Jurnal Teknologi

Full Paper

EFFECT OF THIXOFORMING ON THE WEAR PROPERTIES OF AL-SI-CU ALUMINUM ALLOY

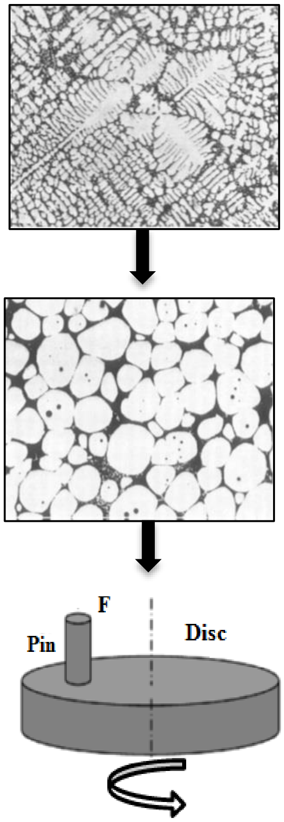
Khaled Salem Alhawari[a], Mohd Zaidi Omar[a*], Mariyam Jameelah Ghazali[a], Mohd Shukor Salleh[b], Mohammed Naser Abdulrazaq[c,d]

[a]Department of Mechanical and Materials Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Selangor, Malaysia
[b]Department of Manufacturing Process, Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia
[c]Department of Engineering & Technology, Faculty of Information Sciences and Engineering, Management & Science University, Selangor, Malaysia
[d]Center of Scientific Research and Development, Nawroz University-Kurdistan Region, Iraq

Article history
Received
30 August 2016
Received in revised form
13 November 2016
Accepted
13 March 2017

*Corresponding author
zaidiomar@ukm.edu.my

Graphical abstract



Abstract

In this study a hypoeutectic Al-6Si-3Cu aluminium alloy was synthesized using two different routes: the thixoforming process and the conventional mould casting process. The microstructural features, hardness and wear behavior of thixoformed alloy have been evaluated and compared with that of as-cast alloy. Cooling slope method was used to produce the non-dendritic microstructure feedstock for thixoforming. Thixoforming was carried out at 50% liquid fraction. The dry sliding wear behaviour of the produced alloys was investigated under two loads; namely, 10 and 50 N and 1m/s sliding speed for 9 km sliding distance. The thixoformed alloy exhibited globular primary phase morphology with fine and uniform distributed Si and intermetallic particles. On the contrary, dendritic primary phase, coarse flaky silicon particles and segregated microstructure has been observed in conventional cast alloy. Thixoformed alloy exhibited improvement in the wear resistance in comparison to the conventional cast alloy, which may be attributed to the microstructural enhancement resulting in improved hardness. The thixoformed samples displayed lower volume loss of ~16.20 mm^3 and ~42.40 mm^3 at loads of 10 and 50 N respectively compared with that of conventional cast samples. On the basis of observations and analyses on the wear rates and worn surfaces, the wear mechanism of the alloys was dominantly controlled by abrasive, adhesive and minor delamination.

Keywords: Thixoforming, cooling slope casting, microstructure, wear properties, Al-Si-Cu

1.0 INTRODUCTION

Semi-solid material processing is a promising processing technique, in which a material is forming at a temperature above the solidus and below the liquidus temperatures. The main advantages of semi-solid processing over the conventional processing are; near net shape forming capabilities in one step with high quality, a reduction of the solidification shrinkage since the material is already partially solid, low level of porosity and decreased macro segregation [1, 2]. Thixoforming is one type of semi solid metal processing which involves the preparation of feedstock material followed by partially re-melting the feedstock before forming to near net shaped products [3].

For thixoforming it is necessary to have a spheroidal non-dendritic structure of the solid phase, this microstructure can be obtained by a number of methods such as mechanical stirring, magneto hydrodynamic stirring, strain induced melt activation (SIMA), recrystallization and partial melting (RAP), grain refinement and cooling slop (CS) method [4, 5]. Among all methods, CS method possesses some advantages in comparison with other methods. The technique is simple and does not need complicated equipment [6]. The non-dendritic microstructure is produced by pouring the molten alloy with a modest amount of superheat on an inclined plate [7].

