Microstructure, Phases Transformation and Hardness of Sintered Fe-Mo-Si Alloys Prepared by Powder Metallurgy Technique

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Abstract. The transition-metal silicides are attractive materials for high-temperature applications due to its mechanical properties and resistance to oxidation-corrosion at high temperature. In this paper, the development of silicides alloy based on ferromolybdenum (Fe-Mo) and ferrosilicon (Fe-Si) lumps as starting materials were discussed. The Fe-Mo and Fe-Si lumps were manually crushed into small granules. Afterwards, the small granule of Fe-Mo and Fe-Si were separately milled into fine powder and were then mixed by using Wet-High Energy Milling technique for 4h and 2h, respectively. The powders were compacted and then sintered at 1200°C for 2h in a vacuum. The microstructure of sintered alloys was observed by using SEM-EDX. Meanwhile, the formation of silicides phases was identified by using XRD. The Vickers hardness testing was performed to measure the hardness of sintered alloys. According to the results, the MoSi₂ phase was detected in the (Fe-Si)-30(Fe-Mo) alloy. When the Fe-Si concentration was decreased to 40 % at, the FeMoSi phase was formed. The detail results of this study are presented and discussed in this paper.

Keywords: Fe-Mo-Si alloys; powder metallurgy; sintering; microstructure; hardness

1. Introduction
Transition-metal silicides constitute intermetallic compounds of inorganic solids have attractive physical and technical properties, such as high melting temperature (much greater than 2000°C), good oxidation and corrosion resistance, relatively low density, high electrical conductivity, high strength and excellent creep behavior at elevated temperature [1, 2]. Therefore, these materials are widely used in the different and modern engineering applications as gas turbines, combustion chamber components, missile nozzles, diesel engine glows plugs and industrial gas burners and furnaces [3].

One of the attractive transition-metal silicide materials is MoSi₂. It was considered as a candidate material to substitute nickel-based super-alloys for aircraft applications [4]. This is because MoSi₂ have moderate density and high melting-point temperature, namely 6.24 g/cm³ and 2050°C, respectively [5]. Si element in the alloys plays a role in promoting the formation of glassy protective silica (SiO₂) scale at high temperatures. This compound will protect the alloys from the oxidizing and aggressive environments. Meanwhile, Mo element content in the alloys can prevent embrittlement
caused by Oxygen and Nitrogen [1]. Moreover, MoSi$_2$ has a good ductility and toughness, resistance to corrosion and fatigue crack growth at high-temperature that is better than the nickel-based super-alloy [4]. In the previous study, MoSi$_2$ was successfully applied as a coating material on the molybdenum-based substrate using a thermal spray method [6]. On the other hand, the manufacturing MoSi$_2$ has also been successfully created by the self-propagating high-temperature service (SHS). The other processing techniques, often with two or more combination methods, including arc-melting and casting, mechanical alloying, hot pressing, reaction sintering, spark plasma sintering, combustion synthesis, and solid-state displacement reactions were used [7].

The unique of other intermetallic silicide compounds is iron disilicides (FeSi$_2$). In contrast to the MoSi$_2$, FeSi$_2$ is generally used for high-temperature electrical applications, such as thermoelectric, semiconductor and magnetic materials [8, 9]. Furthermore, the FeSi$_2$ compound have also high resistance to oxidation, low vapor pressure, lack of toxicity, lower resistivity and a constituent element that is widely available in the Earth [9]. In the previous study, the nanostructure of FeSi$_2$ material was successfully synthesized using Czochralski growth and chemical vapor transport method, powder metallurgy and a rapid eco-process [9-11].

Up to now, most researches on FeSi$_2$, MoSi$_2$ and other types of alloys still utilize high purity powder as the starting material to synthesis the aforesaid alloys. Though, the purity powder is quite expensive. Therefore, from the view point of material cost, the exploration of other sources of material is needed to fabricate silicides alloy. Ferro-lumps materials are considerably low cost material compared to high purity powder that has been commonly used in steel fabrication. Previously, our groups have utilized the lumps materials, such as ferrochrome (Fe-Cr), ferroboron (Fe-B) and ferrosilicon (Fe-Si) lumps [12-14] for coating applications. But there is no report in silicides alloys preparation using lumps materials as the starting materials.

