Tribological Behaviour of Al-Si Alloy with Rare Earth and Manganese

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Abstract— **The effect of rare earth Cerium oxide and Manganese on the tribological properties of hypereutectic Aluminium-Silicon alloy has been reported in this paper. Wear studies were carried out on as cast samples of alloy modified with rare earth Cerium oxide (CeO_2) and Manganese (Mn). Results obtained out of wear studies of rare earth Cerium oxide and Manganese modified alloy were compared with authors previous work on rare earth Cerium oxide modified hypereutectic Aluminium-Silicon alloy and hypereutectic Aluminium Silicon base alloy. It was observed that Cerium oxide and Manganese modified alloy reduced the wear rates as compared to Cerium oxide modified alloy and base alloy. An enhancement in mechanical properties was also observed. A comparison showed that Cerium oxide and Manganese modified alloy had least wear rates. Wear rates for Cerium oxide and Manganese modified alloy was 2.78 times lesser than wear rate of base alloy and was 1.68 times lesser than Cerium oxide modified alloy. Wear rates were calculated at loads ranging from 15N to 90N with an interval of 15N and at a constant velocity and sliding distance of 0.4m/s and 500m respectively. It was observed that minimum wear occurred at 15N load and maximum at 90N load. Further, scanning electron micrographs (SEM) of worn surfaces and wear debris of Cerium oxide and Manganese modified alloy showed mild wear.**

Keywords— ***refinement; hypereutectic; Aluminium; Silicon; rare earth; cerium, wear.***

I. INTRODUCTION

Hypereutectic Aluminium Silicon (Al-Si) alloys are widely applied in aerospace, military, automobile and electronic industries because of their excellent wear, corrosion resistance, low density and coefficient of thermal expansion, good strength and castability [1]. The microstructure of hypereutectic Al-Si alloys is composed of primary silicon particles (PSP) and eutectic structure of alpha (α) -Al and Si. The wear resistance and mechanical performance of these alloys is influenced by the formation of primary Si particles and segregation of eutectic Si at grain boundaries. Presence of coarse blocky shape primary silicon particles reduces mechanical properties such as tensile strength and ductility of these alloys. This greatly restricts the application of hypereutectic aluminum silicon alloys in many areas. Refinement of primary silicon particles is an effective way to overcome these limitations of hypereutectic Al-Si alloys which are cast especially under low cooling conditions [2]. A lot of work has been reported on die casting and mechanical stir casting processes [3, 4] for improving the mechanical and wear performance of these alloys. Refinement of primary silicon particles in large castings of these alloys by addition of Phosphorus (P) based compounds puts difficulties like evaporation/oxidation of Phosphorous which is harmful for the health of persons working in casting area. Therefore, refinement by using Phosphorous is not assumed a very effective method. It has been reported that rare earth element Cerium oxide (CeO_2) helps to modify the morphology of primary and eutectic silicon particles [5, 6]. Cerium helps to reduce the size of primary silicon particles and beta phase iron needles. Small size primary silicon particles are helpful in increasing the strength of a hypereutectic Al- Si alloy but beta phase iron needles although in reduced size are not good as they provide easy path for crack nucleation and growth. So, introduction of another element Manganese helps to neutralize the formation of beta needles in the hypereutectic and hypoeutectic alloys [7, 8]. The effect of Cerium oxide on the hypereutectic Aluminium Silicon alloys has already been established using different manufacturing techniques [9]. Further, the effect of Cerium oxide on the wear performance has also been presented in the literature [10]. But the effect of Cerium oxide along with neutralizing element Manganese has not been studied so far. The present work is therefore an attempt to study the wear performance of hypereutectic Aluminium Silicon alloy modified with rare earth Cerium oxide and Manganese under low, medium and high loads ranging from 15 N to 90 N at an equal interval of 15 N at constant velocity (0.4 m/s) and sliding distance (500 m) conditions. Further, to compare wear rates of rare earth Cerium oxide and Manganese modified hypereutectic Al-Si alloy with Cerium oxide modified Al-Si alloy and hypereutectic Al-Si base alloy evaluated in previous work [10].

II. EXPERIMENTAL PROCEDURE

This section presents the experimental procedure followed for the development of casting and standard procedure followed for wear testing of the present alloy under different load, velocity and sliding distance conditions.

