High heat load optics: an historical overview

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Abstract. As power levels of synchrotron beamlines increase, the heat flux on optical components attains or exceeds levels of that for high-energy laser (HEL) optics. The synchrotron technical community may benefit from the experiences gained as a result of the development activities associated with cooled mirrors for HELs. Such activities span a period of about 25 years, consider numerous design concepts, and evaluate many construction materials along with related fabrication processes. The quantity of work performed on cooled mirrors for HELs is too extensive to allow a single paper to summarize all potentially useful information. The purpose of this overview is to highlight much of the past work, with emphasis on more recent technology, and to provide a bibliography that should aid in accessing pertinent literature. Although heat loads are similar, hundreds of watts per square centimeter, some aspects of the laser and synchrotron application differ. Generic characteristics of each are summarized before prior cooled laser mirror technology is discussed. This should allow a meaningful assessment of the applicability of prior heat exchanger designs, material selections, and operational experiences to synchrotron beamline usage.

Subject terms: high heat flux; cooled mirrors; laser mirrors; synchrotron mirrors; high-energy lasers.

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1 Introduction

In the 1960s interest emerged in high-energy lasers (HELs) for possible military applications. During the past 30 years analytical studies were conducted to assess the merits of HELs for defense against aircraft and missile attacks. Assumed power levels ranged from kilowatt to megawatt magnitudes in continuous-wave and pulsed modes of operation. System concepts included shipboard devices for fleet defense as well as airborne, ground-based, and space-based devices for the protection of ground-based assets. Concurrent with the system studies were efforts to develop and experimentally evaluate a number of HEL devices that included gas dynamic, electric discharge, chemical, and free electron types. An essential element of the HEL device is the optical subsystem that includes resonator and beamline mirrors subjected to high heat loads. Because of the severity of the heating conditions it is necessary to actively cool the laser mirrors.

The technological sophistication of cooled laser mirrors has been inversely related to the wavelength of the laser devices of interest. The earliest high-powered devices operated on 10.6 μm; later devices of interest utilized wavelengths of 3.8, 2.7, and approximately 1 μm. As wavelength was reduced, sophistication increased because allowable distortion is a function of the operational wavelength. Initially, the organizations intimately involved with HELs addressed the optical issues as part of the device itself. Later, optical component specialists participated in the technology development. The major supplier of cooled laser mirror substrates over the last 25-year period was United Technologies Corporation; activities were associated with various corporate organizations, Pratt and Whitney, United Technology Research Center, and United Technology Optical Systems. Other early participants included Air Research, Avco, Hughes Aircraft, and Rocketdyne. Later contributors included Bell Aerospace, ltek, Perkin-Elmer, TRW, and Thermacore. The Bell Aerospace technology now resides at Rocketdyne–Albuquerque Operation. All of these organizations contributed to the technology development. However,

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United Technology supplied more cooled laser mirror substrates, most fabricated from molybdenum, than all others combined.

All three of the military services sponsored HEL programs that spawned initial development of cooled mirrors. When shorter laser wavelengths became of interest, demands on optical components increased and greater emphasis was directed toward improving cooled mirror performance. The Air Force Weapons Laboratory, now the Air Force Phillips Laboratory, sponsored much technology development. The Strategic Defense Initiative Organization (SDIO) sponsored much of the most recent work through the Air Force Weapons Laboratory/Phillips Laboratory, the Air Force Materials Laboratory, the Los Alamos National Laboratory, and the MIT Lincoln Laboratory.

Because interest in HELs has waned, many of the organizations that participated in the development of cooled laser mirror substrates are no longer active developers/suppliers of such optical components.

Technology development incorporated simultaneous advances in heat exchanger designs, material selection, and fabrication processes. For convenience, each area is discussed separately as related to mirror substrates. Polishing aspects are not discussed.