A powder metallurgy technique consisting of powder mixing, compaction and sintering was widely used for preparing the compact alloys. Firstly, two or more kinds of powders were alloyed using a mechanical milling, either under wet or dry milling condition. During MA, the collision of balls mill and powder can reduce the powder particle size from micro to nano. It can also be used to synthesis new or amorphous phases. With the small particle size, it is expected that the powder compaction produces more dense, smooth and uniform structure. In order to avoid the sample oxidation, sintering process can be conducted in a vacuum or inert atmosphere [15].

In this study, Fe-Mo-Si alloys were developed using a powder metallurgy method using ferromolybdenum (Fe-Mo) and ferrosilicon (Fe-Si) lumps as the starting materials.

2. Experimental method

In the present study, the Fe-Mo-Si alloys were synthesized from Fe-Si and Fe-Mo lumps with the chemical composition as presented in Table 1 and 2, respectively. The raw materials were manually crushed into small granules. Afterwards, the small granule of Fe-Mo and Fe-Si were separately milled and then mixed by using Wet-High Energy Milling technique for 4h and 2h, respectively at oscillation frequency of about 700/min in order to obtain a fine powder. Based on the broadening of the XRD peaks, it was known that the crystallite size of Fe-Si and Fe-Mo powder are less than 360nm.

| Table 1. Chemical composition of Ferrosilicon (Fe-Si) lumps (at%). |
| Fe | Si | Al |
|---|---|---|
| 13.7 | 85.12 | 1.18 |

| Table 2. Chemical composition of Ferromolybdenum (Fe-Mo) lumps (at%). |
| Fe | Mo | Si | Cu | P | S | C |
|---|---|---|---|---|---|---|
| 49.14 | 45.45 | 3.88 | 0.57 | 0.12 | 0.23 | 0.61 |
The Fe-Mo-Si alloys preparation procedures were carried out according to the following steps. Firstly, the various compositions of Fe-Si and Fe-Mo powders as presented in Table 3 were mixed in the 70ml steel vial for 2h using Wet-high Energy milling technique with the ball mill (a diameter of around 5mm) and powder ratio of 5:1. Secondly, 1g of mixed powder was put in a diameter of 1cm of steel dies and compacted with a pressure of about 7 metric-tons for 5 minutes. The powder compaction produces of a pellet sample with a diameter of about 1cm and a thickness of around 0.3 cm. Then, the alloys were sintered in an alumina tube furnace at 1200°C for 2 h and vacuum atmosphere. The sample heating rate was 20°C/min from room temperature to 1200°C. The sintered alloys were polished using SiC papers from #500 until #1500 grades.

Table 3. The various composition of Fe-Mo-Si powder (at%).

| Samples | Fe-Si  | Fe-Mo  |
|---------|-------|-------|
| 1       | 100   | -     |
| 2       | 70    | 30    |
| 3       | 40    | 60    |
| 4       | -     | 100   |

For the density measurement, an Archimedes’s principles were applied. The mass measurement was carried out using an electronic balance and calculated using the following formula

\[ \rho = \frac{A - B}{A - R} \times \rho_o \]  

Where, \( \rho \) is a density of sample (g/cm³), \( A \) is mass of sample in air (g), \( B \) is mass of sample in liquid (g) and \( \rho_o \) is a density of liquid at a certain temperature (g/cm³). In this study, aquades was used as immersing medium and measured at 30°C.

The microstructure of sintered alloys was observed by using Scanning Electron Microscope equipped with Energy Dispersive X-ray spectrometer (SEM Hitachi SU3500-EDX Horiba). The formation of silicides phases of the sintered alloys was identified by using X-ray Diffractometer (XRD SmartLab Rigaku) with Cu Kα radiation at 40kV; 30mA. The hardness of sintered alloys was measured by micro-Vickers hardness tester (Leco Microhardness Tester LM 100AT). The sample indentation was carried out using 500kgf in load for 15s.