A. *Development of casting*

The experimental alloy namely hypereutectic Al-16 (wt%) Si alloy was prepared by melting Al-50%Si master alloy and pure Aluminium ingot in an induction furnace at 900º - 950ºC. Graphite crucibles were used for melting and casting and casting was done by conventional green sand mould casting technique. Cerium oxide - 0.2 (wt %) (Lobba chemicals Pvt. Ltd.) was introduced to the prepared hypereutectic Al-Si alloy at about 850º - 900ºC in separate crucible and kept there for an hour to provide the proper mixing of the alloy and then cast separately. Similarly, Manganese at 0.4 (wt%) was added to Cerium oxide modified hypereutectic Al-Si alloy in separate crucible and kept at 800º - 900º C for proper mixing and then cast in green sand moulds. Samples of Cerium oxide and Mn modified hypereutectic Al-Si alloy were cast and taken for characterization.

B. *Wear testing of the alloy*

Wear testing was done under dry sliding conditions on a reciprocating wear test rig. The apparatus used for wear testing was made under ASTM standard G-133-05 and wear testing of the alloy was also done following the same standards. Size of the wear pins for testing was 6mm diameter and 30 mm length. A grey cast iron plate was used against the wear pins whose average surface roughness (Ra) was 235 nm. Wear testing was done at a constant sliding distance of 500 m and a constant sliding velocity of 0.4 m/s at loads varying from 15N to 90N at an equal interval of 15N. Amplitude of the reciprocating motion was 54 mm and frequency of the reciprocating motion was 1.85 Hz.

C. *Metallurgical examination*

Cut samples of alloys of CeO_2 modified and CeO_2 + Mn modified alloys were polished on polishing machine with emery papers of various sizes ranging from 220 to 1000 number. Polished samples were further polished on cloth polishing machine and then etched with Keller's reagent. Etched samples were mounted inside the microscope and then micrographs were taken.

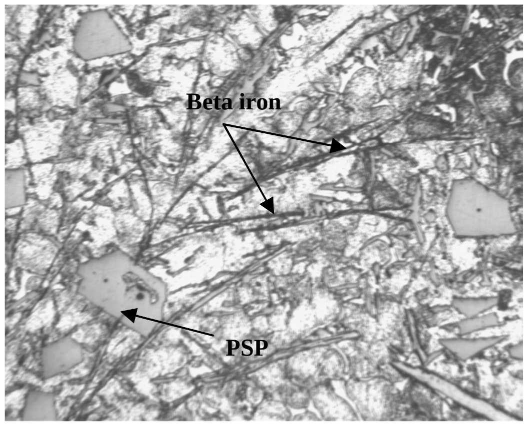
D. *Scanning electron micrograph (SEM)*

Samples prepared by cutting worn surfaces of CeO_2 and Mn modified hypereutectic Al-Si alloy at different loads were mounted inside the scanning electron microscope for examination. Wear debris were directly put on the mount and then micrographs were taken.

III. RESULTS AND DISCUSSION

Many studies were done for determining the wear rates of alloys in dry sliding adhesive wear under reciprocating conditions [11]. Authors have already established in their earlier work [10] that improvement of wear and mechanical properties can be achieved by adding Cerium oxide to a hypereutectic Al-Si alloy. Present work is an extension of the previous work by adding Mn to the hypereutectic alloy which has not been done earlier as per literature [12]. So, in the present study a comparison of wear rates of hypereutectic Al-Si base alloy [10] and Cerium oxide modified alloy with Cerium oxide and Mn modified alloy has been done to establish that Mn helps to reduce the wear rates of Cerium oxide modified hypereutectic Al-Si alloy. Figure 1 shows microstructures of alloys in present study a) base alloy (9), b) CeO_2 modified alloy and c) CeO_2+Mn modified alloy. It can be observed from Figure 1a and 1b that there is a reduction in size of PSP and beta iron needles in CeO_2 modified alloy. Further, Figure 1c shows that there is a reduction in beta iron needles after the introduction of Mn in CeO_2 modified alloy. Figure 1a, 1b and 1c shows that CeO_2 modification helps to reduce the size of PSP and beta iron needles (phases) and Mn helps to reduce quantity of needles in the microstructure. Further, improvement in mechanical properties such as hardness justifies the Mn addition. Hardness of base alloy was 99 BHN (9), hardness of CeO_2 modified alloy was 120 BHN and that of CeO_2 and Mn modified alloy was 129 BHN.

