# Microstructural Evolution and Mechanical Properties of Mo40/C93200 Bimetal Processed by Compound Casting

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**ABSTRACT**

Compound casting refers to a process that is used to produce bimetals. This study investigates the interface of Mo40/C93200 that is produced by compound casting process. In this research, molten bronze is poured around the steel core, and interaction between liquid and solid creates a diffusion zone and is followed by a transition layer which leads to the creation of a diffused region between the interfaces of metal layers. The results of micro-hardness and macro hardness tests were used to complete the studies. The results of the hardness of the Mo40 alloy revealed that the alloy micro-hardness was almost 308 Vickers which confirms the ferrite-pearlite state of microstructures. The results of metallography revealed that the boundary between steel and bronze alloys due to the difference in electric potential during etching evolved a galvanic cell and one section was formed as the cathode and the other section as the anode. In this situation, steel was corroded and bronze was protected. Also, the results of SEM show that the boundaries between two alloys have an acceptable adhesion and the strength of interface is sufficient.The result of tensile test indicates that the final yield strength was about 800 MPa and the elongation increases by 2%, which is an acceptable value. It is also observed that the failure is a soft defect type and a sufficient connection between steel and bronze is formed.

## 1-Introduction

With increasing industrial needs for metals, conjunction of two metals and making bimetals with optimized physical and mechanical properties has attracted the attention of metallurgy researchers. The industry needs materials that simultaneously provide several features of the desired properties. There are different methods of connecting metals to each other such as friction-turbulent welding [1], explosive welding [2-6], laser welding [7,8] and it is necessary to consider the advantages and disadvantages of each method according to the needs of the industry. The main drawback of the above mentioned methods is the inability to produce bimetals with a complex design or large dimensions. Compound casting is an economical way to produce the bimetals with unlimited geometric shapes and sizes [8]. Compound casting is the pouring of molten metal into or around a solid metal, which necessarily leads to the formation of a diffusion region at the interface of the two metals [9]. In this process, a diffusion region is formed

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between two metals, and subsequently a continuously transition layer leads to the formation of intermetallic layers in the joint of the two metals [10]. Therefore, the first condition of compound casting is to create a healthy connection in the presence of a diffusion zone. Using this method, components with complex connection can be made by casting around the complex specimen. Previously, some researches were carried out using a compound casting method to connect similar and non-similar metals such as steel/cast iron [11], aluminum/silicon [12], aluminum/copper [13], aluminum/aluminum [14], magnesium/magnesium [15], by material scientists. In a research conducted by Hajery et al. [8], a bimetallic bond involving Al/Mg light metals was formed in a compound casting process. The result of this study showed that the bond between aluminum and magnesium is possible only in the melting of magnesium and casting it around the aluminum insert. While aluminum casting around the magnesium insert produced a cavity at the Al/Mg interface, due to the presence of oxide layers at the aluminum and magnesium surface and also due to the soft (semi-solid) interface, which is because of higher thermal expansion coefficient of magnesium than the casting aluminum. The formation of the interface in the process is piercing control and the interface is composed of three different layers. The adjacent layers of aluminum and magnesium are composed of the base metals and $Al_3Mg_2$, as well as the eutectic formation ($Al_{12}Mg_{17}+ \delta$) respectively and also the middle layer which consists of $Al_{12}Mg_{17}$. The maximum and minimum connection thickness is 90µm and 50µm, respectively. The shear strength of the joint depends on the thickness of the interfaces, and varies from 20.2 to 39.9 MPa. In a research by Papis et al. [16], light metal casting was studied. In this study, the casting of magnesium/aluminum, zinc/aluminum, silicon/aluminum and aluminum/pure aluminum was investigated. Scanning electron microscopy and EDS investigations as well as optical micrographs of the interfacial areas revealed their continuously metallic constitution. Diffusion of the alloying elements leads to heat-treatable microstructures in the vicinity of the joining interfaces in Al–Al couples. This permits significant variability of mechanical properties. Cast iron and low-carbon steel composite by casting and hot rolling was produced by Xiong et al. [17]. High chromium cast iron (HCCI) and low-carbon steel (LCS) have been successfully produced as a coat by compound casting and hot rolling, followed by quenching and tempering treatments. The results of micro structural and micro hardness studies after the process express that metallurgical bond between HCCI and LCS is formed and a uniform distribution of alloying elements is observed. After quenching, micro hardness of HCCI increased to HV750 and hardness of HCCI reached HV600-750 after tempering. In a paper by Zare et al. [18], the interface of aluminum/copper bimetal produced by compound casting method was investigated. They found that hardness decreases from the copper to the aluminum side. In a study by Emami et al. [19], conventional and lost foam compound casting of Al/Mg were compared. The results of Vickers micro-hardness tests at the interface zones showed that the hardness of the middle layer increased in comparison to the hardness of the base metals. Using the LFC method reduced the thickness of interface as a result of both lowering the temperature and the speed of melting. In a research by Jiang et al. [20], compound casting process was used to obtain steel and aluminum bimetallic castings. They found that in the case of the coating surface modifier method, the integrity of the interface greatly increased because of the improvement of the incompatibility between steel and aluminum, which indicated a mechanical bonding without a reaction layer, resulting in a limited improvement of the bonding. In a research conducted by Tavassoli et al. [21], the controlling of IMCs layers formation sequence, bond strength and electrical resistance in aluminum/copper bimetal were investigated by compound casting method. It was concluded that the control of the preheating temperature of solid copper was far more influential on the formation, thickness, and type of intermetallic phases than the controlling the melt pouring temperature of aluminum. In an article by Guler et al. [22], fabrication of Al/Mg bimetal compound casting by lost foam technique and liquid-solid process was investigated, and transition zone