2 Requirements for Laser and Synchrotron Optics

The local heat fluxes absorbed in cooled laser and synchrotron mirrors cover the same general range, but the unique characteristics of each type of beamline must be considered when transferring technology from one to the other. In the HEL, a near circular beam is reflected, at near normal incidence, by a relatively large number of mirrors, from about 6 to 20, each separated by less than 100 m. The laser beam is relatively large in diameter, although usually less than 50 cm, as it passes through the optical train and is focused on its target after passing through a beam director. The laser beam train usually contained corrective optics such as dither and/or deformable mirrors. Most of the energy is concentrated in the central 75% of the beam diameter, the central half of the beam area. Rarely is the angle of incidence greater than 45 deg.

In contrast, the synchrotron beamline utilizes relatively few mirrors set at grazing incidence to enhance reflectivity and to spread the high-intensity beam in order to reduce the heat flux absorbed by the mirrors while minimizing the energy spread so as to focus maximum flux at a small focal spot.

The absorbed energy produces thermal distortions that alter the character of the incident beam. Figure 1 identifies various types of distortion induced by thermal input and internal pressure associated with an actively cooled mirror. Distortions are directly related to thermal and pressure loads. The required geometry and flow rate parameters are defined to meet design objectives.

For laser mirrors, irradiance mapping distortion, sometimes called "thermal bump" in the synchrotron community, is of primary interest. Bowing distortion is of little consequence for cooled laser mirrors but is of primary concern for synchrotron mirrors, where slope error can result in excessive spreading of the beam. Local distortions associated with the geometry of the heat exchanger and the manifolding system can influence optical performance but these tend to be of second order for well-designed mirrors. Their relative importance increases greatly when the limits of cooled mirror technology are taxed for a particular application. As points of reference, irradiance mapping distortions of the order of 0.05 μm and a thermal bowing slope error of about 100 μrad are acceptable for cooled laser mirrors. For cooled synchrotron optics a thermal bump of 0.05 μm would cause a slope error of 0.1 μrad on a 50-cm-long synchrotron mirror; such mirrors require thermal bowing slope errors to be less than 10 μrad.

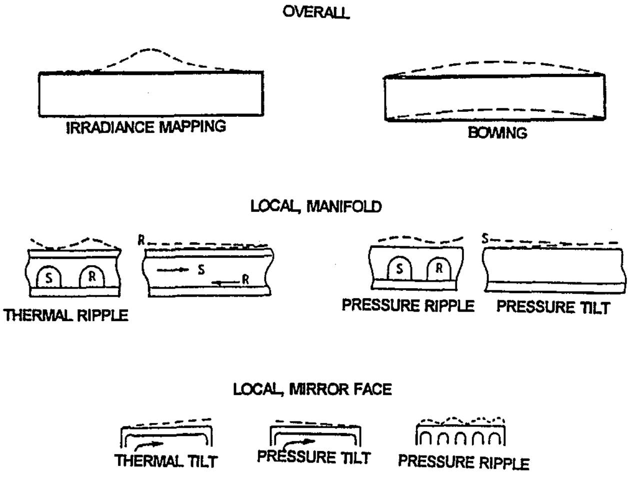

Fig. 1 Types of overall and local distortion.

3 Heat Exchanger Designs

The primary function of the heat exchanger immediately behind the mirror face is to remove the thermal energy input and to control surface temperature; its structural aspects are also important when distortion is to be minimized. Thermal distortions are related to temperature rise and uniformity, as induced by the heat flux absorbed, heat exchange characteristics, and material properties. Pressure-induced distortions are related to the thickness of the mirror face plate and separation between support elements. To minimize thermal distortions, the mirror face tends to be thin, a millimeter or less; this dictates a close spacing of structural support elements, usually ribs or posts. First approximations of desirable structural parameters, such as face thickness and support spacing, can be obtained from plate theory.[1]

The simultaneous consideration of thermal and structural aspects has led to the investigation of a number of different heat exchanger concepts that are illustrated in Fig. 2. The question marks associated with the drilled hole concept, Fig. 2(a), indicate that the author has no personal knowledge of such mirrors being fabricated but strongly suspects that early mirrors may have used such an approach. The majority of actively cooled laser mirrors incorporated cooling channels such as those shown in Figs. 2(b), 2(c), and 2(d). The level of complexity from single-layer to multiple-layer designs is chronological as dictated by the need for improved performance as heating intensities increased and shorter wavelength devices were developed.[2–4] Multilayer configurations with