a)



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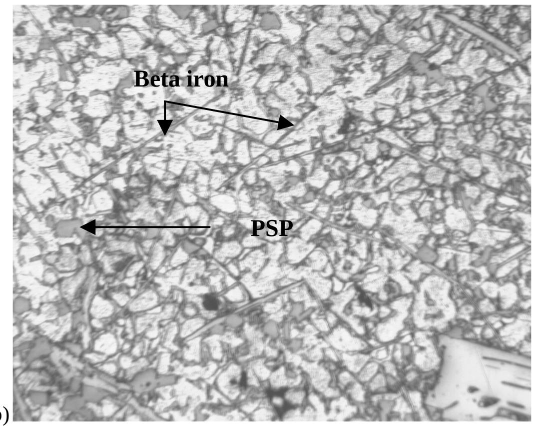

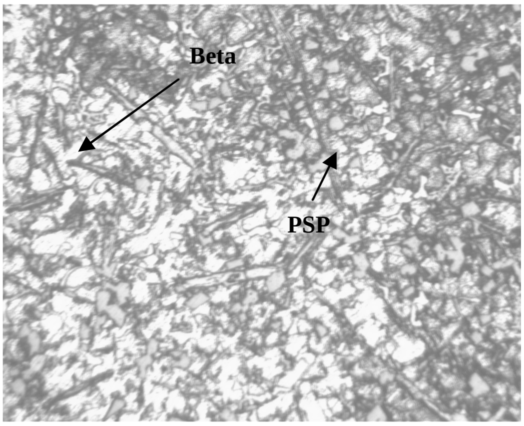

c)

Fig. 1. Microstructures of alloys in present study a) base alloy (9), b) CeO2 modified alloy and c) CeO2+Mn modified alloy

Mn modification increased the hardness of the CeO_2 modified alloy by 7.5% and combined CeO_2 and Mn modification increased the hardness of the base alloy by 30%.

Wear studies were done at a constant sliding distance of 500m, a constant velocity of 0.4 m/s and applied loads ranging from 15N to 90N at an equal interval of 15N. Figure 2 shows the comparison of wear rates of base alloy, CeO_2 modified alloy and CeO_2 and Mn modified alloy a) at 15N and b) at 90N.

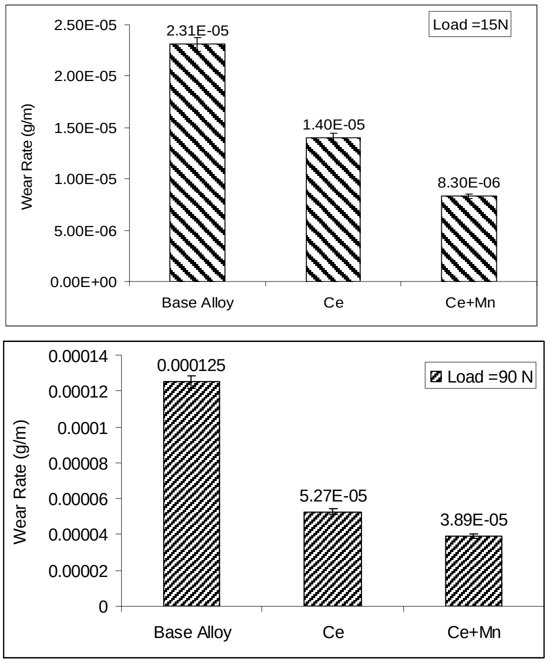

Fig. 2. Comparison of wear rates of hypereutectic base alloy in as cast condition (Base alloy), Cerium oxide modified condition (Ce) and Cerium oxide and Mn modified condition (Ce+Mn).