and Al/Mg interface were in the focus of their research.
Bimetals are used in a situation where we need the properties of two metals simultaneously. Most of these bimetals are used in places where high corrosion resistance is needed; for example, in turbine blades, chemical transfer pipes, etc. The metal coating prevents corrosion of the base metal. The purpose of this study was to investigate the possibility of binary Mo40/C93200 beryllium alloy in a compound casting method and examine the bonding method in the joint between two alloys. In the same way, the process and equipment used to produce the microstructure, as well as the mechanical properties of the alloy will be discussed. At the end of the discussion on how to connect these two alloys using the results of metallographic tests, tensile test and scanning electron microscopy will be done.

## 2- Research method

In this study, Mo40 steel and C93200 bronze have been used to carry out a compound casting process and the chemical composition analysis of these alloys is shown in Tables 1 and 2.

**Table 1.** Results of the quantumetry for the chemical composition of bronze C93200

| Element | Cu | Sn | Pb | Fe | S | Ni | Sb | Si | Al |
|---|---|---|---|---|---|---|---|---|---|
| %wt. | Balanced | 0.1 | 0.08 | 2.9 | 0.06 | 0.3 | 0.01 | 0.005 | 0.07 |

**Table 2.** Results of the quantumetry for the chemical composition of steel Mo40

| Element | C | Si | P | S | MO | Mn | Cr | Fe |
|---|---|---|---|---|---|---|---|---|
| %wt. | 0.5 | 0.2 | 0.02 | 0.02 | 0.1 | 0.9 | 0.2 | Balanced |

In order to execute the process, the wooden and foam molds were made using an analog device. Also, for the casting process, an under vacuum induction furnace was used. After preparing the raw materials and supplying the necessary equipment for casting, as well as selecting and producing the mold, it is time for prototype molding. To do this, at first, the steel is melted at 1600 ˚C and then poured into the sand mold. Then, at the same time as controlling the temperature of steel, the bronze is melted and molded at about 700˚C around the cast steel and then cooled inside the furnace. After that, the heating treatment is carried out on the sample. Then the sample cools slowly. Fig. 1 shows an example of a casting piece.
To study the microstructure of castingMo40/C93200 composite, "cam scan MV2300" scanning electronic microscope was used. For microstructural analysis, after specimen preparation and machining, polishing operations were executed with sand papers in the range of 80 to 1200, respectively, and finally finished with polishing wool (fig. 2). Finally, the polished piece is placed inside the electron microscope, in the form of line and map for microstructural photography. To execute the tensile test, at first, the samples, according to the ASTM E8 / E8M standard, must be cut in the dimensions shown in Fig. 3 [23]. The samples were cut with a wire cut machine, then tensile tests were carried out using a Zwick/Roell-Z010 tensile test machine at a speed of 1 mm/min, in longitudinal and transverse directions.

An "OLAMPYUS" optical microscope was used for metallographic examination. Macro hardness tests were performed using a macro hardness device of the F-1105 model for metallographic and micro-hardness tests accomplished with the micro-hardness device of the M-400G-GT-G3-G3 model and according to the ASTM E-384-11e1 standard. The load time is 10 seconds and the load is 200 grams for the steel and 50 grams for the bronze samples.


