Mechanical Characterisation Of Aluminium Bronze-Iron Granules Composite

O. I. Sekunowo, S. O. Adeosun, G. I. Lawal, S. A. Balogun

ABSTRACT:- Despite some of the desirable characteristics most aluminium bronze exhibits, abysmally deficient responses in certain critical applications necessitate mechanical properties enhancement. Hence, the microstructure and mechanical properties of cast aluminium bronze reinforced with iron granules (millscale) were investigated in this paper. Cast samples of the composite made from metal mould contain millscale in varied amount from 2-10 wt.%. The samples were homogenised at 1100^{0}C for 10 minutes in order to relief the as-cast structures. Standard specimens were prepared from these homogenised samples for tensile, charpy impact and microhardness tests while the composite microstructures were studied using an optical microscope. Results show that optimum improved mechanical properties were achieved at 4 wt.% millscale addition with ultimate tensile strength (UTS) of 643.8MPa which represents 10.1% improvement over conventional aluminium-bronze. The composite also demonstrated impact resilence of 83.9J and micro-hardness value of 88.7HRB. Millscale presence in the aluminium bronze system induced a stable reinforcing kappa phase by nucleation mechanism which resulted to enhancement of mechanical properties. However, the composite properties were impaired on millscale addition above 4 wt.% due to grain clustering.

Keywords:- Aluminium-bronze, iron millscale (IMS), mechanical properties, kappa-phase

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INTRODUCTION

Aluminum bronze is very useful in a great number of engineering structures with a variety of the alloy finding applications in different industries (CDA, 1986). According to ISO 428 specifications, most categories of aluminiium bronze contain 4-10 wt.% aluminium in addition to other alloying agents such as iron, nickel, manganese and silicon in varying proportions. The relatively higher strength of aluminium bronze compared with other copper alloys makes it suitable for the production of forgings, plates, sheet, extruded rods and sections (Pisarek, 2007). Its excellent corrosion resistance property recommends it as an important engineering material for highly stressed components in corrosive environments (www.morganbronze.com). The alloy is available both in wrought and cast forms and is readily weldable and fabricated into components such as pipes and pressure vessels. Despite these desirable characteristics most aluminium bronze exhibit deficient responses in certain critical applications such as in sub-sea weapons ejection systems, aircraft landing component and power plant facility. The need to overcome obvious performance limitations in aluminium bronze is imperative to meet today emerging technologies.

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This will help to extend the frontier of usage and provide the platform to fully harnessed the potentials and versatility of aluminium bronze apllications in aircraft, petrochemical and offshore components. The feasibility of the foregoings hinges on microstructural modification of the alloy such that relevant physical and mechanical properties improvement are achieved (Yang, et al.,2011). Structure modifications in aluminium bronze are often accomplished through any or a combination of the following processes namely; alloying, heat treatment and deformations. The choice of method however is usually determined by cost and effectiveness. The mechanical properties of aluminium bronze apart from aluminium depend on the extent to which other alloying elements modify the structure. In this regard, iron has been found to be both effective and efficient grain refiner in aluminium bronze systems. The presence of iron in the system enables the inducement of a hard reinforcing phase, $CuAl10Fe_{3,}$ in proportion to the amount of iron and other alloying agents. According to Oh-Ishi and McNelley (2004), this structure has proven to be responsible for the significant improvement in tensile strength while other desirable properties are not compromised. Cenoz, (2010) also observed that the addition of Fe in the aluminium bronze system in varying amounts may cause just a small change in the transformation products but will definitely contribute significantly to the refinement of the structure. Modification of structure predicated on iron addition affects both the size and morphology of phases (Hassan, et al. 1985). In particular, the precipitation of different stable α, and β phases with intermetallic precipitates of Al_3Fe, Al_5Fe_2 and $Al_{13}Fe_4$ (depending on both the quantity of Fe in the system and other processing conditions) impact significantly the alloy mechanical chacteristics. Iron (Fe) granules can be cheaply obtained in commercial quantity from its generic oxide for the purpose of alloying same with aluminium bronze. Granulated iron oxide, commonly called millscale is usually formed on the surface of hot rolled profiles such as plates, sheets, bars, etc. Millscale formation invariably represents a significant level of yield loss to millers as it often reflects in huge differences between input stock and final output tonnages (Danilov, 2003). The accumulation of millscale on the shopfloor over time usually create handling and disposal challenges.