It can be observed from Figure 2 that there was a reduction in wear rate of Cerium oxide and Mn modified hypereutectic Al-Si alloy as compared to wear rates of Cerium oxide modified hypereutectic Al-Si alloy and hypereutectic Al-Si base alloy. Wear rate of Cerium oxide modified hypereutectic Al-Si alloy was 2.78 times lesser than the wear rate of hypereutectic Al-Si base alloy and 1.68 times lesser than the wear rate of Cerium oxide modified hypereutectic Al-Si base alloy. Thus, Manganese modification to rare earth Cerium oxide helps in improving the wear resistance of hypereutectic Al-Si alloy. Figure 3 shows a comparison of wear rates of Al-Si base alloy, CeO_2 modified Al-Si alloy and CeO_2 and Mn modified Al-Si alloy at various loads ranging from 15 N to 90 N at an equal interval of 15 N.

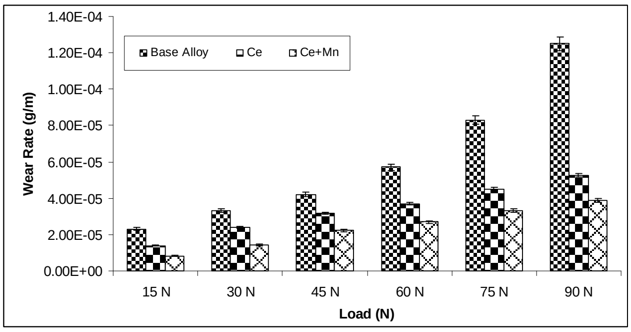

Fig. 3. Comparison of wear rates of Al-Si base alloy, CeO_2 modified Al-Si alloy and CeO_2 and Mn modified Al-Si alloy at various loads ranging from 15 N to 90 N at an equal interval of 15 N and constant velocity 0.4m/s and sliding distance of 500m.

It can be observed that wear rate of Cerium oxide and Manganese modified hypereutectic Al-Si alloy at 45 N (2.24E-05 g/m) is lesser than wear rate of hypereutectic Al-Si base alloy at 15N (2.31E-05). Similarly, wear rate of Cerium oxide and Manganese modified hypereutectic Al-Si alloy and wear rate of Cerium oxide modified hypereutectic Al-Si alloy at 30N (1.43E-05) is slightly more than wear rate of Cerium oxide modified hypereutectic Al-Si alloy (1.40E-05). It can be observed that although the wear rates reduced after modification at all loads (15N to 90N) and in all cases (base alloy, CeO_2 modified alloy and CeO_2 and Mn modified alloy) yet the effect of CeO_2 modification and CeO_2 and Mn modification is more prominent at higher loads such that the difference in wear rates of modified alloys and base alloy start increasing rapidly at 60N load and further increases at 75N and is more than double at 90N. Thus, CeO_2 and Mn modification reduced the wear rates by more than ½ and comes in the category of mild wear rate which is further clarified by SEM micrographs of worn surfaces and wear debris. So, Manganese modification to CeO_2 modified Al-Si alloy makes it suitable for working at higher applied loads with lesser wear rates.

It can be observed from Figure 1 that rare earth Cerium oxide reduced the size of primary silicon particles and beta iron phases which are present in hypereutectic Al-Si alloy. The rare earths like Ce improves the chemical composition and provides nucleation sites that further helps in solidification and growth thus, provides equally distributed growth fronts. Primary silicon particles strengthen the alloy and helps in improving the wear resistance but beta iron needler phases are not good for these alloys. These phases although in reduced size after Cerium modification harm the mechanical and tribological properties and in turn increase the wear rates. Element Mn has been reported to neutralize beta iron phases (8, 12) and helps to reduce them. Mn forms intermetallic compounds with Cerium and further improves the chemical homogeneity. So, Mn when added to Cerium oxide decreased the beta iron needler phases that provides easy path for nucleation and growth of cracks and improves wear resistance.

Figure 4a and b shows SEM of wear debris of Cerium and Manganese modified hypereutectic Al-Si alloy at high magnification (500X). It can be observed in Figure 4a that wear debris was fine at low load (15N) due to mild oxidative wear. There were few large size particles seen which were delaminated from the wear surface during the wear process but mostly the particles were of powdery form and small size. This can be attributed to low load as it does not provide a proper material contact and the upper surfaces got rubbed at maximum places and thus fine powder forms mostly. Very few contact points produce delaminated flakes and so called mild wear. Whereas at high load (90N) there are more material to material contact points due to increased pressure that produce more number of delaminates. Here, due to Ce and Mn modification, alloy get strengthened and material properties improved and showed mild wear characteristics