**Fig. 1.** The cast Mo40/C93200 sample

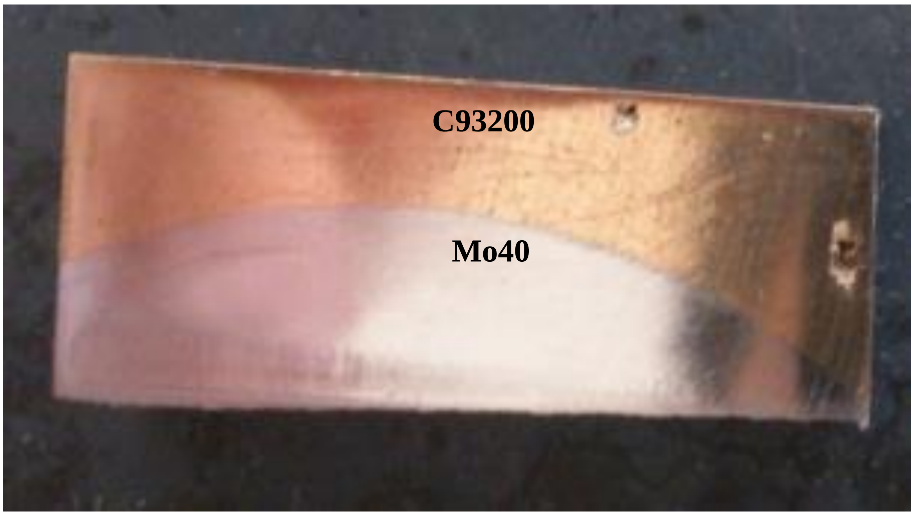
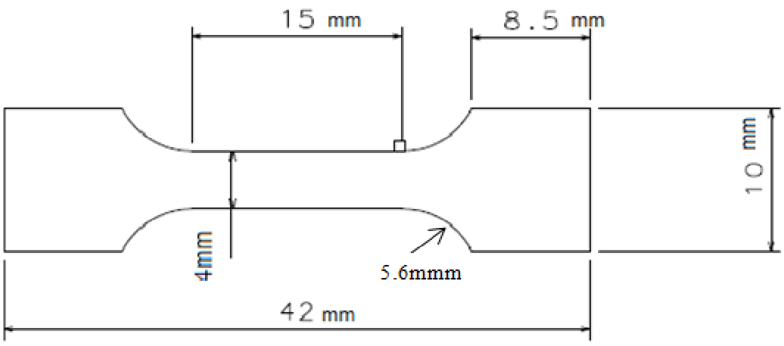