To date, most of the studies of thixoforming have concentrated on the microstructural evolution and how it affects the mechanical properties. These studies show that, relative to the conventional cast materials, thixoforming materials possess better mechanical properties, a combination of higher strength and ductility [8]. However, only very limited attention has been devoted to the wear behavior of these thixoforming materials [9, 10]. The wear properties of thixoforming alloys have not been studied sufficiently; literature did not show any systematic study relating the effect of the processing microstructures on wear properties. The objective of this work is to explain the wear behavior between a thixoforming A319 and the as-cast on the basis of the microstructural differences. This alloy was chosen because it is frequently used in automotive and aerospace industry and because it is scalable for thixoforming.

2.0 METHODOLOGY

2.1 Material Preparation

In this study, Al-6Si-3Cu (A319) aluminum alloy was used with the chemical composition consisting of Si (6.26wt %), Cu (2.96wt %), Mg (0.41wt %), Mn (0.15wt %), Zn (0.71wt %), Ni (0.06wt %), Fe (0.73wt %), Cr (0.03wt %), Ti (0.03wt %), and Al (remainder). Cooling slope casting was used to obtain the feedstock with non-dendritic microstructure. The cooling slope casting procedures and optimization were explained by authors in the previous work [11]. It was carried out at optimum conditions of 630˚C pouring temperature, 400 mm slope length and 60º inclined plate angle. The ingots obtained from CS were machined into 25 mm diameter, 110 mm length slugs and adapted to induction coil for reheating in semi-solid temperature. The required temperature for thixoforming was selected by considering the differential scanning calorimetry (DSC) data (Figure 1). The ingot temperature was controlled with a K-type thermocouple during heating process. The slugs were held for 5 min at the required temperature and then thixoformed by a 20 KN laboratory press.

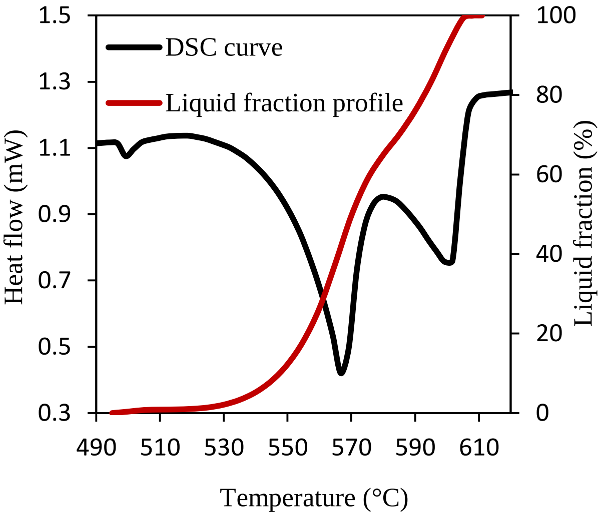


Figure 1 DSC curve and liquid fraction profile

2.2 Characterization

Samples were cut from the thixoformed and mould cast alloys for microstructural examination and hardness tests. The samples were prepared metallographically according to the standard grinding technique and etched with Keller's reagent. Microstructural examinations were performed by optical microscopy (OM), scanning electron microscopy (SEM). Hardness testing was carried out on a digital Rockwell hardness tester using a ball of 1/16 inch diameter and load of 100 kgf.

2.3 Wear Tests

To study the dry sliding wear behavior of the produced alloys, a pin-on-disc apparatus as per ASTM G99 was used. Pins with dimensions of 32 mm long, 10 mm diameter of alloy produced by an ordinary casting method and thixoforming process were prepared by wire cut set. M2 tool steel discs with 160 mm diameter, 8 mm thickness, and 62 HRC hardness were used as the counterface. The wear tests were done under applied normal loads of 10 and 50 N at a constant sliding speed of 1 m/s for a total distance of 9000 m at ambient temperature. The samples were cleaned with acetone in ultrasonic cleaner and weighed to an accuracy of ±0.1mg prior to testing and at every 30 minute intervals. The weight loss was converted to volume loss with the aid of a density measurement using Archimedes' principle. The worn surfaces were examined under SEM.