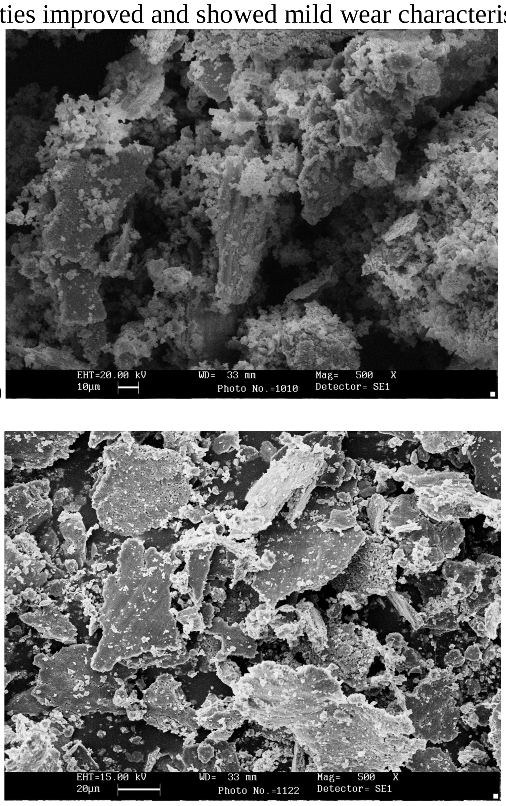

Fig. 4. Comparison of wear debris of Cerium oxide and Mn modified hypereutectic Al-Si alloy a) at low (15N) and b) at high load (90 N)

It means that the Mn addition to Cerium oxide modified hypereutectic Al-Si alloy improved the wear resistance and reduced the wear rates even at high loads (90N).

Figure 5 shows the worn surfaces of Cerium and Manganese modified hypereutectic Al-Si alloy a) at low load (15N) and b) at high load (90N). Figure 5a shows the worn surfaces of the Cerium and Mn modified hypereutectic Al-Si alloy and it can be observed that the alloy at low load shows mild oxidation wear marks prominently and one or two debris particles due to delamination. Figure 5b shows the worn surface of Cerium and Mn modified hypereutectic Al-Si alloy at high load and worn surface has mainly oxidation marks and some marks of delamination and one or two small size craters. The worn surface of Ce and Mn modified alloy at low load showed oxidation marks very prominently due to lesser pressure of lower load and the worn surface is very fine with no scoring marks. Figure 5b shows the worn surface of Ce and Mn modified alloy. It can be observed that surface is still not damaged due to higher pressure at higher load. Worn surface at high load has not been damaged and shows only few craters and oxidation marks which has already been discussed above and shown in Figure 3. Archard’s law also suggests that an increase in hardness decreases the wear rate. This shows that the modified alloy with Mn provides better working conditions even at high loads.

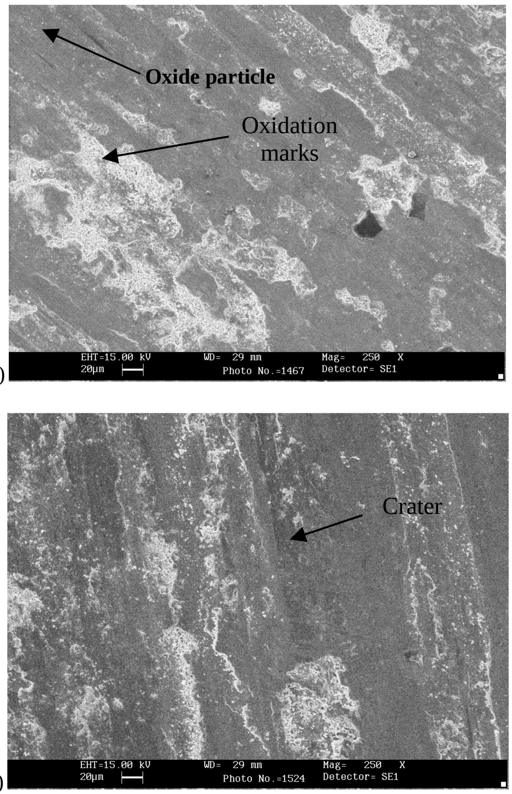

Fig. 5. Comparison of worn surface of Cerium and Mn modified hypereutectic Al-Si alloy a) at low (15N) and b) at high load (90 N)

IV. CONCLUSIONS

The following conclusions were drawn from the above investigation

1. Manganese modification to Cerium oxide modified hypereutectic Al-Si alloy reduces the wear rate due to increase in hardness from 120 BHN to129 BHN.
2. Wear rate of Cerium oxide and Mn modified hypereutectic Al-Si alloy is 2.78 times lesser than wear rate of hypereutectic Al-Si base alloy and

1.68 times lesser than Cerium oxide modified hypereutectic Al-Si alloy.