**Fig. 2.** The polished sample




**(a)**

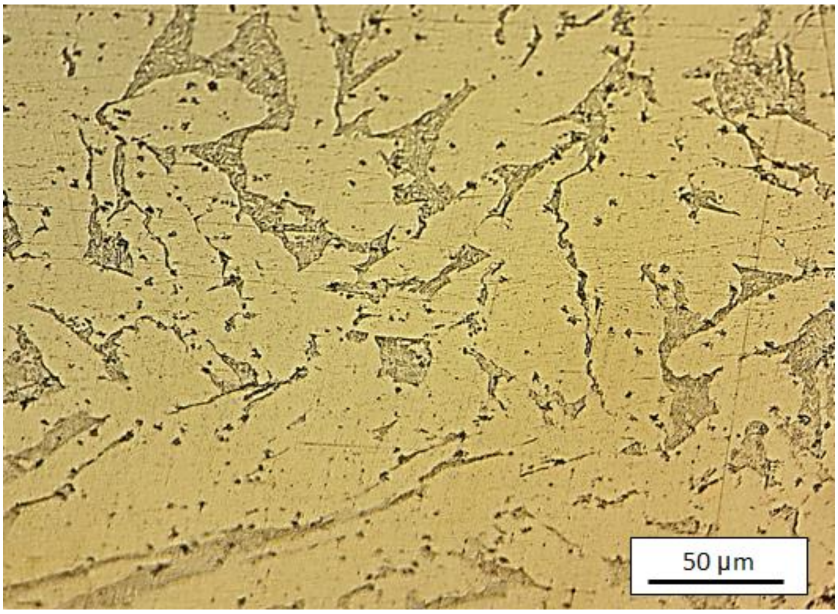

**(b)**

**Fig. 3. (**a) Tensile test sample map [23] (b) wire-cutted specimen for tensile test

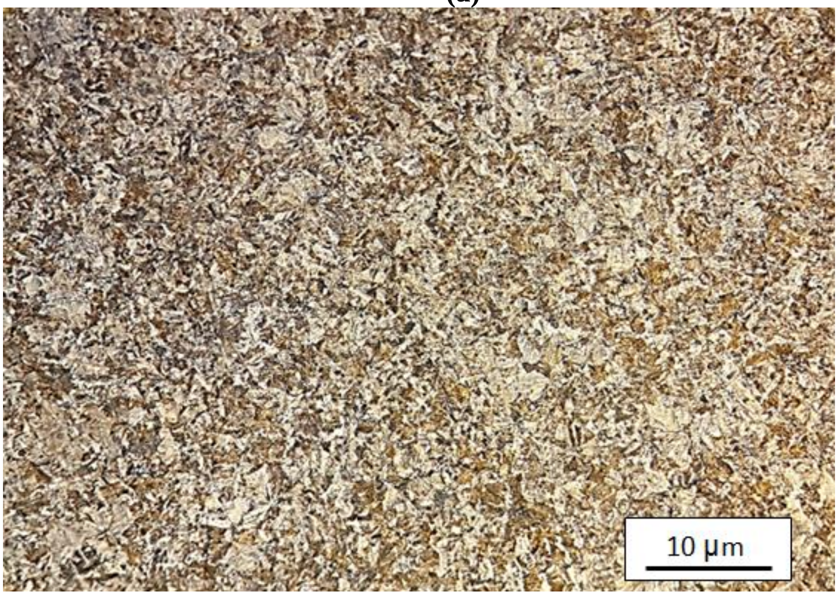
**3. Result and discussion**

The metallographic image of the C93200 alloy is shown in Fig 4a. As it is known, in the microstructure, bronze alpha particles (which are observed in light color as a structure) have grown dendritically and in different directions. The metallographic images of the Mo40 alloy are shown in Fig 4b with 50x magnification. As can be seen, this microstructure consists of pearlite grain with alpha phase and due to its high carbon content, the ratio of ferrite phase to pearlite phase is approximately equal to one. Hence, in this micro structure, the white phase indicates ferrite and the pearlite phase is dark.

According to the TTT diagram of this alloy [24], and considering its chemical composition, the top of ferrite-pearlite is larger and it is possible to obtain this phase at a low cooling rate. But if the cooling rate increases, the cooling line will not cut off the ferrite-pearlite phase and will pass through the bainite phase. Hence, it is more possible to obtain a pearlite-ferrite structure in this alloy.




**(a)**




**(b)**

**Fig. 4.** Metallographic images of samples (a) bronze phosphorus at magnification power of 50x; (b) ferrite pearlitemicrostructure MO40

The results of hardness tests show that the hardness rate of this alloy is about 308 Vickers, which somewhat confirms that the phase of this micro structure is ferrite-pearlite. Fig. 5 shows the microstructure of boundary region of the sample produced by compound casting method. The boundary between steel and bronze in this alloy forms a galvanic cell due to the difference in electrical potential during engraving, resulting in one part being cathode and the other part being the anode. In this case, the steel is corroded and the bronze is protected. As can be seen in this figure, the boundary between these two alloys has an acceptable adhesion. With examination of the interface of these two alloys it can be observed that due to the temperature difference between the bronze casting temperature and surface of the steel part, heterogeneous bronze alpha phase bronze recrystallization begins on the surface and gradually extends to the inside of the alloy. Hence, in the boundary between these two alloys, the alpha phase is formed almost continuously.