Consequently, researchers have proposed various effecient methods and possible areas of its application (Seok-Heum, et al. 2010). For example, in the construction industry, the mixing of millscale in varying proportions has demonstrated increase in soil permeability, strength characteristics and decrease plasticity (Murthy, 2012). Another varitable area in which millscale has found application is in cement mortars (Saud Al-Otabi, 2008). The study reported impressive results on several mortar mixes of concrete made from millscale aggregates in terms of their compressive and flexural strengths including the drying shrinkage. The foregoings indicate high potentials for millscale usage in different engineering materials for enhanced performance. This is also capable of increasing the quantity recyclable thereby reducing drastically the environmental challenges pose by its accumulation on the shopfloor. This has been demonstrated in the recycling of aluminium swarf by direct incorporation in aluminium melts (Puga, et al. 2009). The current study investigates the quantity of iron particles weight percent addition in aluminium bronze that confers improved mechanical properties that makes the material suitable for applications requiring high strength combined with low wear rate.

EXPERIMENTAL PROCEDURE

The materials used comprised of aluminium bronze (ASTM B505 specification with chemical composition as presented in Table 1) and iron-oxide granules (millscale). The aluminium bronze sample was obtained from NIGALEX (A company engaged in extrusion of different aluminium profiles) while the iron oxide granules was supplied by African Steel (Producers of hot rolled mild steel bars used for concrete reinforcement). Aluminum bronze is a special type of bronze in which aluminum is the main alloying element as against the conventional bronze that has tin as the major alloying element.

Table 1. Chemical composition (%)

Cu	Fe	Al	Ni	Mn
89.178	0.835	8.514	1.131	0.342

The millscale was sieved to remove tramps and other hard lumps usually associated with millscale to obtain smooth (homogenous) stream of particles. Further sieving of the millscale was carried out to obtain 170-250µm fine particle size. Melting of the composite matrix material entailed that aluminum bronze having 8.5-10 wt.% was placed in a crucible pot and charged into a pit furnace to be heated until molten. Then, measured proportions of fine millscale at 2, 4, 6, 8 and 10 wt.% were added to the molten aluminum bronze and stirred thoroughly using a long stainless steel tong. The molten mixes were homogenised at 1100^{o}C for 10 minutes and then cast in prepared metal moulds.

Specimens' preparation and tests

The cast composite samples were thoroughly cleaned by cutting all protrusions while particles and blisters were removed from the cast surfaces by sand blasting. Tensile, hardness and Charpy impact test specimens were prepared according to EN 10002-1 (ISO 6892-1) standards. The composite's micro-hardness was obtained through the Rockwell hardness tester on B-scale (R_B) using a steel ball indenter. Micro-hardness values were taken at three different points on the specimen's surface by applying a minor and major indenter load of 10kg and 60kg respectively for a dwelling time of 10 seconds. However, the composite tensile data were obtained through an Instron electro-mechanical tester, model 3369 at a loading rate of 40mm/min while the notch toughness of the test specimen was evaluated with the aid of an Avery impact tester, model 6703 under a striking force of 300J. The results of these mechanical tests are shown in Tables 2 and 3 with their illustrations in Fig 1-4.

