Fabrication and bonding of single crystal silicon

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ABSTRACT

Single Crystal Silicon (SCSi) is a versatile material and is seeing increased use for mirrors and telescopes. In the past, small boule size and the brittle nature of the material have restricted its applications, but that is no longer the case. After much development and testing, we can now fabricate SCSi with near zero surface damage/residual stress and utilize the in-house developed bonding methods to fabricate much larger substrates than available SCSi boules. More importantly, these bonding techniques enable us to bond-in threaded metal inserts for attachments, thereby eliminating the risk of putting threads directly into SCSi components.

Keywords: single crystal silicon, superfinishing, bonding, epoxy, solder, frit, Invar 39 (39Ni/Fe), telescope

1. INTRODUCTION

Single Crystal Silicon (SCSi) is a versatile material and is seeing increased use for mirrors and telescopes as shown in Fig.7. The zero defect nature of the single crystal boules allows for rapid machining and near perfect mirror finishes. And after a number of years of testing, it is now possible to utilize the bonding methods developed to fabricate large substrates in excess of one meter, bond together multi-part components and bond ductile metal inserts for attachments between components.

2. THE MATERIAL

The key to producing stress-free SCSi components is the starting material. McCarter uses only zero-defect, near perfect single crystal boules that are free of residual stress. This enables rapid machining with conventional CNC machines and tools. Boules are readily available from several suppliers in sizes to 300mm diameter, 800mm long as shown in Fig. 1. Larger sizes have also been drawn, but frit bonding makes it possible to build up blanks to sizes in excess of one meter.

3. SHAPING AND FINISHING

Boules are trimmed and etched followed by machining to near shape. When large components are required, surfaces of plank shaped parts are match machined and frit bonded before machining to shape[1]. McCarter's patented superfinishing process[2-4] provides the final low sub-surface damage (SSD) surfaces ready for bonding. Fig. 2 illustrates a surface plate fabricated from frit bonded SCSi planks with a superfinished surface. Superfinishing has been shown to impart better dimensional stability with both time and temperature than other machined or ground surfaces. The finish provided has ≤5μm of SSD and is ready for single point diamond turning and final polishing.

SCSi is readily machined to intricate shapes as shown in Figs. 3 and 4. These components were bonded together into a 28 inch diam. cooled laser mirror[5]. Lightweight mirror cores can be fabricated using CNC machines, ultrasonic machining or abrasive water-jet cutting, whichever is most cost effective considering the complexity of the part.

Mirror finishing is accomplished with a combination of diamond turning, conventional polishing and/or magneto-rheological finishing and near perfect smoothness can be obtained.

4. BONDING AND INSERTS

Due to the brittle nature of Si it should be kept in compression and defects are not allowed. This means that tapping into SCSi would lead to disaster. Therefore bonded-in ductile metal inserts are required. The metal chosen for inserts was Invar 39 (39Ni/Fe), primarily for its close match of coefficient of thermal expansion (CTE) with SCSi over a relatively wide temperature range.

Possible bonding agents for SCSi-SCSi and SCSi-metal fall into three categories: polymer adhesives, solders and frit and/or glass bonding. All have been used, but primary usage is for semiconductor applications. Bonding of SCSi for mirrors and telescopes has been little studied except for the work of Frank Anthony, et al[1,6-7]. In the earliest work[6], adhesives were rejected without testing due to high CTE, moisture sensitivity and outgassing. Over a decade later, TRW looked at frit bonded and Al brazing[8]. They chose brazing for the lower temperature, but the joint was degraded by the Al-Si interaction resulting in a brittle, low strength layer. Experimental bonding tests at Argonne National Labs[9] showed that frit bonded SCSi "… shows the least strains among the crystals we have fabricated so far." More recent work describes successful fabrication and testing of frit bonded lightweight SCSi mirrors[10]. The work reported here examined all reasonable possibilities, and was supplemented with additional testing. Recent SBIR programs at McCarter have looked at bonding of 39Ni/Fe inserts to SCSi using polymers, solders and frit.

Polymers, such as 3M Scotch-Weld 1838 green and 2216 gray[11], have been used with mixed success. Anecdotal evidence suggests low temperature distortions and even fracture from CTE differences. While polymer adhesives have the advantage of low cost, room temperature cure and high strength, the disadvantages outweigh the advantages: high CTE, shrinkage induced strain, dimensional instability, slow outgassing and moisture sensitivity, as well as little control over precise placement and bond line thickness. Therefore, polymer adhesives were not considered viable and were not tested.

Solder has been studied for many years, as noted by Anthony[6], and while there are successes, the difficulties are significant, the two most significant being the solder wetting SCSi and the formation of brittle intermetallic phases. Thin film barrier layers are a possibility, but uniform deposition in blind holes is extremely difficult. And there is still the issue of CTE compatibility. For our testing, we chose a gold/tin (Au/Sn) solder with metallic multi-layer barrier coatings.