3. Results and discussion

The obtained results in the development of Fe-Mo-Si alloys using Fe-Mo and Fe-Si lumps as starting materials can be explained as follows:

3.1 Phase composition of the Fe-Mo-Si alloys

Fig. 1 shows the X-ray diffraction patterns of Fe-Mo-Si alloys sintered at 1200°C. The results reveal that the formation of intermetallic silicides phases is depended on the alloy composition. The 100(Fe-Si) alloy is composed of Si and FeSi₂ phases (Fig. 1a). The present of Si phase is in good agreement with Fe-Si binary phase diagram which shows that the Si phase appears, if the Si content is higher than 65 at% [16]. With the decrease of Fe-Si content in the alloy, instead of FeMo phase, the new phases as MoSi₂ and FeSi are found in the (Fe-Si)-30(Fe-Mo) alloy as shown in Fig. 1b. The absence of Si phase in this alloy suggests that Fe and Mo elements were reacted with Si to form MoSi₂ and FeSi phases, according to the following reaction:

\[ Fe + Si \rightarrow FeSi \]
\[ Mo + 2Si \rightarrow MoSi_2 \]
It can be seen that the Gibbs free energy formation of both reactions is negative. This infers that the above reaction is liable to occur. In addition, it is interesting to note that the diffraction peaks of FeSi$_2$ phase is not observed and the MoSi$_2$ phase was detected as the main phase in the (Fe-Si)-30(Fe-Mo) alloy. Accordingly, it is reasonable to assume that the MoSi$_2$ and FeSi phases formation may also proceed through the reaction below:

$$FeSi_2 + Mo + Si \rightarrow MoSi_2 + FeSi \quad \Delta G_{1200^\circ C} = -126,32 \text{ kJ/mol} \quad (4)$$

The Gibbs energy value of reaction 2-4 is calculated based on the entropy and enthalpy values obtained from literature data [17]. In contrast, the formed phase in the (Fe-Si)-60(Fe-Mo) alloy is totally different compared to that of 100(Fe-Si) and (Fe-Si)-30(Fe-Mo) alloys. The FeMoSi phase was detected as the main constituent of the alloy (see Fig. 1c). This evidence suggests that the lump elements was completely reacted, forming FeMoSi phase at sintering temperature of 1200°C.

$$(Fe - Si) + (Fe - Mo) \rightarrow FeMoSi \quad \text{at } 1200^\circ C \quad (5)$$

Meanwhile, the 100(Fe-Mo) alloy is composed mainly of FeMo and Fe$_2$Mo$_3$ phases (Fig. 1d). As shown in the Experiment, the Fe-Mo lump composition contains a small concentration of Si. However, the silicides formation could not be observed. This is due to the low content of Si (around < 2 at%) in Fe-Mo lumps, as shown in Table. 1. According to Fe-Si and Si-Mo binary phases, Si element doesn’t go through solubility to Fe or Mo element to form intermetallic phase when the Si content is below than 2 at% [16, 18]. Other important results that can be seen from XRD patterns in Fig. 1 are the increase of background noise at diffraction angle of around 20° to 30° in the 100(Fe-Si), (Fe-Si)-60(Fe-Mo), and 100(Fe-Mo) alloys. That is a typical reflection of amorphous phases [19, 20].
Due to the high content of Si and Mo, probably the amorphous Si and/or Mo oxides are formed in the sintered alloys.

3.2 Surface microstructure of Fe-Mo-Si alloys

In order to confirm the XRD results, the surface morphology of sintered alloys was studied using Scanning Electron Microscope (SEM) equipped with Energy Dispersive X-ray Spectrometer (EDX). The BSE comp mode of SEM images of Fe-Mo-Si alloys sintered at 1200°C for 2 h are presented in Fig. 2.

It can be seen that the alloy composition affects the typical microstructure of sintered alloys. Some areas with different contras and brightness associated with phase structure different can be observed in the Fe-Mo-Si alloys, corroborating the results of XRD Analysis. For the 100(Fe-Si) alloy, the microstructure consists of two distinguished areas: gray and dark areas. According to the results of EDX semi-quantitative analysis, the gray area of point 1 and dark gray area of point 2 are composed of (26 at % Fe, 66 at % Si) and (1.48 at % Fe, 95.35 at % Si), respectively. The Fe and Si atomic ratio of gray area is near to that of FeSi$_2$. The dark area is Si-rich which is believed to be Si phase as detected by XRD analysis (Fig. 1a).

On the contrary, the rough microstructure is seen in the (Fe-Si)-30(Fe-Mo) alloys. There are three types of microstructure in this alloy, namely light (point 3), gray (point 4) and black areas (point 5), which are composed of (29.09 at % Fe, 26.06 at % Mo, 49.85 at % Si), (45.10 at % Fe, 1.09 at % Mo, 53.80 at % Si), and (13.97 at% Fe, 7.04 at % Mo, 79.00 at % Si), respectively. Based on the aforesaid atomic ratio, the light area is suspected to be MoSi$_2$ and gray area is believed to be FeSi. While the dark area is rich in Si, composing mainly of Si phase. It can be seem that the fraction of Si phase area is remarkably decreased compared to that of in 100(Fe-Si) alloy.