Microstructural analysis

The Samples were first sectioned to the appropriate sizes after which the surfaces were ground using first a silicon carbide (SiC) impregnated emery paper of 320grits mounted on a rotary wheel. At successive grinding stages, finer emery papers of 400, 600 and 800 grit sizes were used to remove scratches from previous grinding stages. This step was followed by polishing using 6µm metadi paste and nylon as wheel covering. The final stage of polishing to obtain a minor-like surface involved the use of gamma alumina applied on the specimen surface while little pressure was applied on the specimen to avoid overheating. The mirror-like surface was then washed under a running tap water and then dried. In order to reveal the specimen's microstructural features, 50ml hydrochloric acid in 100ml distilled water was used as etchant which was allowed to remain for 20 seconds and the microstructure examined using an optical microscope model Ferox PL at x400 magnification.

RESULTS AND DISCUSSION

Results of the ultimate tensile strength (uts), impact strength and micro-hardness responses by test specimens are displayed in Figs 1, 2, 3 and 4 while the microstructures developed by the specimens are shown in Plates 1(a-f).

Microstructure

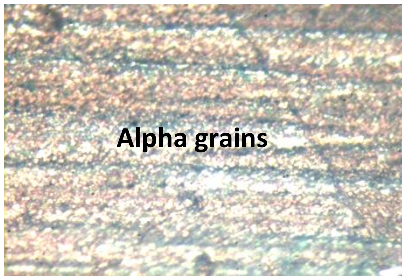
The different microstructures developed by the alloys corressponding to the amount of iron particles (millscale) addition are shown in Plates 1(a-f). Apart from different intermetallics, two major phases are revealed under the optical microscope as comprising of lamellar kappa (**κ**) precipitates and needle-like alpha (α) aluminium within the aluminium-bronze matrix. The control specimen microstructure is shown in Plate 1(a) while composite with varied amount of iron millscale are presented in Plates 1(b-f). It is observed that the microstructure in Plate 1(a) contains alpha (**α**) phase of the aluminium-bronze in which the alpha grains appear to have subsumed (absorbed) the aluminum thereby preventing the precipitation of other phase(s) out of solution. This must have been due to the relative low content of aluminum in the alloy which is about 8.51 wt.% (see Table 1) compared to standard aluminium bronze having between 10-11 wt.% aluminium. However, precipitation of fringe grains of the kappa (**κ**) phase appear to evolve due to the combination of 2wt.% iron millscale presence in Plate 1b and a relatively fast cooling rate of the melt in the metal mould. The presence of iron particulates actually aided the nucleation of a few fine lamellar kappa precipitates. Plate 1(c), shows the effect of 4 wt.% iron particulates addition on the aluminum bronze microstructure. The amount of the fine lamellar kappa phase transformed within the matrix increased compared to 2 wt.% iron millscale addition (Plate 1(b). The presence of more iron in the system must have provided increased nucleation sites for the transformation. In addition, the preponderance of iron in solution effectively suppressed the formation of gamma (γ) phase within the matrix. Increase in iron millscale addition into the alloy (6 wt.%, Plate 1d), appears to have drastically reduced the kinetics of kappa phase transformation which gave rise to coarse precipitates. Matrices containing iron millscale up to 8 wt.% and 10 wt.% as in Plates 1(e) and 1(f) respectively resulted in clustering of the kappa grains within the alpha matrix. It should be expected according to Cenoz, (2010) that at all levels of iron particles addition, the formation of Fe-Al intermetallics in various stoichiometry compositions cannot be ruled out. However, this could not be ascertained through optical microscope used in this study.

