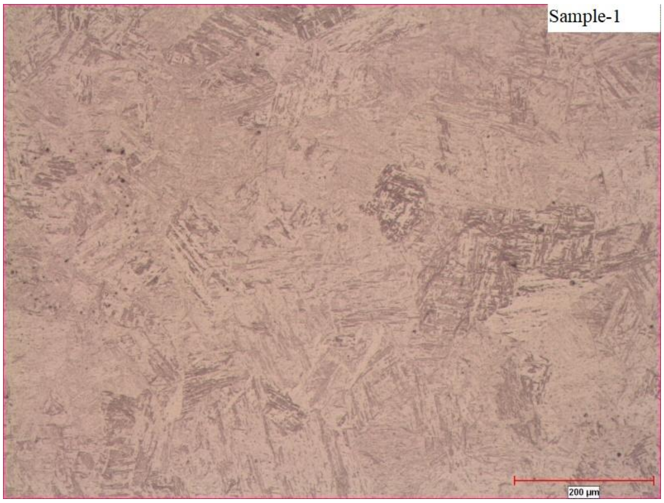

Fig. 7. Microstructure of sample 1.

As seen in Fig. 8., chromium carbides were sparsely distributed in the iron matrix but homogeneously without accumulation. This homogeneous distribution brings a huge advantage by ensuring that the hardness and wear properties of the weld metal are transmitted homogeneously to the construction. This includes also martensitic structure, but carbides are observed more clearly, that makes this sample suited in impact and pressure stress situations, but machining of the weld deposit is available only by grinding [44].

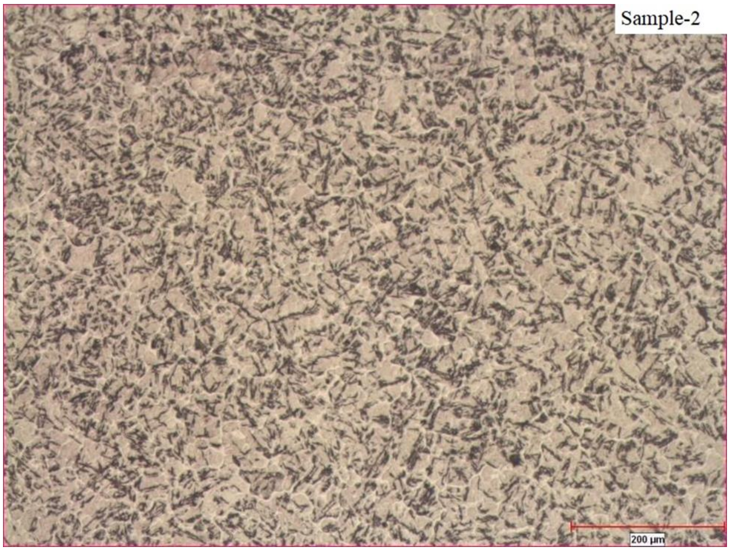

Fig. 8. Microstructure of sample 2.

In Fig. 9., the homogeneous distribution of increasing chromium carbides in the microstructure is clearly detected. It is observed that the chromium carbide density in the grains has increased compared to sample number 1. This increase in the chromium carbide density within the grains is the difference's reason in the hardness values between samples number 1 and 2. The high chromium carbides alloyed hardfacing sample is used for surfacing on parts made of carbon steel, cast steel or Mn-steel, which are subject to grinding wear, such as idlers, digging buckets, digging teeth, ploughshares, mixing wings and conveyor screws [45].