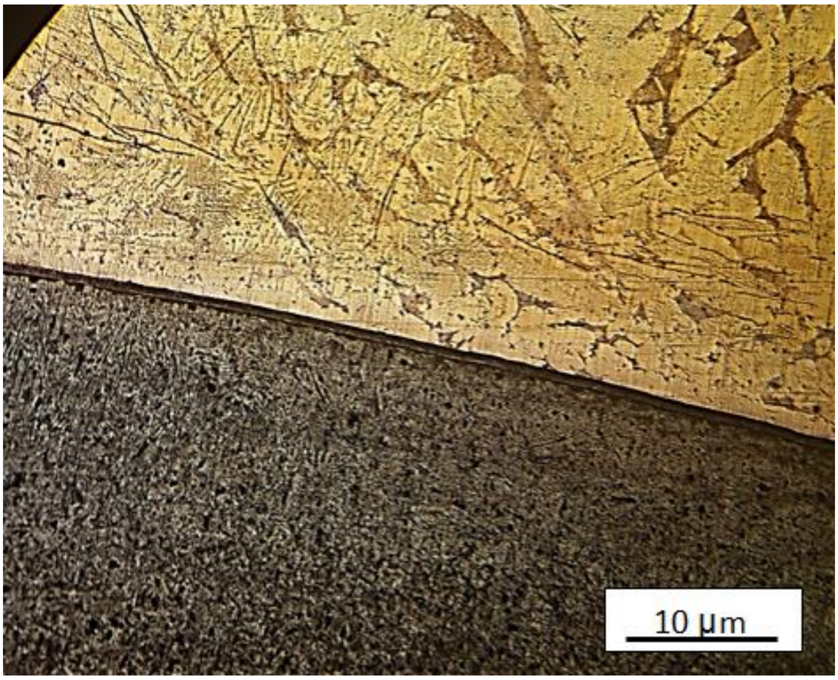



**Fig. 5.** Interface microstructure of Mo40 and C93200

On the other hand, because of the high melting temperature of bronze, the surface temperature of the steel part is increased and austenite is re-created. Hence, in this case, the cooling mode of the middle of the steel is different from the surface, and thus the microstructure of these two parts will be different. Such a difference in micro structure image is clear to see.

The most important parameter in compound casting is adhesion between two metals. In order to examine this factor, several points of the intersection have been considered to provide SEM images. In Fig. 6, two images of different points and different magnitudes (50 times and 100 times) are given as examples. As can be seen, these two metals