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The wear rates and performance of three mold insert materials

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ABSTRACT

In this study, a rapidly solidified aluminum alloy was compared with beryllium copper and 6061 aluminum alloys in terms of their wear rates, hardness and performance as mold insert materials. A Vickers hardness measuring machine and a tribometer were used to determine the hardness values and wear rates of the materials. Three sets of mold inserts were made of these materials, and the insert surfaces and the molded plastic lens surfaces were characterized using a scanning electron microscope and a surface profilometer, respectively. The investigation results indicate that the BeCu alloy has the lowest wear rate, while aluminum 6061-T6 has the highest wear rate. Although the rapidly solidified aluminum alloy is not as hard as the BeCu alloy, the differences between their wear rates and hardness values are not as great as the differences between aluminum 6061-T6 and the BeCu alloy. The results also indicate that the rapidly solidified aluminum alloy performs much better than aluminum 6061-T6 in molding of plastic lenses and is comparable to the BeCu alloy. It is able to attain finer surfaces of the molded plastic lenses. This is an important finding, and this means that the rapidly solidified aluminum alloy can replace the BeCu alloy as a good mold insert material, because beryllium (Be) is a toxic element. The finding gives the industry a better choice for selection of mold insert materials.

1. Introduction

High technologies continue to be developed for the design and manufacturing of advanced products made of advanced materials [1–3]. Advanced technologies have also been developed for various applications on micro-scales such as micro-lenses, micro-sensors [4,5], micro-machining [6], micro-actuators [7], micro-systems [8], and micro-assemblies [9]. Molding plays an important role in the manufacturing industries, and many products including micro components such as micro-lenses are manufactured by molding, which is widely adopted in the plastic and glass lens production, automobile, aerospace, and other manufacturing industries, as it has many advantages over the processes for manufacturing of products one by one [10–13]. The materials widely used for making lens mold inserts are mainly 6061 aluminum alloys, beryllium copper alloys and nickel coated steel alloys [14].

One preferred metal for making industrial mold inserts is aluminum, although the advantages of aluminum have decreased due to its strength and wear-resistance limitations [10,13,14]. Aluminum 6061-T6 is a good choice for fast prototyping of mold inserts [14]. It is highly machineable, which enables fast cutting [13,14] and diamond turning [15]. Its low specific density allows ease during mold making, assembling, and setting up of the molding machine [13], and therefore lowers the manufacturing cost. However, it has lower strength than beryllium copper and nickel coated steels [13,14]. In the molding process, the high temperature of the polymer melts degrades the insert surface and the entire mold [14].

Beryllium copper is another preferred mold insert alloy [6]. Its mechanical and thermal properties such as wear-resistance behavior are based on its chemical compositions [13]. This metal has high temperature conductivity, enabling high production speeds [16]. It is suitable for molding on a large production scale because of its relatively high strength [13,14], which on the other hand requires relatively costly tools for machining.

Steel alloys are often used in making of molds, because they can have improved strength, reliable mold functioning, and long service lives, while their high strength hinders the machinability and increases the production cost [13]. Very often, polishing of steel molds has to be conducted [17,18]. Furthermore, steel alloys cannot be simply turned using a single-point diamond tool because of the rapid tool wear, which requires the use of a special vibration-assisted cutting system to reduce the cutting force and tool wear [19]. Coating a layer of nickel on steels can enhance the machinability, but this also increases the production cost [13] and time.

The quality of molded lenses very much depends on the surface topographic condition of the mold insert, and with the advancement in material sciences, materials with better strength and

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machinability (leading to better surface finish) can be produced [10,13,14]. Aluminum alloys produced by rapid solidification processing are such examples [20]. A process called rapid solidification has been introduced, which can produce properties and microstructures much better than those of the conventionally-cast alloys [10].

Rapid solidification processing involves rapid extraction of thermal energy during the transition of liquid state at high temperatures to solid materials [10]. The solidification rate plays an important role in the refinement of alloy structures, and significantly influences the mechanical properties [21,22]. A high cooling rate and a short solidification time can result in the formation of a refined microstructure [22].