Table 2. Mechanical properties test results

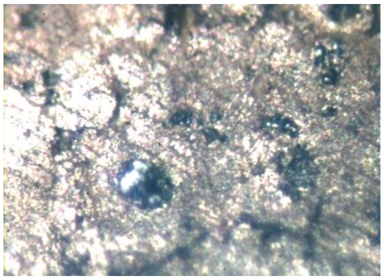
Millscale (wt.%)	**Ultimate tensile strength (**MPa)				**Impact strength (**J)				**Micro-hardness (**HRB)			
	A	**B**	**C**	**AVEG**	**A**	**B**	**C**	**AVEG**	**A**	**B**	**C**	**AVEG**
0 (control	429.7	431.6	428.3	**429.9**	63.6	63.5	63.7	**63.6**	64.7	63.9	64.3	**64.3**
2	543.4	536.8	541.9	**540.6**	67.3	67.1	67.2	**67.2**	72.7	73.8	73.9	**73.5**
4	640.3	644.2	646.8	**643.8**	84.0	83.9	83.8	**83.9**	89.1	88.3	88.7	**88.7**
6	562.5	564.1	561.3	**562.6**	69.8	70.6	70.7	**70.4**	71.6	70.2	71.8	**71.2**
8	457.6	455.8	454.7	**456.0**	61.6	62.1	61.7	**61.8**	66.8	66.9	68.2	**67.3**
10	44i.2	447.5	442.3	**412.5**	58.4	58.7	58.4	**58.5**	62.9	61.8	62.9	**62.5**

Table 3. Ductility response of Aluminium bronze-iron granules composite

Millscale (wt.%)	0	2	4	6	8	10
Elongation (%)	27.1	23.8	21.7	18.2	13.5	11.4



(a)



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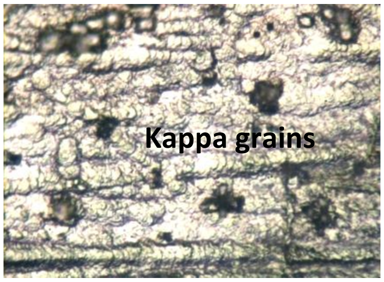

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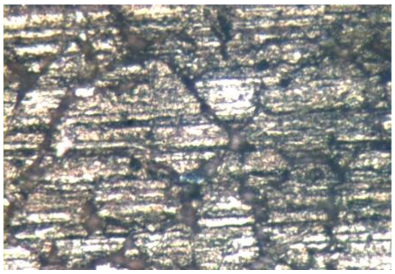

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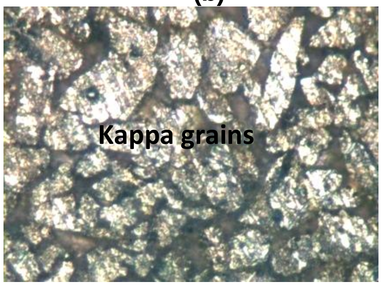
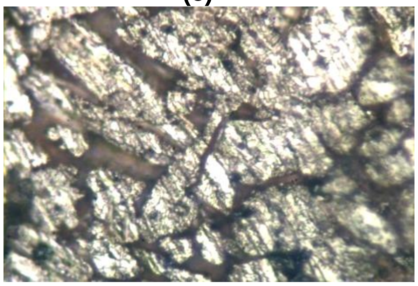


(e)



(f)

Plate 1: Aluminium-bronze morphologies with iron millscale at (a) 0% (b) 2 wt.% (c) 4 wt.% (d) 6 wt.% (e) 8 wt.% (f) 10 wt.%

Tensile strength

Fig. 1 illustrates the tensile strength of aluminium bronze at different 0-10 wt.% iron millscale (IMS) addition. The flow curve is parabolic indicating an optimum ultimate tensile strength (uts) of 643.8MPa at 4 wt.% iron addition which is about 10.1 percent above the standard tensile strength of conventional aluminium-bronze which is usually in the range of 540-585MPa. The tensile strength parabolic pattern must have been due to the different microstructures developed in the alloy at varying amount of IMS addition. The inducement of varying fractions of kappa (κ) precipitates in alpha (α) aluminium matrix, their morphology and size significantly influenced the alloys response under tensile load. This corroborates the work of Oh-Ishi and Mcnelly (2004) who also made similar observation.