As the Fe-Mo content in the alloy increases to 60%, the sintered alloys have a smoothest, dense and more uniform microstructure compared to the other alloy compositions. From the BSE comp image as shown in Fig. 2c, two different areas can be observed: gray area matrix and black precipitates. The result of EDX point analysis of point 7 in Figure. 2c indicates that the matrix is composed of 36.37 at % Fe, 29.75 at % Mo, 24.95 at % Si, and some amount of O, suspected to be FeMoSi phase, as indicated by XRD analysis. Meanwhile, the black precipitates as seen in point 6 of Figure. 2c, contains 11.46 at % Fe, 5.42 at % Mo, 19.42 at % Si, and 63 at % O which should be amorphous SiO$_2$ as detected by XRD measurement (see Fig. 1c).

In the 100(Fe-Mo) alloys, the microstructure presents the matrix marked by gray region (point 8). Based on the result of EDX point analysis, the gray region is consisted of 49.26 % Fe, 48.57 % Mo, and 2.17 % Si (in at%) which is probably composed of FeMo and Fe$_3$Mo phases in the XRD analysis. The fine pores seem to be found at the grain boundaries. This could be related to not fully sinter of the samples. Based on the results as presented in Fig. 2, the different in microstructure of the Fe-Si alloys with the increase of Fe-Mo content might be strongly affected by solubility of Mo in the Fe-Si phase.

3.3 Density and Vickers hardness of Fe-Mo-Si alloys

The density of Fe-Mo-Si alloys sintered at 1200°C for 2 h is presented in Figure. 3. Table 4 shows the literature data of density and hardness of constructed phases of sintered alloys. According to Fig. 3, the density of the alloys containing 0, 30, 60 and 100(Fe-Mo) is 3.43; 5.75; 6.82; and 8.18, respectively. Evidently, the density of the Fe-Mo-Si alloys increases almost linearly with the decrease of Si content. These results are in a good agreement with the results of a previous study [21]. In comparison to the literature data as shown in Table 4, the results of density measurement strongly suggest that the phase fraction affects the final end density of the alloy.
Figure 2. BSE comp images of (a) 100(Fe-Si), (b) (Fe-Si)-30(Fe-Mo), (c) (Fe-Si)-60(Fe-Mo), and (d) 100(Fe-Mo) sintered alloy.

Figure 3. Density of sintered Fe-Mo-Si alloys at 1200°C for 2 h.
Table 4. Density and hardness of Fe-Mo-Si phases.

| No. | Phases | Density (g/cm³) | References | Hardness (Hv) | References |
|-----|--------|----------------|------------|---------------|------------|
| 1   | Si     | 2.328          | [22]       | 560           | [26]       |
| 2   | FeSi₂  | 4.930          | [23]       | 572.4         | [26]       |
| 3   | FeSi   | 5.100          | [24]       | 936           | [26]       |
| 4   | MoSi₂  | 6.240          | [5]        | 876.92        | [27]       |
| 5   | FeMoSi | Not available  | -          | Not available | -          |
| 6   | FeMo   | 9.000          | [25]       | 931.98        | [28]       |
| 7   | Fe₃Mo  | Not available  | -          | Not available | -          |

Fig. 4 show the Vickers hardness of Fe-Mo-Si alloys sintered at 1200°C. The hardness value as presented in Fig. 4 is an average value of 5 times measurement which carried out randomly in the samples.

Figure 4. Vickers hardness of the sintered Fe-Mo-Si alloys at 1200°C for 2 h.