In this study, a rapidly solidified aluminum alloy was compared with beryllium copper and 6061 aluminum alloys in terms of their wear rates, hardness and performance as mold insert materials.

2. Methodology and materials

Having the right steps to design and make an injection mold is important as this determines the performance of the molding process [13]. In this study, the molds produced have a cavity insert and a core insert with dimensions of 100 mm × 60 mm × 18 mm and 100 mm × 60 mm × 13 mm, respectively. The core insert has a spherical convex surface and the cavity insert has a spherical concave surface, for molding a plastic lens with spherical surfaces of 15 mm radii and a thickness of 2 mm.

Three sets of the pattern inserts of the molds were made of three materials. Two of them are commonly used in the industry as mold insert materials for manufacturing of optical lenses: a beryllium copper alloy (UNS C17200) and an aluminum alloy (6061-T6). The other material is a rapidly solidified aluminum alloy (RSA 905 [20]).

The rapidly solidified aluminum alloy investigated in this study is produced by melt-spinning. The process applies a sudden temperature drop at over 1,000,000 K/s when the molten alloy at 800 °C hits a fast rotating copper wheel and instantaneously releases a continuous metal ribbon at 20 °C, which is converted to flakes by a chopper as the raw material for metal extrusion [20]. With extremely rapid solidification during melt-spinning, the crystalline structure in the alloy is very small [10,20], and inter-metallic compounds and insoluble components are distributed to form a fine microstructure with high strength [20], leading to smooth surfaces after diamond cutting or polishing [20,23].

The body components of the pattern inserts were machined using a CNC milling machine. The spherical convex surfaces of the core inserts were machined using a CNC turning machine. The spherical concave surfaces of the cavity inserts were machined by single-point diamond turning using an ultra-precision turning machine at a depth of cut of 6 μm, a workpiece rotational-speed of 2000 rpm, and a feed rate of 5 μm/rev. Figs. 1 and 2 show the mold inserts produced.

An injection molding machine was used to evaluate the performance of the mold inserts. Incorrect process parameters may lead to defects such as air bubbles, incompletion, or even burn marks on the surfaces of the plastic lenses [24]. Therefore, the mold inserts were carefully tested to determine the molding parameters, which are shown in Table 1. Then, 1500 pieces of plastic lenses were produced using each of the three sets of the mold inserts.

As the surface quality of mold inserts directly affects the quality of the plastic lens molded, a scanning electron microscope (SEM) was used to analyze the surfaces of mold inserts. Surface profilometers are also commonly used for surface characterizations [25,26]. In this work, a surface profilometer was used to determine

Table 1
Parameters used in the injection molding process.

Injection pressure	628 kg/cm^2
Injection rate	22.6 cm^3/sec
Barrel temperature	240 °C
Holding pressure	94.2 kg/cm^2
Holding time	5 s
Cooling time	10 s
Total cycle time	20.4 s
Shot size	20 mm

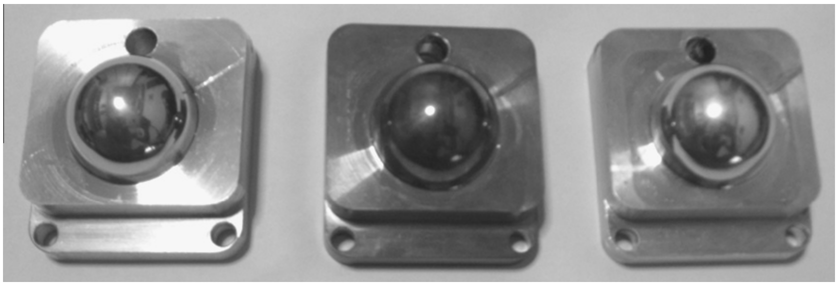

Fig. 1. Core inserts with spherical convex surfaces machined using a CNC turning machine.