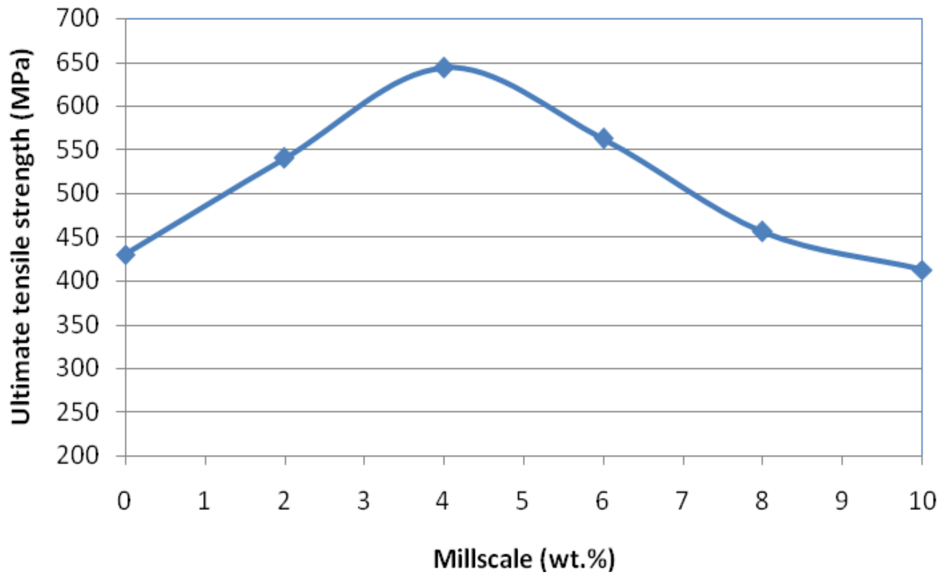


Fig. 1. Variation of ultimate tensile strength of aluminium-bronze with millscale content

The kappa precipitates, being a stable and coherent secondary phase in the matrix provided substantial level of impediment to dislocation motion which increased the composite strength in proportion to the amount of fine lamellar kappa precipitates present. Gradual decrease in strength from 562.6-456.0 MPa, was observed as IMS content increased from 6-8 wt.% while the minimum value of 412.5MPa was exhibited at 10 wt.%. The development of coarse kappa reinforcing precipitates at 6 wt.% iron addition was responsible for decrease in UTS and clustering of the precipitates at 8 wt.% and 10 wt.% millscale additions further compromise the reinforcing influence of the precipitates.

Impact energy

The dynamic strength characteristics of aluminum bronze at varied millscale addition are shown in Fig. 2. Given that there is correlation between static and dynamic strength of a material, the response of the composite under dynamic load is valid. The highest impact energy of 83.9J that fractured the specimens was obtained at 4 wt.% millscale addition in the composite. This agrees well with literature as the impact energy of a material is structure dependent (Jun, et al, 2011). The optimum impact energy of 83.9J also compared well with the standard value which are between 81 and 88J. Hence, the type of microstructure developed in the alloy significantly influenced the composite toughness responses which correspond to the fractions of coherent reinforcing precipitates present in the matrix. For instance, the best toughness supporting microstructure consisting of fine lamellar kappa precipitates (Plate 1(c)) was induced in the composite at 4 wt.% millscale addition whereas at 6 wt.%, the precipitates appeared coarse and clustered exhibiting impact energy of 70.4J. Similar microstructural features developed at both 8 wt.% and 10 wt.% millscale contents further diminish the composite impact integrity. This gave rise to the lowest impact energy of 61.8 J and 58.5 J respectively compared with 63.6J of the control sample.