3.0 RESULTS AND DISCUSSION

3.1 Microstructure Analysis

Figure 2 demonstrates both optical and SEM micrographs of conventional mould cast A319 alloy. As it can be seen from the micrographs, the mould cast alloy consists of primary α-Al dendrites and interdendritic irregular eutectic regions. The eutectic region comprises large and individual flake eutectic silicon particles with different sizes (as shown in the right-corner of OM image), and some intermetallic phases such as θ-(Al_2Cu) white contrast, α-($Al_{15}(Mn,Fe)_3Si_2$) Chinese script and β-(Al_5FeSi) needle-like , Q-$Al_5Cu_2Mg_8Si_6$ Chinese script. Microstructural observation revealed that the distribution of Si particles and the intermetallic phases was non-uniform, and there is some pores in the sample.

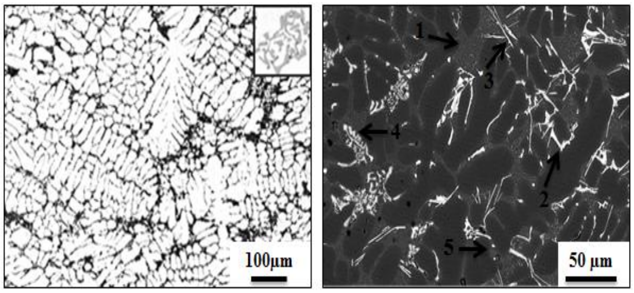


Figure 2 OM and SEM microstructures of the mould cast A319 alloy. (Arrows 1: Silicon, 2: Al_2Cu, 3: β-Al_5FeSi, 4: α-$Al_{15}(Mn,Fe)_3Si_2$, 5: Q-$Al_5Cu_2Mg_8Si_6$)

Cooling slope method was used to obtain a suitable non-dendritic microstructure feedstock for thixoforming. The microstructure of cooling slope cast samples was investigated in details by authors in the previous work [11]. Based on the DSC result, the knee temperature for this alloy, i.e. the temperature corresponding to the complete melting of the eutectic occurs at around 50% liquid fraction. Therefore, 571 °C is considered a suitable temperature for thixoforming A319 alloy. The slugs sectioned from CS-cast ingots were thixoformed at this temperature. Figure 3 shows the SEM and optical images of the thixoformed A319 alloy. As can be seen from the optical micrograph, the features of the thixoformed samples are typical of semi-solid state processing with predominantly fine solid α-Al globules surrounded by the eutectic liquid phase. The morphology of silicon particles considerably changed from large individual flakes to a fine skeleton network with Chinese script morphology. It is clearly seen from the SEM micrograph that the size of intermetallic has decreased considerably and their distribution is enhanced in comparison with the conventional cast samples. The (Q, α) intermetallic particle were observed polyhedral morphology in thixoformed alloy while they were observed Chinese script morphology in conventional mould cast alloy. It is further found that the as-cast needle-like β particles were fragmented to small plate. In addition, the quantity of the pores in the thixoformed alloy is significantly reduced as compared with the mould casting.

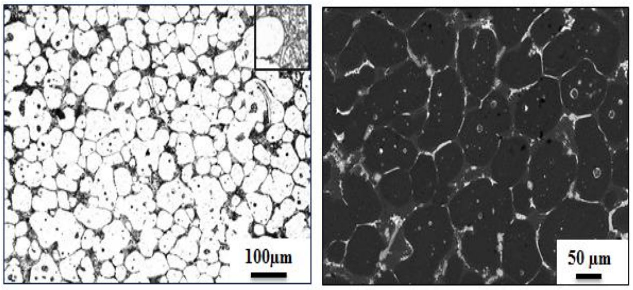


Figure 3 OM and SEM microstructures of the thixoformed A319 alloy

Hardness and density values of mould cast and thixoformed A319 alloys are presented in Table 1. The hardness and density values of the thixoformed alloy are higher than that of the conventional cast alloy. The difference in hardness between thixoformed alloy and the as-cast alloy is attributed to smaller globule size, better distribution of intermetallic particulates and porosity reduction.

Table 1 Measured hardness and density values of tested alloys

Alloy	Hardness (HRB)	Density (g/cm^3)
As-cast A319	35.4 ± 2.4	2.73
Thixoformed A319	43 ± 3.5	2.74

3.2 Wear Properties

3.2.1 Wear Loss

The variation of the wear volume loss with sliding distance is shown in Figure 4 at 10, 50 N loads for the conventional cast and thixoformed alloys. These results show that the wear volume loss increases with an increase in the sliding distance and the load irrespective of the alloy processing condition. Furthermore, the thixoformed samples display lower volume loss compared with the samples processed by the mould casting at both loads, which indicates an improvement in wear resistance.