are continuously bounded to each other and a good conjunction is established between the two metals. In these images, the upper part is related to the bronze alloy and the lower part is related to the Mo40 steel. The image of the Cu atoms distribution, in the form of EDX plate on the interface between the steel and the bronze taken by SEM microscope is shown in Fig. 7a and the Fe atoms distribution image in the intersection is shown in Fig. 7b.

In order to study the mechanical properties of sample produced by the compound casting method, the hardness test is used as an example of mechanical properties. Hence, several different hardness tests are performed on the produced sample and the results are presented in Figs. 8 and 9.

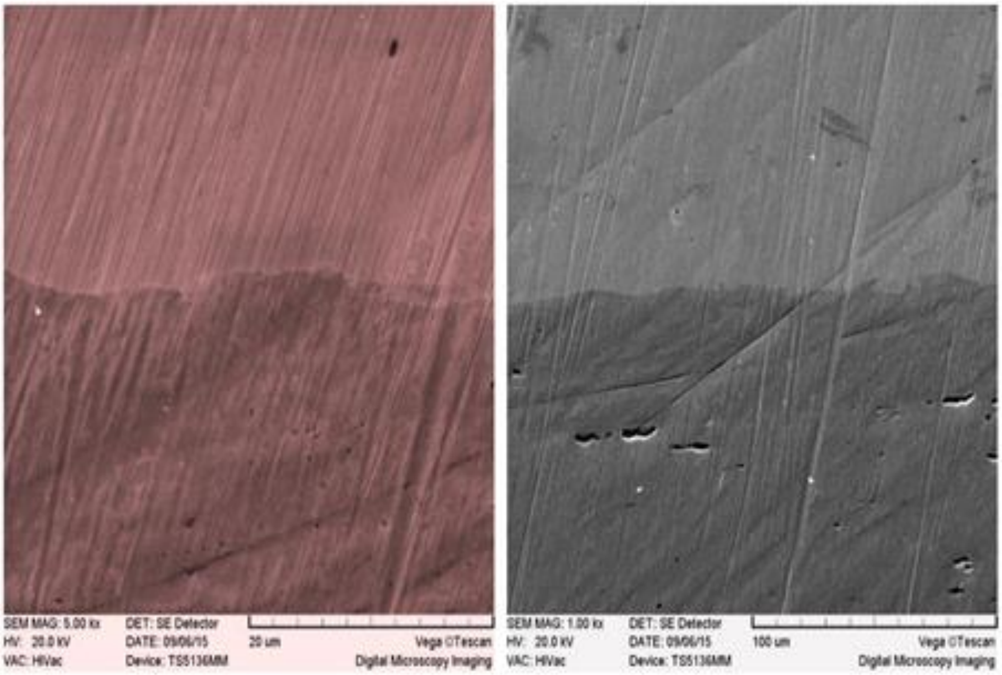
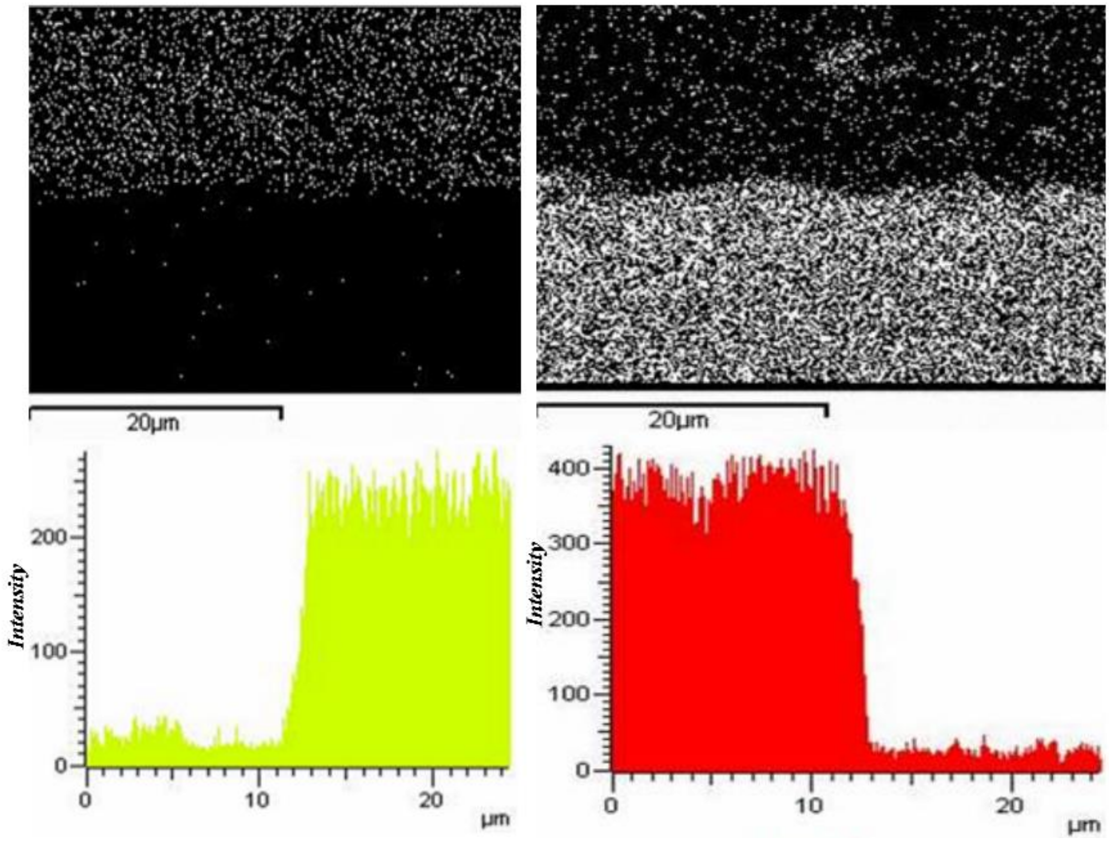