The obtained results show that the hardness of the samples is varied with the decrease of Si content in the alloy. For 100(Fe-Si) and 100(Fe-Mo) alloys, the measured hardness is 251.174 HV and 176.018 HV, respectively. While the hardness of (Fe-Si)-30(Fe-Mo) and (Fe-Si)-60(Fe-Mo) alloys is about 121.787 HV and 1037.934 HV, respectively. It can be seen that the hardness of (Fe-Si)-60(Fe-Mo) alloy is remarkably high compared to the other composition. In General, the material hardness was affected by microstructure and the phase composition of the alloys. Accordingly, a dense and relatively homogeneity microstructure of (Fe-Si)-60(Fe-Mo) alloy increases the hardness value of the alloy. Furthermore, the presence of ceramic SiO₂ also increases the hardness of this composition. The present results are in good agreement with the results of a previous study [12] which found that more homogeneous and denser structure have the higher hardness. On the contrary, the rough microstructure of (FeSi)-30(FeMo) alloy leads to the lowest hardness value among all alloy composition. It is important to note that the hardness of 100(Fe-Si), 30(Fe-Mo) and 100(Fe-Mo) is
smaller compared to the hardness of Si, FeSi, FeSi$_2$, MoSi$_2$ and FeMo as shown in Table 4. This indicates that the aforesaid alloys seem to be not fully sintered.

4. Conclusions
The Fe-Mo-Si alloys are successfully synthesized by powder metallurgy technique using Fe-Si and Fe-Mo lumps as starting materials at sintering temperature of 1200°C. The phase formation and surface microstructure of sintered Fe-Mo-Si alloys are depended on the alloy composition. The (Fe-Si)-60(Fe-Mo) alloy exhibits more homogenous and dense microstructure compared to the other composition, leading to the highest sample hardness.

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References
[1] F. Chu, D. J. Thoma, K. J. McClellan, and P. Peralta, "Mo$_5$Si$_3$ single crystal : physical properties and mechanical behaviour," Journal of Materials Science and Engineering, A26, 1999
[2] P. S. Tantri, A. K. Bhattacharya, and S. K. Ramasesha, "Synthesis and properties of MoSi$_2$ based engineering ceramics," Proc. Indian Acad. Sci. (Chem. Sci), vol.113, pp. 633-649, Oct. – Dec. 2001
[3] Z. Yao, J. Stiglich, and T. S. Sudarshan, "Molybdenum silicide based materials and their properties," Journal of Materials Engineering and Performance, vol. 8 (3), 291-304, Jun. 1999
[4] M. C. Kushan, Y. Uzunonat, S. C. Uzgur and F. Diltemiz, "Potential of MoSi$_2$-Si$_3$N$_4$ composite for aircraft gas turbine engines," in Recent Advances in Aircraft Technology, Dr. Ramesh Agarwal (Ed.), ISBN: 978-51-0150-5, InTech, 2012, 98-116.
[5] G. Ouyang, P. K. Ray, M. J. Kramer, and M. Akinc, "Pressureless sintering of Mo-Si-B alloys with Fe additive," Journal of Materials Engineering and Performance, vol. 26 (5), 2417, May. 2017
[6] S. Weis, T. Uhlig, G. Wagner, T. Lampke, W. Bauer and A. Moldenhauer, "High-temperature corrosion and radiation characteristics of thermal sprayed molybdenum disilicide-based coatings," IOP Conf. Series: Materials Sciences and Engineering, vol. 118, 1-7. 2016
[7] C. –L. Yeh, and J. –A. Peng,"Combustion synthesis of MoSi$_2$-Al$_2$O$_3$ composites from thermite-based reagents," Metals, vol. 6, 235, 2016
[8] H. S. Kim, W. Liu, G. Chen, C. –W. Che, and Z. Ren, "Relationship between thermoelectric figure of merit and energy conversion efficiency," Proc. The National Acad. Sci. United States of America, vol. 112,8205-8210, Jul. 2015
[9] C. Kloc, E. Arushanov, M. Wendl, H. Hohl, U. Malang and E. Bucher," Preparation and properties of FeSi, α-FeSi, and β-FeSi single crystals, " Journal of Alloys and Compounds, vol. 219, 93-96, 1995
[10] H. Inoue, T. Kobayashi, M. Kato, and S. Yoneda," A low-cost production method of FeSi$_2$ powder generation thermoelectric modules, " Journal of Electronics Materials, Dec. 2015
[11] M. Shihuya, M. Kawata, Y. Shinohara, and M. Ohyanagi," Eco-fabrication process and thermoelectric properties of β-FeSi$_2$, " Trans. Mat. Res. Soc. Japan, vol. 40(3), 219-222, 2015
[12] Ciswandi, D. Aryanto, Irmaniar, A. Tjahjono, and T. Sudiro, " The effect of annealing on structure and hardness of (Fe-Cr)-50 at.% Al coatings synthesized by mechanical alloying," AIP Conf. Proc. Series1964, 020005-1-020005-7, 2018
[13] R. Y. Sundawa, D. Aryanto, A. S. Wismogroho, and T. Sudiro," Microstructure and phase composition of Fe-B-Al coatings on low carbon steel prepared by using mechanical alloying technique," IOP Conf. Series : Journal of Physics: Conf. Series 817, 2017
[14] D. Aryanto and T. Sudiro, "Preparation of ferrosilicon-aluminium coating using mechanical alloying technique: study of thermal annealing on their structural characteristics," *Journal of Surface and Coatings Technology*, vol. 337, 35-43, Dec. 2018