Based on prior testing[5,10], we chose two frits with different firing temperatures that best match both SCSi and 39Ni/Fe for strength and CTE match. As a comparison with the prior testing where the frit was applied directly to SCSi, the frits were applied over thin film metallization.

We tested threaded metal inserts bonded into SCSi blocks as shown in Fig. 5. Test results showed that metallization did not significantly increase bond strength of either frit, with breaking loads of 350 to 450 lbs in the SCSi, roughly comparable to the compressive fracture strength of SCSi. Soldering of inserts to SCSi was very difficult and not always successful. All soldered joints failed in handling or at negligible loads.

We evaluated cost of bonding, and as shown in Figure 6, the actual cost of attaching one metal insert with epoxy is $230, with solder is $3100, and with frit is $1215.

In summary, the relative characteristics of the three bonding agents are:

Epoxy bonding may be the cheapest, but has low creep strength, temperature and chemical resistance, large CTE mismatch to SCSi and potential for outgassing,

Solder is the most expensive, is sensitive to elevated temperature, has very low fatigue strength and also has a large CTE mismatch, and

Glass frit has moderate cost, is the most dimensionally stable at all temperatures and has the greatest production repeatability.

5. SUMMARY

We have shown that SCSi is a near-perfect material that is readily machined into complex shapes and finished with near-zero SSD for stable mirrors and structures. When larger blanks are required, machined planks cut directly from available boules can be frit bonded to obtain blanks greater than one meter in size. Frit bonding is the most reliable and stable method for attaching SCSi both to 39Ni/Fe and to itself.

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Figure 1. 300mm SCSi Boule.

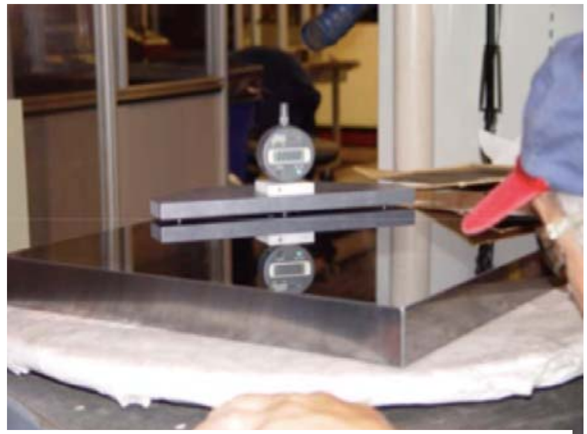

Figure 2. Frit-Bonded/superfinished 500mm SCSi surface plate.

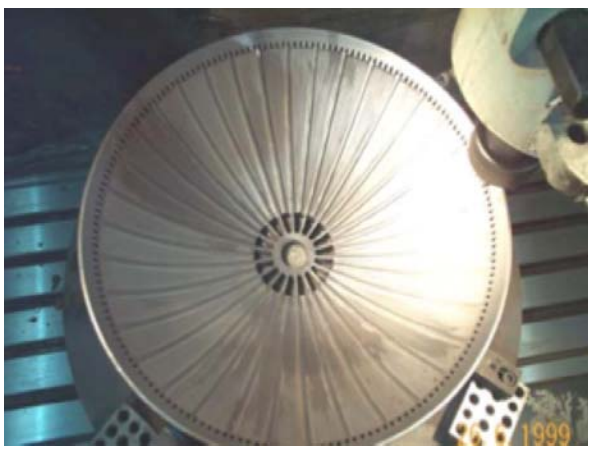

Figure 3. Core drilling produced 0.49mm dia. x 157mm long cores - 711mm frit-bonded cooled mirror.

Figure 4. Slotting and boring across frit-bonded 711mm structure.

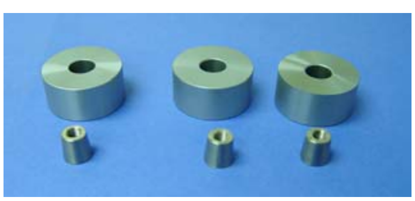

Figure 5. Bond strength pull test specimens.

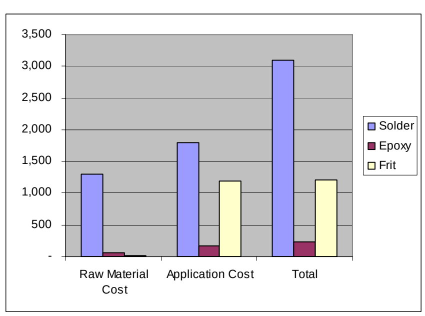

Figure 6. Actual cost comparison of 39Ni/Fe to SCSi bonding.

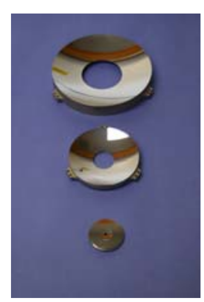

Figure 7. Silicon Frit-bonded Telescope Mirrors.