**Fig. 6.** Interface of steel and bronze in the SEM microscopy




**(a)** **(b)**

**Fig. 7.** The image of the distribution of atoms (a) Cu (b) Fe; in the form of a plate EDX at the interface of steel with bronze in a SEM microscope

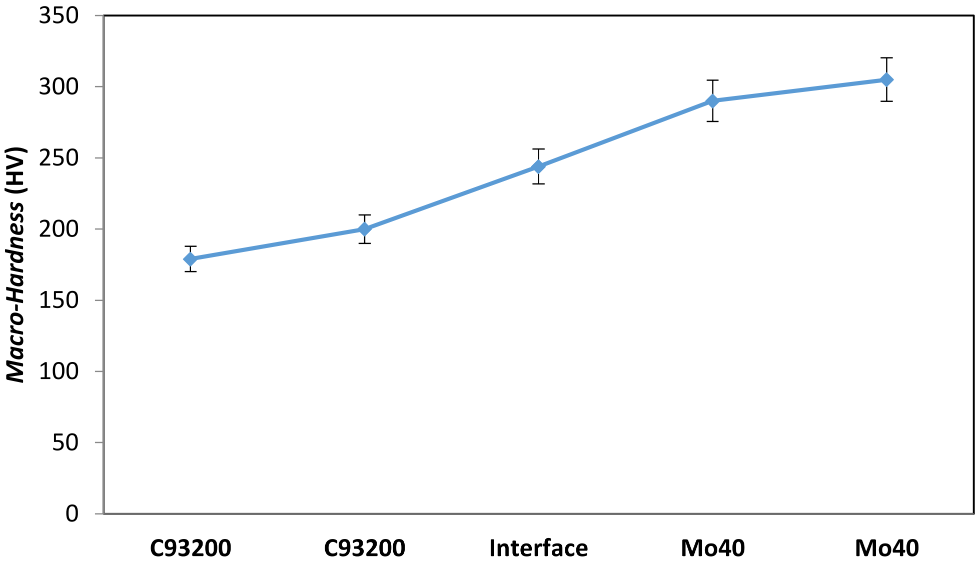



**Fig. 8.** The results of testing the macro-hardening

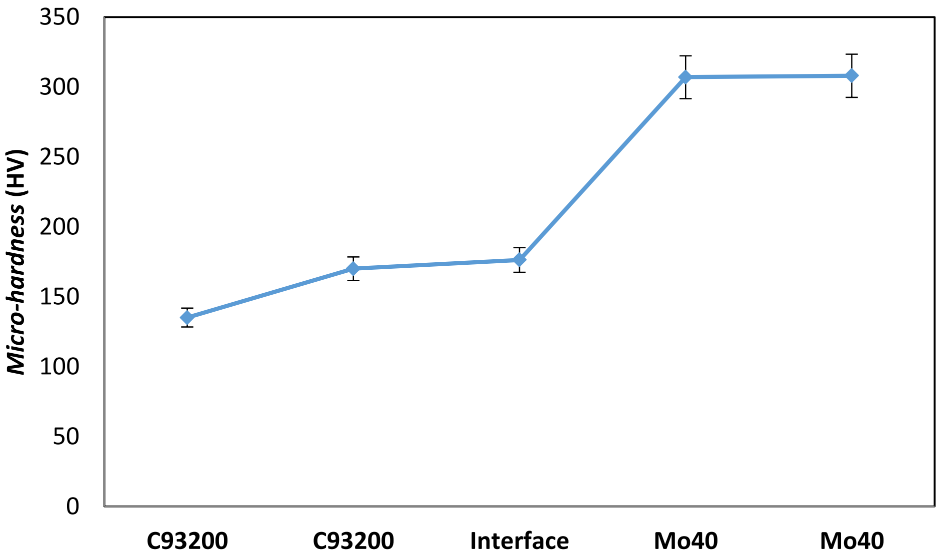
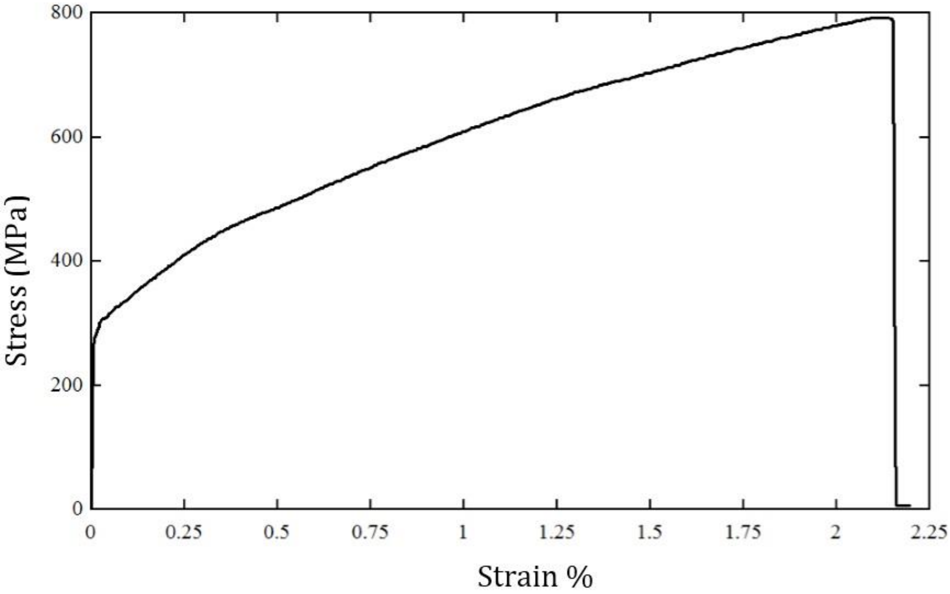