[15] M. J. B. Suleiman, A. M. A. B. Ahmad, R. B. Ibrahim, M. B. Mohamad, N. B. A. Kasim, M. R. B. D. A. Kadir, S. B. Muhamad, Y. Itoh, K. Hanada, and T. Shimizu, "Effect of sintering conditions on mechanical properties and microstructure of Titanium alloy produced by metal injection moulding (MIM)," *Advanced Materials Research*, vol. 686, pp. 164-169, Mar. 2013

[16] I. Ohnuma, S. Abe, S. Shimenouchi, T. Omori, R. Kainuma, and K. Ishida, "Experimental and thermodynamic studies of the Fe-Si binary system," *ISIJ International*, vol. 52, pp. 540-548, Dec. 2011

[17] Ihsan Barin. *Thermochemical Data of Pure Substances*, Third ed. Reading, VCH Verlagsgesellschaft mbH, Weinheim, 1995

[18] B. Paul, S. P. Chakraborty, J. Kishor, I. G. Sharma and A. K. Suri."Studies on synthesis and characterization of Mo based in situ composite by silicothermy co-reduction process, " *Metallurgical and Materials Transaction B*, Apr. 2011

[19] E. A. Okoronkwo, P. E. Imoisili, S. A. Olubayode, and S. O. O. Olusunle,"Development of silica nanoparticles from corn cob ash," *Advances in Nanoparticles*, vol. 5, 135-139, May. 2016

[20] Y. Li, H. Yu, X. Huang, Z. Wu, and M. Chen,"A simple synthesis method to prepare a molybdenum oxide hole-transporting layer to efficient polymer solar cells," *Royale Society of Chemistry*, vol. 7, 7890-7900, Jan. 2017

[21] V. Kumar, H. Mehdi, and A. Kumar, "Effect of silicon content on the mechanical properties of aluminium alloy," *International Research Journal of Engineering and Technology (IRJET)*, vol.02, 1320-1330, Jul. 2015

[22] I. J. Majhi, S. K. Sahoo, S. C. Patnaik, B. Sarangi, and A. Behera, "Effect of pouring temperature in Al-16Si-1% Al2O3 hypereutectic alloys," *IJSRD – International Journal for Scientific research and Development*, vol. 6, 698-700, 2018

[23] K. Takakura, and H. Ohyama, "Hole mobility of p-type β-FeSi2 thin films grown from Si/Fe multilayers," *Journal of Applied Physics*, vol. 97,093716-1 – 093716-5, 2005

[24] Y. Shin, D. A. Tuan, Y. Hwang, T. V. Cuong, and S. Cho,"Formation and ferromagnetic properties of FeSi thin films," *Journal of Applied Physics*, vol. 113, 17C306-1 – 17C306-3, Apr. 2013

[25] J. Arvidsson, Iron and molybdenum containing pellets, European Patent Application 11190836.4 (2011)

[26] V. Milekhine, M. I. Onsoien, J. K. Solberg, and T. Skaland, "Mechanical properties of FeSi, FeSi2, and MgSi," *Intermetallics*, vol. 10, 743-750, Apr. 2002

[27] S. K. Ramasesha, P. S. Tantri, K. B. Anup, "MoSi2 and MoSi2 – based materials as structural ceramics," *Metals Materials and Processes*, vol. 52, pp. 181-190, Jan. 2000

[28] Y. S. Borisov, A. L. Borisova, E. A. Astakhov, A. N. Burlachenko, Z. G. Ipatova, and V. F. Gorban, "Detonation coatings of composite powder of ferromolybdenum-silicon carbide produced using method of mechanical-and-chemical synthesis," *The Paton Welding Journal*, 25-32, Mar. 2014