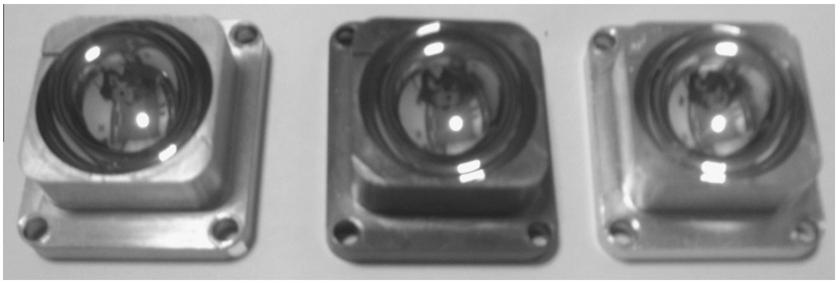

Fig. 2. Cavity inserts with spherical concave surfaces machined using an ultra-precision turning machine.

Table 2
Testing conditions to determine the wear rates using the tribometer.

Cutting tool	A steel ball with a diameter of 6 mm
Velocity	10 cm/s
Distance	1 km
Load	2 N

the surface texture of the plastic lenses produced using the three sets of mold inserts. The surface roughness heights of the 1st, 500th, 1000th, 1250th, and 1500th pieces of the plastic lenses produced using every set of the three mold inserts were measured.

The hardness and the wear-resistance of an insert surface are important indicators of the insert life and durability. The three materials were machined to circular disk specimens with a diameter of 45 mm and a thickness of 4.3 mm. A Vickers hardness measuring machine was used to determine the hardness of the specimens made of the three materials. A tribometer was used to determine the wear rates of the specimens made of the three materials, under the testing conditions shown in Table 2. A new steel ball was used for every new wear test, and three readings were taken for every weight measurement.

3. Results and discussions

Fig. 3 shows SEM micrographs of the spherical concave surfaces of the three mold inserts machined using the ultra-precision turning machine. Based on the SEM observation, after the diamond turning, the insert surface of the rapidly solidified aluminum (RSA) alloy had the best surface texture, followed by the surfaces of the beryllium copper alloy and the aluminum alloy 6061-T6. Dimples could be seen on the insert surface of 6061-T6. Compared with the machined insert surface of the rapidly solidified aluminum alloy, the cutting streaks were deeper on the machined insert surface of the beryllium copper alloy.

One reason for the fine surface finish of the rapidly solidified aluminum alloy is its fine microstructure formed in the rapid solidification process. During the extremely fast solidification, the crystalline structure formed in the material is very small (about the size of 2 μm), and both the number and the size of segregated phases are reduced. In other words, the main mechanism to affect the microstructural refinement is to cool down the material at a speed of, for example, over 1,000,000 K/s, leading to a freezing phenomenon of the liquid alloy with very fine grain sizes and superior properties [10,20]. As inter-metallic compounds and insoluble components are distributed in a fine homogeneous manner over the aluminum matrix, forming a favorable microstructure of the rapidly solidified aluminum alloy [20], a very smooth surface can be obtained after the diamond turning.

Fig. 4 shows the total average surface roughness (R_a) values of the convex surfaces of the plastic lenses produced by the cavity inserts made of the aluminum alloy (6061-T6), the beryllium copper (BeCu) alloy, and the rapidly solidified aluminum (RSA) alloy. The total average surface roughness values in this figure were calculated based on all of the roughness measurement readings for the convex surfaces of all the 1st, 500th, 1000th, 1250th, and 1500th pieces of the plastic lenses produced using each set of the three mold inserts. In general, as shown in Fig. 4, among the three mold inserts, the cavity insert made of the rapidly solidified aluminum alloy resulted in plastic lens surfaces with the best surface finish, and the cavity insert made of 6061-T6 led to plastic lens surfaces with the worst surface texture. The reasons for the differences are considered and explained in the next paragraphs.