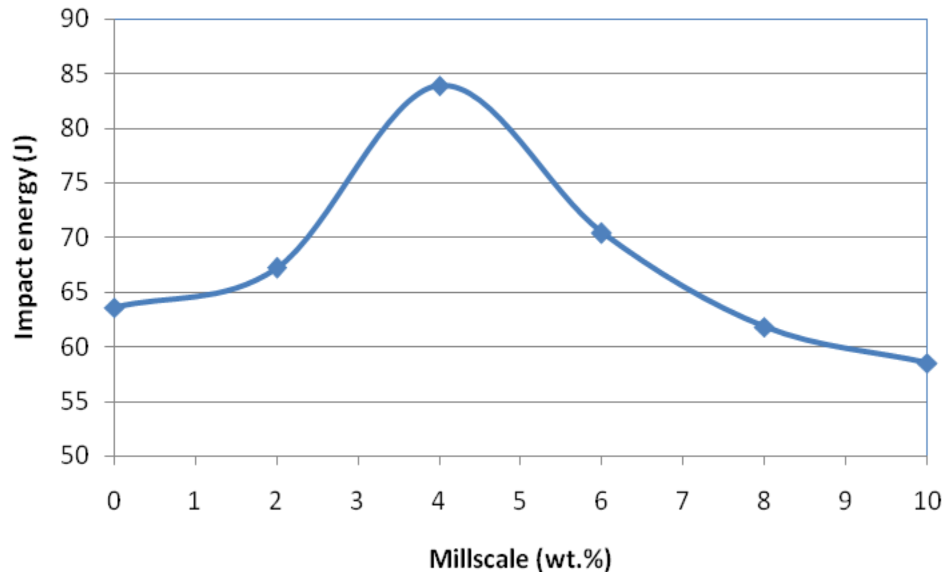


Fig. 2. Variation of impact fracture responses of aluminium-bronze with millscale content

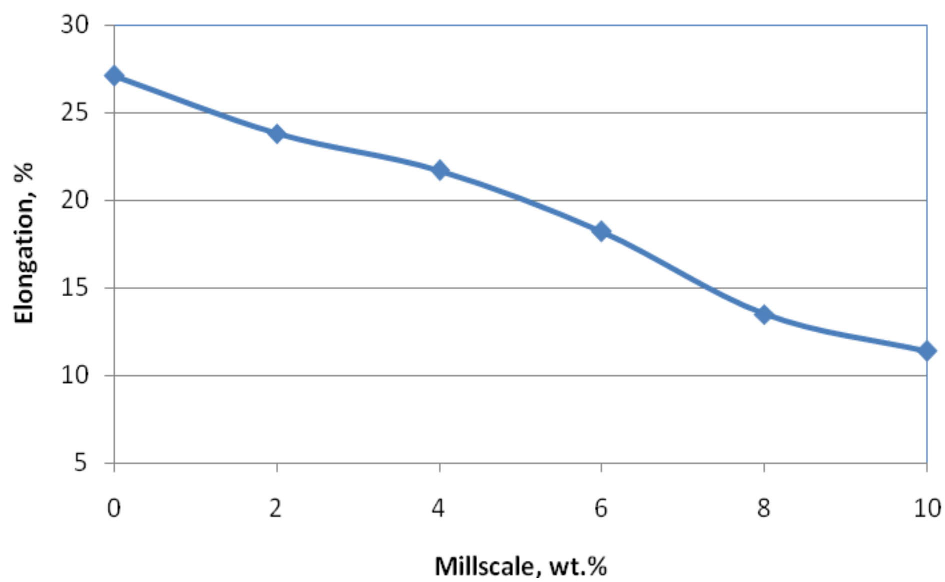


Fig. 3. Variation of ductility of aluminium-bronze with millscale content

Ductility response

Fig. 3 depicts the composite's response with respect to its linear elongation under deformation. The curve is slightly wavy showing reduction in elongation as millscale addition increases. This trend is an indication that the composite ductility was influenced by the amount of millscale in its matrix. Generally, the extent of linear stretch a material suffers is a measure of its formability since the phenomenon incorporates both elastic and plastic deformation responses (Callister, 2005). However, percent elongation is majorly influenced by the strain-hardening capacity of an alloy in which the material's micro-constituents suffered significant flow before dislocation tangle sets-in. In the present study, the combination of clustered precipitates (Plate 1e and 1f) coupled with the presence of other intermetallics (Fe-Al) dispersed at the grain boundaries must have sustantially impaired the composite ductility which is 13.5% and 11.4% respectively for 8 wt.% and 10 wt.% millscale addition. The latter value is rather below the minimum standard of 12% for conventional aluminium bronze. Notwithstanding, the inducement of fine lamellar kappa precipitates within fine needle-like alpha matrix supports optimum ductility up to 21.7% exhibited by the composite at 4 wt.% millscale addition.