According to the previous studies [12, 13], the wear resistance of Al-Si alloys is closely related to the microstructure of the alloys. It is known that the microstructural features like morphology, size and distribution of hard intermetallic phases have a large effect on the dry sliding wear properties of alloys [14]. Hence, the improved wear performance of the thixoformed A319 alloy compared to the mould cast alloy can be explained based on the microstructural features of the alloys as seen in the Figures 2 and 3. The small size and uniform distribution of the silicon and intermetallic phases in the matrix enhance the interfacial bonding between them and the matrix alloy that could assist in retaining the intermetallic particles within the matrix alloy [15, 16]. Compared with those of as-cast samples, applied pressure on thixoformed samples had significant effect on the reduction of porosity level and therefore, the formation of fractures can be reduced, implying the improvement in the wear performance. Therefore, the improvement in wear behavior observed in thixoformed samples can be attributed to the collective effects of low level of porosity, a small globular grain and uniform distribution and modification of silicon and intermetallic phases.

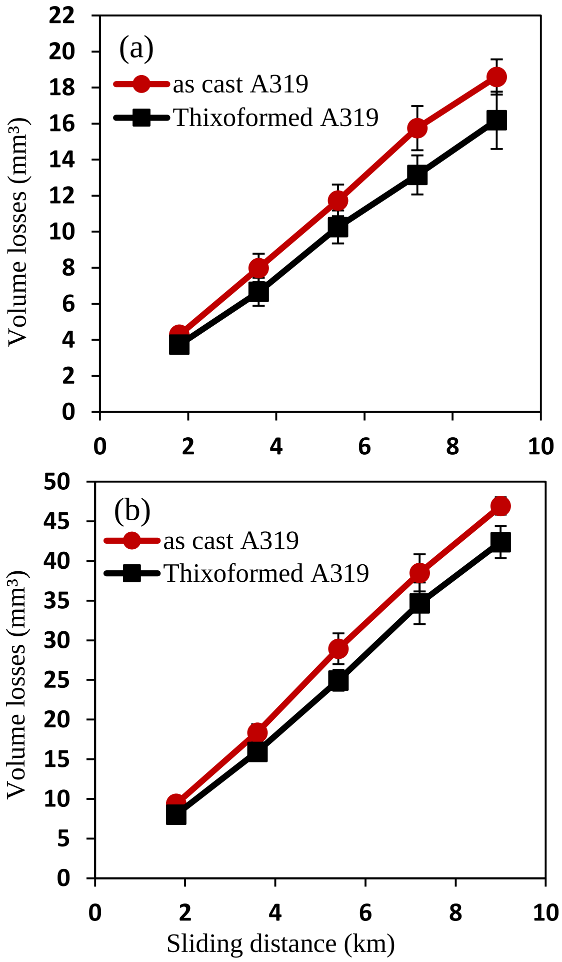


Figure 4 Volume losses as a function of sliding distance for: (a) 10 N and (b) 50 N of as-cast and Thixoformed A319 alloy

3.2.2 *Worn Surface Morphology*

Figure 5 shows the SEM morphologies of the worn surfaces of the as-cast and thixoformed A319 alloys at applied loads of 10 N, 50 N. From the micrographs it can be seen that the worn surfaces of as-cast alloy was more damaged than that of the thixoformed alloy. It is evident that the extent of wear in the thixoformed samples is lower than that of the as-cast.

At load of 10 N the worn surface of both alloys is characterized by deep parallel grooves which are indicative for abrasion wear, and small adhesive pits. Nevertheless, the worn surface of the as-cast sample was more heavily scored in comparison with that of the thixoformed sample. Based on the observation of the SEM images and the transverse subsurface cutting, the width and the depth of the continuous grooves on the conventionally cast sample are larger than those on thixoformed sample. The grooves width and depth on the worn surface of as cast alloy were up to ~50 µm and ~30 µm respectively. While on the worn surface of thixoformed alloy they were reduced to ~40 µm and ~25 µm respectively. At high load of 50 N, both samples' worn surfaces show similar features to those of the 10 N load samples but have bigger craters (up to 250 µm) particularly in the as cast alloy .