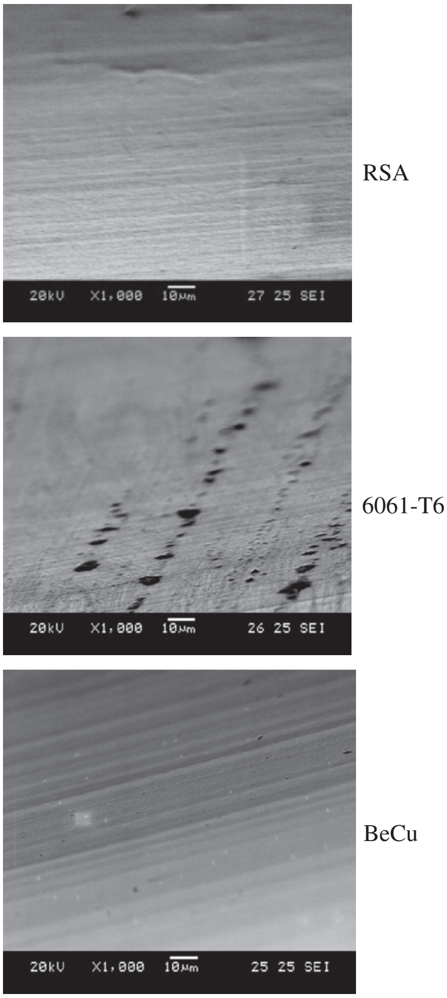

Fig. 3. SEM micrographs of the spherical concave surfaces of the three mold inserts machined using the ultra-precision turning machine.

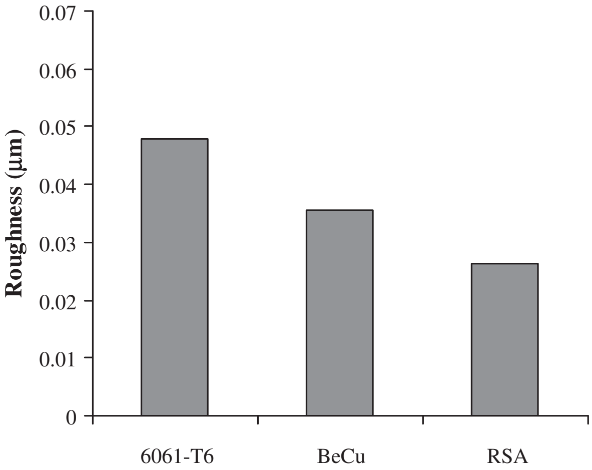

Fig. 4. The total average surface roughness (R_a) values of the convex surfaces of the plastic lenses produced by the cavity inserts made of the aluminum alloy (6061-T6), the beryllium copper (BeCu) alloy, and the rapidly solidified aluminum (RSA) alloy.

Fig. 5 shows the respective surface roughness (R_a) values of the convex surfaces for the 1st, 500th, 1000th, 1250th, and 1500th pieces of the plastic lenses produced by the cavity inserts made of the aluminum alloy (6061-T6), the beryllium copper (BeCu) alloy, and the rapidly solidified aluminum (RSA) alloy. For every roughness measurement, seven scans were performed, seven

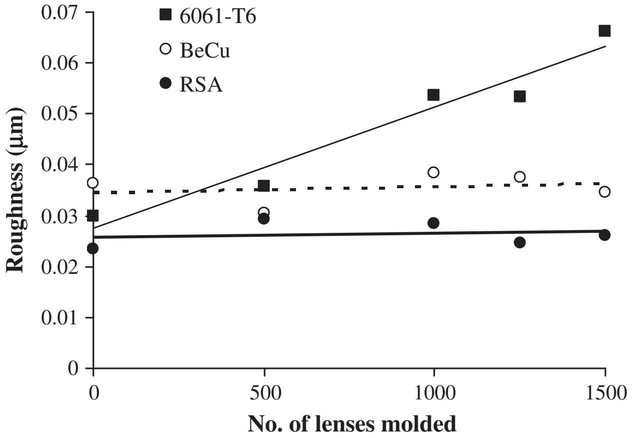

Fig. 5. The respective surface roughness (R_a) values of the convex surfaces for the 1st, 500th, 1000th, 1250th, and 1500th pieces of the plastic lenses produced by the cavity inserts made of the aluminum alloy (6061-T6), the beryllium copper (BeCu) alloy, and the rapidly solidified aluminum (RSA) alloy.

readings were taken, and an average roughness value was obtained for that measurement, which is shown in Fig. 5 using a marker (●, ○ or ■).