Microhardness

The surface integrity of the alloy in term of ability to resist wear and indentation at varying amount of millscale addition is illustrated in Fig. 4. It is evident that the extent of micro-hardness induced in the composite is determined by the proportion of hard and fine lamellar kappa (κ) precipitates present in the matrix of each specimen. The control specimen exhibited the least micro-hardness value of 64.3HRB due to the absence of requisite reinforcing phase in its structure. This might have paved the way for the precipitation of a rather deleterious and soft gamma (γ) phase within the matrix as millscale was not added to the system. However, the preponderance of fine kappa precipitates in higher amounts above the soft needle-like alpha grains that were induced at 4 wt.% iron addition support modest increase in hardness from 73.5-88.7HRB. The highest value of 88.7J falls within conventional aluminium-bronze standard hardness range of 82-91HRB. This level of micro-hardness inducement was achieved without compromising ductility since the hard and brittle beta (β) phase was not precipitated. According to Cenoz, (2010), beta precipitates are formed if the alloy is quenched or fast cooled, which is not the case in this study.

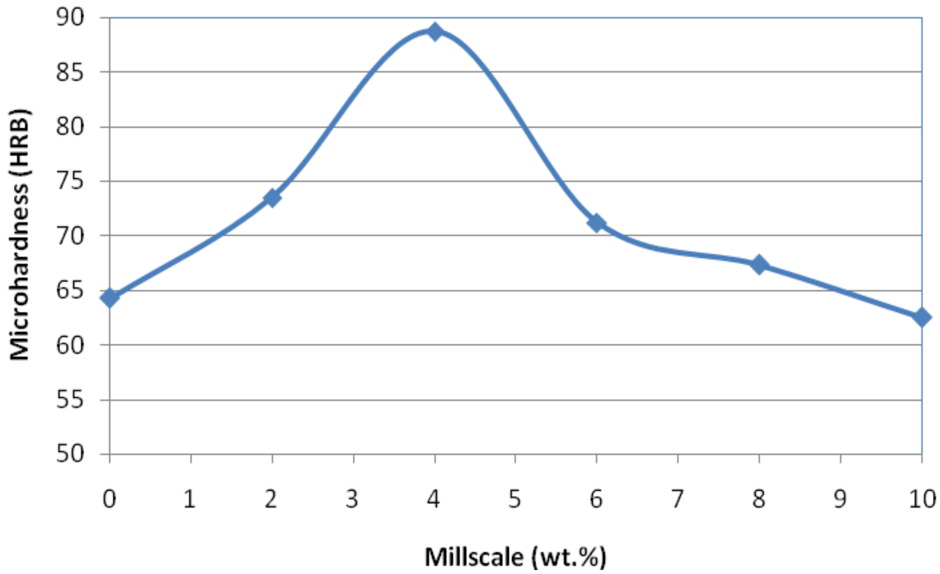


Fig. 4. Variation of micro-hardness of aluminium-bronze with millscale content

CONCLUSION

The processing of aluminium bronze for enhanced mechanical properties through the addition of iron granules (millscale) was investigated. The presence of IMS particles in the alloy significantly influenced the microstructure which affected the composite mechanical properties. In summary, the overall results of this study show that:

1. Fine lamellar and coherent kappa phase can be evolved in aluminium-bronze using iron millscale particles without quenching or fast cooling process as stated by Cenoz (2010).

2. Optimum combination of UTS, ductility impact toughness and microhardness are attainable with 4 wt.% of iron millscale addition which is superior to the conventional aluminium-bronze alloy.

The aluminium bronze-iron granules composite developed is recommended for application as structural members in automobiles and allied engineering facilities. Further work may be carried out using millscale on nanoscale for possible application of the composite in advance devices such as in aerospace and nuclear facilities.

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