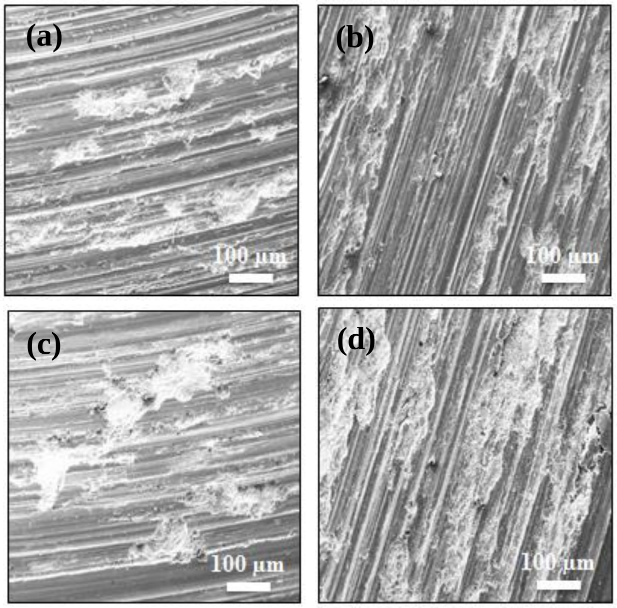


Figure 5 SEM morphologies of worn surfaces of (a) as-cast alloy at 10N, (b) thixoformed alloy at 10N, (c) as-cast alloy at 50N and (d) thixoformed alloy at 50N

3.2.3 *Friction Coefficient*

The curves of the coefficient of friction show significant fluctuations for both the as-cast and thixoformed alloys and the difference between them is insignificant. In this case to reduce the effect of these fluctuations an average coefficient of friction was estimated to provide a more comprehensive evaluation of the influence of thixoforming on the friction. Therefore, Figure 6 depicts the variation in the average coefficient of friction of the as-cast and thixoformed A319 alloys as a function of load. The results demonstrate that thixoforming process leads to a small improvement in the average value of the coefficient of friction at 10 N with values varying from 0.91 to 0.86, whereas at 50 N, both alloys show almost similar values of friction coefficient with very small difference. The reduction in the coefficient of friction of thixoformed alloy is owing to its higher hardness value[17].

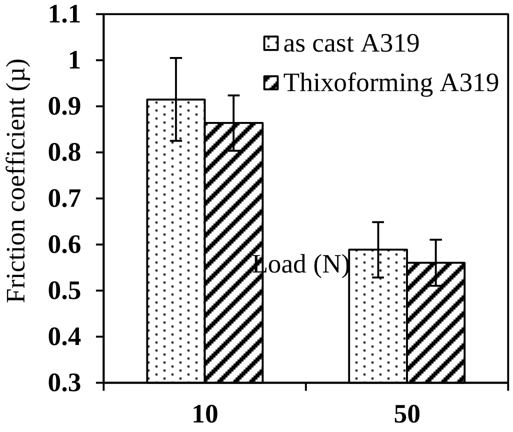


Figure 6 Average friction coefficient as a function of load for as-cast and thixoformed A319 alloys

4.0 CONCLUSION

Thixoforming process results in, transforming of Al dendrites of the conventional cast alloy into a fine globular one, modification of the silicon particles, and a uniform distribution of the silicon and intermetallic phases particles. The thixoformed A319 displayed higher hardness compared with the as-cast material. The thixoformed A319 exhibited better wear resistance and lower coefficient of friction compared with the as-cast material, this is believed to be due to the improved hardness value, which is linked to the significant enhanced microstructure of the thixoformed samples. The mechanism of wear for both alloys was a combination of, abrasion, adhesion and minor delamination.

Acknowledgement

The authors would like to thank Universiti Kebangsaan Malaysia (UKM) and Ministry of Higher Education (MOHE), Malaysia, for the financial support under research grants AP-2012-014 and FRGS/1/2014/TK01/UKM/01/2.

References

[1] Omar, M. Z., A. Alfan, J. Syarif, and H. V. Atkinson. 2011. Microstructural Investigations of XW-42 and M2 Tool Steels in Semi-solid Zones via Direct Partial Remelting Route. *Journal of Materials Science*. 46: 7696-705.