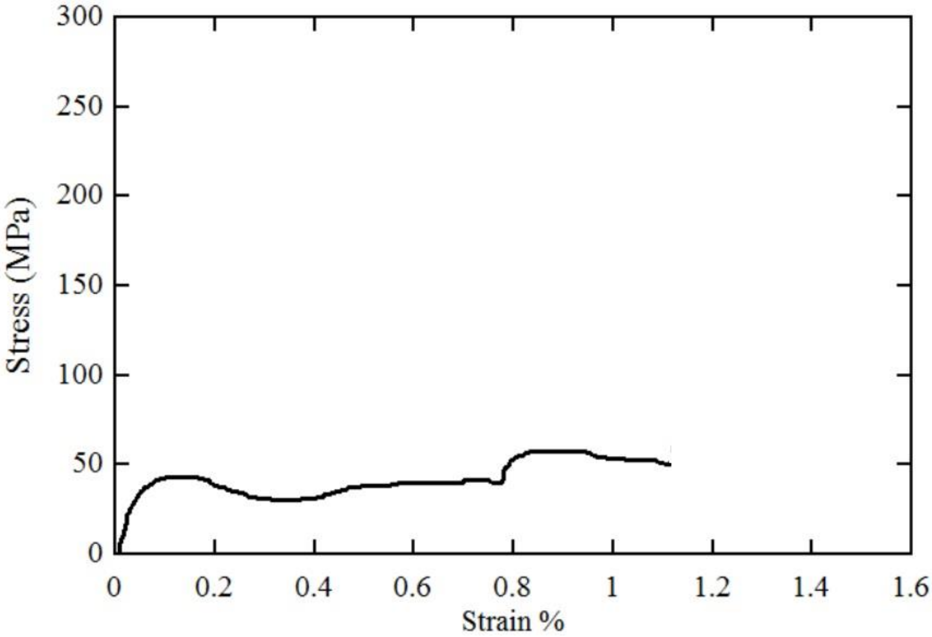

**Fig. 9.** The results of testing the micro-hardening

As the diagram shows, with moving from the bronze side toward the steel part the sample hardness increases about 36%. Moving from intersection to steel in distant parts of the intersection, the sample hardness reaches to about 305 Vickers. This hardness is equal to the hardness of pearlite-ferrite steel and the results are consistent with the metallographic images obtained from the specimen.

Another test to examine the mechanical properties is the tensile test. In this test, the sample is subjected to an increasing tensile force to rupture. Usually, the results of this test are presented in the form of stress-strain engineering diagrams. Fig. 10a shows the result of tensile test in the form of stress-strain diagram of transverse section and Fig. 10b shows stress-strain diagram of longitudinal section.




**(a)**




**(b)**

**Fig. 10.** Stress and strain diagram of (a) transverse section, (b) longitudinal section

As can be seen in Fig. 10, the tensile strength is about 800 MPa, and the percentage of elongation increase in length is 2%, which is an acceptable value. It is also observed at the breakdown of the tensile test specimen (shown in Fig. 11) that the failure is a soft defect type and a sufficient connection between steel and bronze is formed.

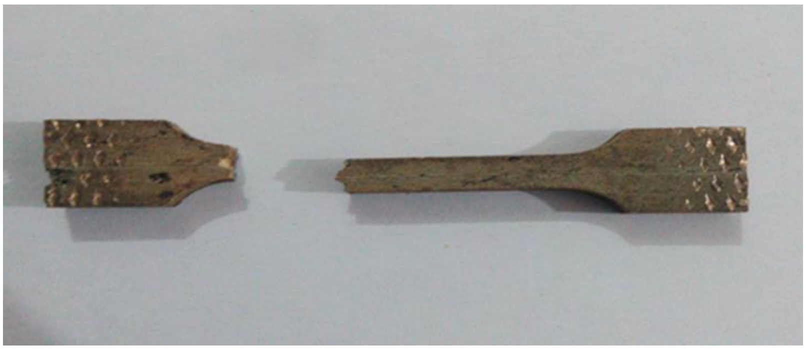


**Fig. 11.** One of the samples after the tensile test

## 4- Conclusions

In this study, the prototype of the Mo40/C93200 bimetal was successfully produced by compound casting, which has not been reported until today to study the compound casting process to produce the Mo40/C93200 bimetal sample. The result of micro structural studies and mechanical properties of this alloy are briefly presented as follows:

1. The results of hardness test indicated that the hardness rate of the C93200 alloy is about 176.3 Vickers.
2. The metallographic image of the C93200 alloy showed that bronze alpha grains (which are observed in white color in the structure) have dendritically grown in different directions. The metallographic image of the Mo40 alloy showed that this microstructure consists of pearlite grains with alpha phase and due to high carbon content, the ratio of the ferrite phase to the pearlite phase is approximately equal to one.
3. The results of the Mo40 alloy hardness test showed that the hardness of this alloy was about 308 Vickers, which somewhat confirms that the micro structure is ferrite-pearlite.
4. The metallographic results showed that the boundary between steel and bronze in this alloy forms a galvanic cell due to the difference in electrical potential during engraving, resulting in one part being the cathode and another part being the anode. In this case, the steel is corroded and the bronze is protected. The boundary between these two alloys has an acceptable adhesion and sufficient strength.
5. With moving from the bronze side toward the steel part the sample hardness increases about 36%. Moving from intersection to steel in distant parts of the intersection, the sample hardness reaches to about 305 Vickers. This hardness is equal to the hardness of pearlite-ferrite steel and the results are consistent with the metallographic images obtained from the specimen.
6. The result of tensile test indicates that the tensile strength was about 800 MPa and the elongation increases by 2%. It is also observed that the failure is a soft defect type and a sufficient connection between steel and bronze is formed.

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