As shown in Fig. 5, the differences of the average roughness values of the 1st pieces of the plastic lenses produced by the cavity inserts made of the three materials are relatively small. However, the plastic lens surfaces produced by the cavity insert made of 6061-T6 have significant deterioration of their surface texture with increased surface roughness heights over 1500 molding operations. In contrast, the figure demonstrates the good stability in maintaining good surface quality of the plastic lens surfaces produced by the cavity inserts made of the beryllium copper alloy and the rapidly solidified aluminum alloy. This performance difference of the three insert materials can be explained by investigating the hardness and wear rate values of the insert materials.

Figs. 6 and 7 show the measured Vickers hardness and wear rate values of the three insert materials investigated, and they demonstrate that the harder a material is, the lower its wear rate is. Among the three insert materials investigated, the beryllium copper (BeCu) alloy is the hardest, has the lowest wear rate, and therefore is most likely to result in the longest mold insert lifespan and has the good stability in maintaining good surface quality of the produced plastic lens surfaces as illustrated in Fig. 5. In contrast, the aluminum alloy (6061-T6) is the softest, has the highest wear rate (about 1440 and 672 times higher than those of the beryllium copper and rapidly solidified aluminum alloys, respectively), and thus leads to the shortest mold insert lifespan, among the three insert materials, producing the plastic lens surfaces that have significant deterioration of their surface texture with increased surface roughness heights over 1500 molding operations as indicated in Fig. 5.

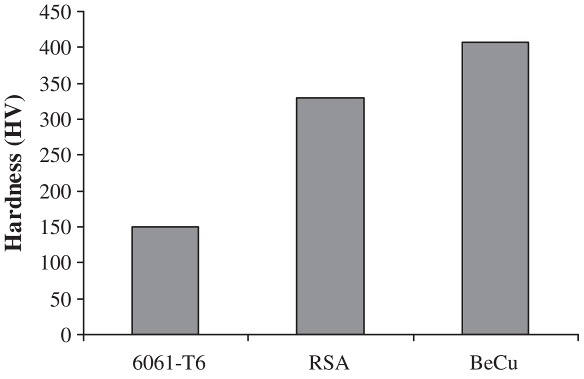

Fig. 6. The measured Vickers hardness values of the three insert materials: the aluminum alloy (6061-T6), the beryllium copper (BeCu) alloy, and the rapidly solidified aluminum (RSA) alloy.

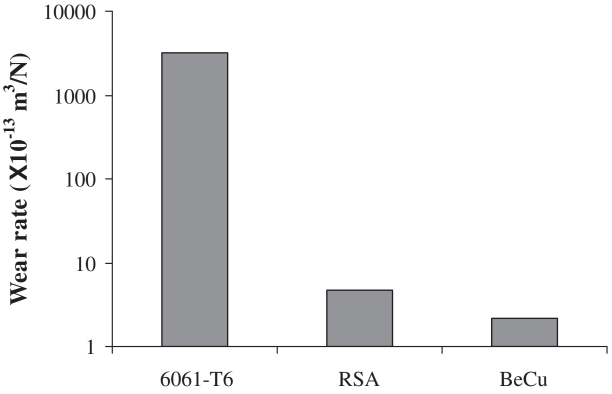

Fig. 7. The measured wear rate values of the three insert materials: the aluminum alloy (6061-T6), the beryllium copper (BeCu) alloy, and the rapidly solidified aluminum (RSA) alloy. Note: the *Y*-axis in this figure is on a log scale.