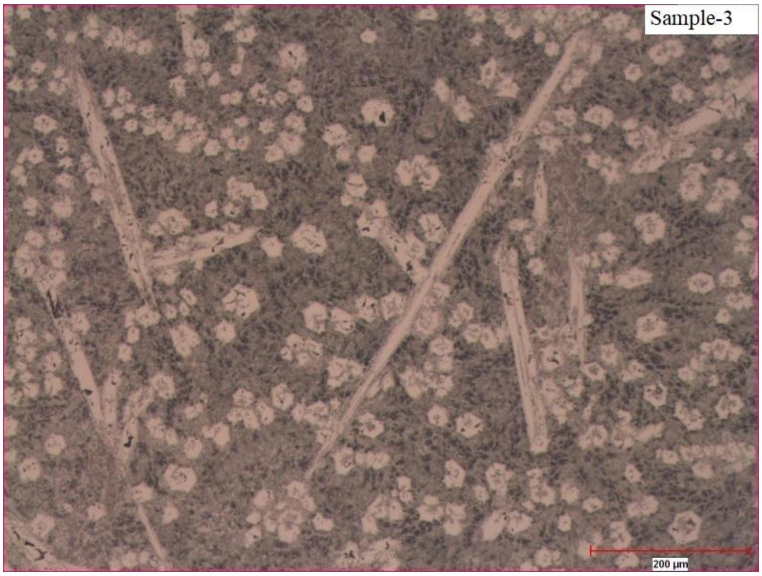

Fig. 9. Microstructure of sample 3.

Graphite formation resulting from increased carbon in the metal matrix in sample number 4 was detected in Fig. 10. The increased amount of carbon did not directly affect the hardness but provided an advantage in wear resistance compared to sample number 3. It is suited for highly wear resistant claddings on parts subject to strong grinding abrasion combined with medium impact, such as conveyor screws, scraper blades, digging teeth, mixer wings, sand pumps [46].

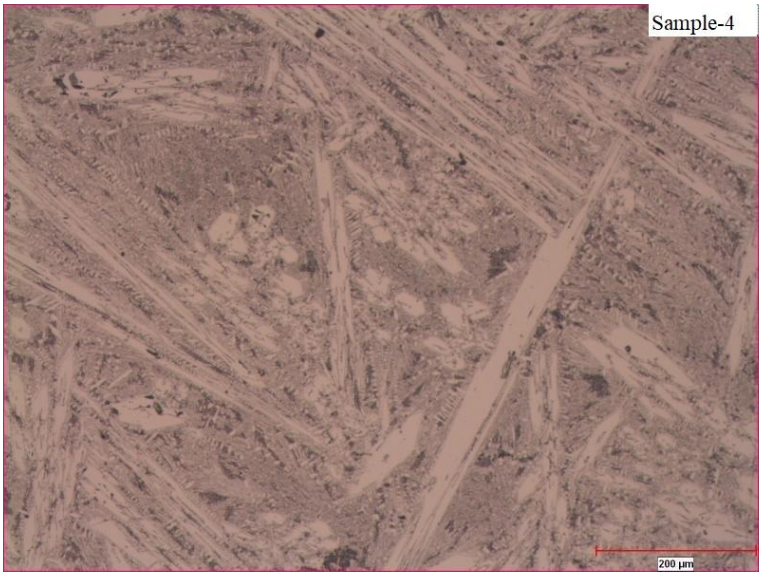

Fig. 10. Microstructure of sample 4.

The increased amount of carbon in sample 5 compared to sample 4 increased the ratio of graphite in the matrix, and the added niobium formed carbides within the grains, creating the eutectic structure. This formation can be seen clearly in the microstructure in Fig. 11.

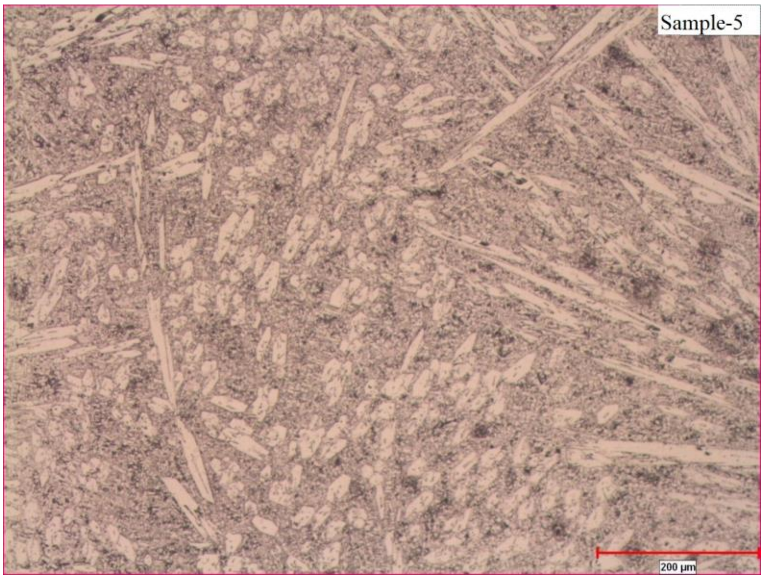

Fig. 11. Microstructure of sample 5.