3. Wear rates of Cerium oxide and Mn modified hypereutectic Al-Si alloy at higher loads (45N) were lesser or just slightly above (fifth decimal) than the wear rates of hypereutectic Al-Si base alloy (15N) and Cerium oxide modified alloy (30N) at lower loads. Wear rates especially reduces after 60N and reduces to more than ½ at 90N load.
4. Wear debris of Cerium and Manganese modified hypereutectic Al-Si alloy at low load (15N) and high load (90N) showed mild oxidative wear.
5. Worn surface of Cerium and Manganese modified hypereutectic Al-Si alloy at low load (15N) and high load (90N) also showed mild oxidative wear.

REFERENCES

[1] Rooy Elwin L. “Aluminium and Aluminium alloys”, Aluminium Company of America. 2002.

[2] Nafisi S. Emadi D. Shehata M.T. Ghomashchi R., “Effects of electromagnetic stirring and superheat on the microstructural characteristics of Al-Si-Fe alloy”, Materials Science and Engineering A 2006; 432: 71-83.G. Eason, B. Noble, and I.N. Sneddon, “On certain integrals of Lipschitz-Hankel type involving products of Bessel functions,” Phil. Trans. Roy. Soc. London, vol. A247, pp. 529-551, 1955.

[3] Fan Z. “Semisolid metal processing”, International Materials Review 2002; 47(2): 1-37.

[4] Atkinson Helen. “Current status of semi-solid processing of metallic materials. In: Advances in material forming”, Esaform 10 years on, ISBN-13: 978-287-72142-7, Springer-Verlag France, Paris 2007, 81-98.

[5] Xiao DH, Wang JN, Ding DY, et al., “Effect of rare earth Ce addition on the microstructure and mechanical properties of an Al-Cu-Mg-Ag alloy”, Journal of Alloys and Compounds 2003; 352: 84–88.

[6] Zhang H, Duan H, Shao G, et al., “Modification mechanism of cerium on the Al-18Si alloy”, Rare Metals 2006; 25(1): 11–15.

[7] Prabhkiran kaur (2011), “Improving microstructure, mechanical properties and adhesive wear behaviour of hypoeutectic Al-Si alloy by electromagnetic stirring”, International Journal of Engineering Science and Technology (IJEST),Vol. 3 No.10, pp. 7525-7529.

[8] Abouei. V, Saghafian. H, Shabestari. S. G, Zarghami. M (2010), “Effect of Fe-rich intermetallics on the wear behaviour of eutectic Al-Si piston alloy (LM13)”, Materials and Design, 31, pp. 3518-3524.

[9] Prabhkiran Kaur, D. K. Dwivedi, P.M. Pathak (2012), “Effects of electromagnetic stirring and rare earth compounds on the microstructure and mechanical properties of hypereutectic Al-Si alloys”, International Journal of Advanced Manufacturing Technology, volume 63, issue 1-4, pp 415-420.

[10] Prabhkiran Kaur, Dheerendra Kumar Dwivedi, Pushpraj Mani Pathak, Sergio Haro Rodriguez, (2011), “The effect of electromagnetic stirring and cerium addition on dry sliding reciprocating wear Al-Si alloy”, Proceedings of Institute of Mechanical Engineers Part J: Journal of Engineering Tribology. 226(30) 251-258.

[11] Dwivedi D K (2010), “Adhesive wear behavior of cast aluminium-silicon alloys: Overview”, Materials and Design, 31, pp. 2517-2531.

[12] Fang. X, Shao. G, Liu. Y. Q, Fan. Z. (2007), “Effects of intensive forced melt convection on mechanical properties of Fe containing Al-Si based alloy”, Material Science and Engineering A, 445-446, pp. 65-72.