The rapidly solidified aluminum (RSA) alloy is ranked the second in terms of the hardness and wear-resistance among the three materials. Although it is not as hard as the beryllium copper alloy, the differences between their wear rates and hardness values are not as great as the differences between the aluminum alloy (6061-T6) and the beryllium copper alloy. Therefore, the mold insert lifespan and the performance of the rapidly solidified aluminum alloy may not differ so much from that of the beryllium copper alloy. As already shown in Fig. 5, both mold inserts made of the beryllium copper alloy and the rapidly solidified aluminum alloy demonstrated good stability in resulting in stable and good surface finish of the molded plastic lenses, which did not deteriorate much after 1500 molding operations, despite that the rapidly solidified aluminum alloy has a slightly lower wear-resistance than the beryllium copper alloy.

Rapid solidification of micro-crystalline alloys produced by melt-spinning can result in a new generation of aluminum alloys with superior strength, comparable to titanium [27]. Increasing the cooling rate to 5×10^7 K/s by melt-spinning can lead to super-saturation of the aluminum matrix and the formation of nanometric precipitates [28]. The micro-hardness of the melt-spun hypoeutectic aluminum alloy can be an improvement of 2.7 times than that of the conventionally-cast aluminum alloy because rapid solidification has a significant impact on the alloy hardness [29].

Among the three materials investigated, the BeCu alloy was the hardest, and had the lowest wear rate. The mold insert made of the BeCu alloy demonstrated good stability resulting in stable and good surface finish of the molded plastic lenses. However, similar to lead-containing materials, beryllium-containing materials may cause some concerns depending on individual cases. According to the literature, beryllium poses a health risk, because beryllium is a toxic element and is responsible for a lung disease called chronic beryllium disease [30–32]. A journal article entitled “Beryllium: A Modern Industrial Hazard” [33] reports detailed research findings and preventive management. According to the Internet, BeCu does not pose a particular health hazard in a solid form as a finished part, but breathing its dust formed by machining or welding may cause a serious problem [34]. It presents a health risk only if it is mishandled, most manufacturing operations performed properly can safely process BeCu, and the risk from fine particulates can be minimized using proven engineering controls [35].

Materials play a crucial role in design and manufacturing processes, and selection of proper materials is one most challenging task for engineering applications [36–38]. Because of the increased demand for environmentally responsible developments and more stringent environmental requirements derived from the legislation [39], not only the technical performance of the materials but also the health and environmental factors should be considered for the manufacturing of cleaner and more sustainable products [40–42]. Researchers now increasingly pay attention to the impacts of design and manufacturing processes on our environment and health. There has been more interest in making manufacturing technologies more environmentally and economically attractive [43–47], and in manufacturing and processing hazard-free materials [48–52]. More regulations demand a reduction in environmental and health impacts of the materials used in manufacturing [53]. One key objective of the environmental policies is to integrate economic growth, welfare and environmental sustainability [54]. Because global trade agreements become more stringent, obedience to environmental regulations for manufacturers becomes more expensive [55]. However, actions must be taken as early as possible for the manufacturing of products to reduce their overall environmental impacts [56]. This global trend may have to be taken into account when we select and process any materials.

4. Conclusions

Among the three insert materials investigated, the BeCu alloy is the hardest and has the lowest wear rate, while aluminum 6061-T6 is the softest and has the highest wear rate. Although the rapidly solidified aluminum alloy is not as hard as the BeCu alloy, the differences between their wear rates and hardness values are not as great as the differences between aluminum 6061-T6 and the BeCu alloy. The investigation results indicate that the rapidly solidified aluminum alloy performs much better than aluminum 6061-T6 in molding of plastic lenses and is comparable to the BeCu alloy. It is able to attain finer surfaces of the molded plastic lenses. This is an important finding, and this means that the rapidly solidified aluminum alloy can replace the BeCu alloy as a good mold insert material, because beryllium (Be) is a toxic element. The finding gives the industry a better choice for selection of mold insert materials.

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