It was determined that the eutectic phase was formed in sample number 5, resulting from increase in carbon content and the high melting temperature of wolfram added to sample number 4, and this microstructure is shown in Fig. 11. The presence of these structures brings high macro hardness and micro wear resistance. This is suited for highly abrasion resistant claddings on parts subject to extreme sliding mineral abrasion, also at elevated temperatures in the range of 500°C. Elements containing quite high carbides, such as wolfram, cause high abrasion resistance. Main application fields are surfacing on earth moving equipment, working parts in the brick, cement industry or in steel mills for radial breakers and revolving-bar screens of sintering plants [47].

The Fig.12 shows the SEM image comparison of sample 5 before and after the wear test, where small carbides in the metal matrix are visible. In sample 5 compared to other samples, more carbides in the matrix structure and appears to exhibit a more homogeneous distribution. In the SEM image of the same sample, only the abrasive counterpart left the material in fine scratches. The wear marks are not deep, and superficial wear on the material appears to occur.

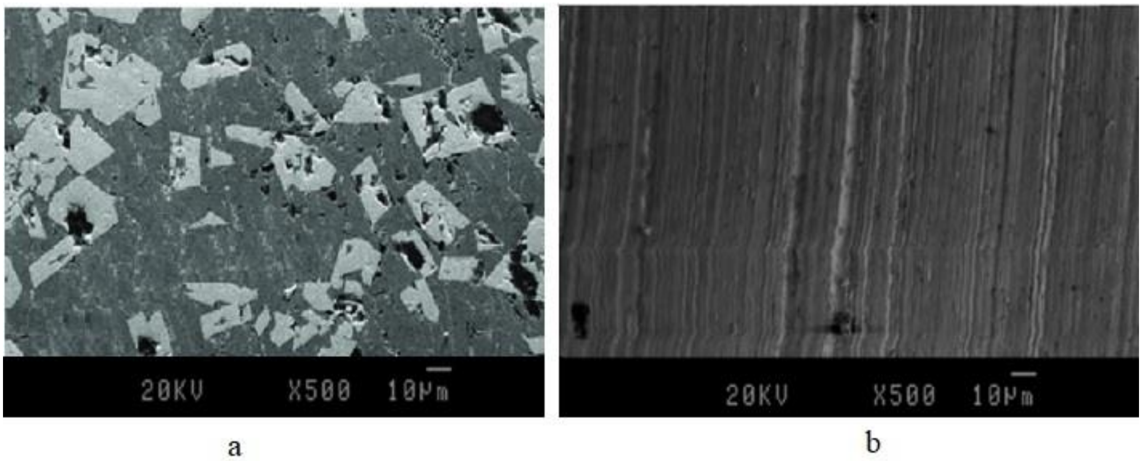

Fig. 12. SEM microstructure of sample 5 before (a) and after (b) wear test.

4. Conclusion

It has become possible to obtain weld fillers with the desired chemical analysis by using the production technique developed with the combination of FCAW and SAW. In this way, an advantageous method has been developed by adjusting the chemical composition homogeneously as desired. The advantage of this process has been clearly observed, especially in refractory metal-based welding fillers due to its high wear resistance. Furthermore, with the increase in the hardness of the samples then their wear resistance also increases, and it has been clearly determined that chemical analyses directly affect the microstructures. While the increasing amount of chromium carbide clearly changed the microstructure, the addition of other refractory metals enabled the formation of eutectic and dendritic structure. Finally, it was determined that the highest hardness and best wear resistance were obtained in the material sample containing dendritic structures in the eutectic phase containing 35% chromium, 7% niobium and 3% wolfram. In conclusion, the problems of low efficiency in FCAW and alloying in SAW were solved by this combination method. In this way, it is possible to prepare recipes that provide the chemical content requested by the end user.

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