[2] Fan, Z. 2002. Semisolid Metal Processing. *International Materials Reviews*. 47: 49-85.

[3] Tahamtan, S., A. F. Boostani, and H. Nazemi. 2009. Mechanical Properties and Fracture Behavior of Thixoformed, Rheocast and Gravity-cast A356 Alloy. *Journal of Alloys and Compounds*. 468: 107-14.

[4] Haghdadi, N., A. Zarei-Hanzaki, S. Heshmati-Manesh, H. R. Abedi, and S. B. Hassas-Irani. 2013. The Semisolid Microstructural Evolution of a Severely Deformed A356 Aluminum Alloy. *Materials & Design*. 49: 878-87.

[5] Mohammed, M N., M. Z. Omar, M. S. Salleh, K. S. Alhawari, and P. Kapranos. 2013. Semisolid Metal Processing Techniques for Non-dendritic Feedstock Production. *The Scientific World Journal*. 2013: 1-16.

[6] Salleh, M. S., M. Z. Omar, K. S. Alhawari, M. N. Mohammed, MAM. Ali, and E. Mohamad. 2016. Microstructural Evolution and Mechanical Properties of Thixoformed A319 Alloys Containing Variable Amounts of Magnesium. *Transactions of Nonferrous Metals Society of China*. 26: 2029-42.

[7] El-Mahallawi, IS-E., T. S. Mahmoud, A. M. Gaafer, and F. H. Mahmoud. 2015. Effect of Pouring Temperature and Water Cooling on the Thixotropic Semi-solid Microstructure of A319 Aluminium Cast Alloy. *Materials Research*. 18: 170-6.

[8] Tahamtan, S., M. A. Golozar, F. Karimzadeh, and B. Niroumand. 2008. Microstructure and Tensile Properties of Thixoformed A356 Alloy. *Materials Characterization*. 59: 223-8.

[9] Birol, Y., F. Birol. 2008. Wear Properties of High-pressure Die Cast and Thixoformed Aluminium Alloys for Connecting Rod Applications In Compressors. *Wear*. 265: 590-7.

[10] Vencl, A., I. Bobić, and Z. Mišković. 2008. Effect of Thixocasting and Heat Treatment on the Tribological Properties of Hypoeutectic Al–Si alloy. *Wear*. 264: 616-23.

[11] Salleh, M. S., M. Z. Omar, J. Syarif, K. S. Alhawari, and M. N. Mohammed. 2014. Microstructure and Mechanical Properties of Thixoformed A319 Aluminium Alloy. *Materials & Design*. 64: 142-52.

[12] Prasad, B. K. 1997. Dry Sliding Wear Response of Some Bearing Alloys as Influenced by the Nature of Microconstituents and Sliding Conditions. *Metallurgical and Materials Transactions A*. 28: 809-15.

[13] Prasad, B. K., K Venkateswarlu, O. P. Modi, and A. H. Yegneswaran. 1996. Influence of the Size and Morphology of Silicon Particles on the Physical, Mechanical and Tribological Properties of Some Aluminum-Silicon Alloys. 15: 1773-6.

[14] wang, Y., W. M. Rainforth, H. Jones, and M. Lieblich. 2001. Dry Wear Behaviour and Its Relation to Microstructure of Novel 6092 Aluminium Alloy–Ni3Al Powder Metallurgy Composite. *Wear*. 251: 1421-32.

[15] Anasyida, A. S., A. R. Daud, and M. J. Ghazali. 2010. Dry Sliding Wear Behaviour of Al–12Si–4Mg Alloy with Cerium Addition. *Materials & Design*. 31: 365-74.

[16] Alhawari, K. S., M. Z. Omar, M. J. Ghazali, M. S. Salleh, and M. N. Mohammed. Dry sliding wear behaviour of thixoformed. 2016. Hypoeutectic Al–Si–Cu Alloy with Different Amounts of Magnesium. *Composite Interfaces*. 23: 519-31.

[17] Majzoobi, G. H., A. Atrian, and M. H. Enayati. 2015. Tribological Properties of Al7075-SiC Nanocomposite Prepared by Hot Dynamic Compaction. *Composite Interfaces*. 22: 579-93.