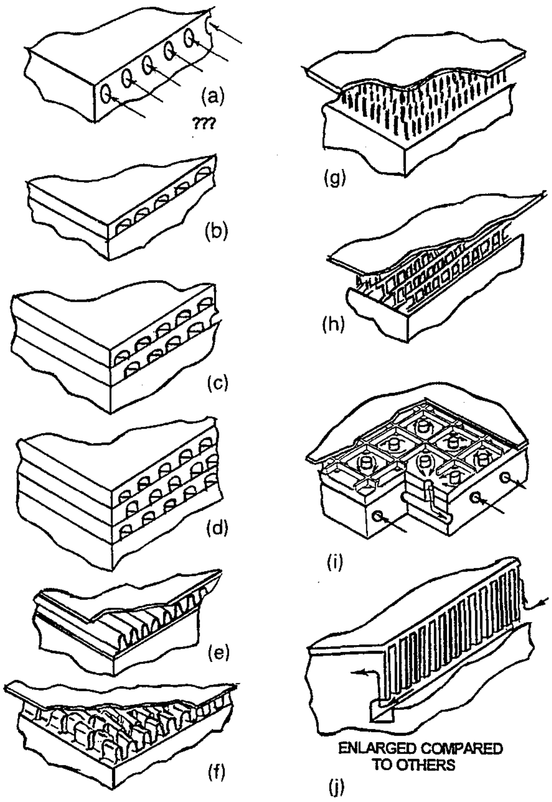

Fig. 2 Heat exchanger concepts.

series flow will minimize tilt distortion. Considerable effort has been devoted to the optimization of channel configurations, including such refinements as relatively large corner radii that improve flow uniformity and stiffen the mirror face, between ribs, so as to minimize pressure-induced ripple.

With a single layer of flow channels, about 5% of the incident heat leaks to the rear portion of the structure. The exact amount depends on details of the design and operational conditions. This gradual heating of the backup structure causes a change in the curvature and mapping distortions of the mirror. The addition of a second layer reduces this rearward leakage of heat significantly. A third layer reduces it even further. Not only is the magnitude of the thermal distortion reduced but the time constant for equilibrium is shortened also. With reasonable flow rates of water as the coolant and passages of these types, irradiance mapping distortion coefficients range from about 50 to 10 Å/W cm^{-2}. Absorbed fluxes can be in the hundreds of watts per square centimeter.

In addition to straight channels, consideration has been given to curved channels in continuous spiral and in parallel flow arrangements. Only in special circumstances is curvature particularly beneficial; the straight parallel passage configuration is usually adequate.

One disadvantage of the straight parallel channel configuration is the tilt that is experienced due to the sensible temperature rise of the coolant as it flows the length of the channel. By introducing two independent flow networks within a single mirror substrate, counterflow arrangements can be provided that eliminate the tilting tendency and replace it with a ripple of much smaller magnitude and higher frequency that is perpendicular to the channels.

Figure 2(e) illustrates an adaptation of plate-fin technology to cooled laser mirrors. Passages are formed easily from a thin sheet and brazed between a thin mirror face and the backup structure that contains the manifolding. An extensive literature base addresses various forms of compact heat exchanger channeling; Ref. 5 is a particularly good summary. Straight channels can have continuous or interrupted walls. The interrupted wall concept, Fig. 2(f), minimizes the boundary layer thickness because the boundary layer is reinitiated at each discontinuity. This enhances the effectiveness of the webs as fins but does increase pressure drop. The desired characteristics of the flow channel dictate the use of a relatively thin sheet that is sensitive to corrosion problems. Although investigated, this concept did not find widespread application.[6–8]

Inasmuch as many cooled laser mirrors were circular in shape, axisymmetric geometries were considered, with radial flow. Posts between the mirror face and the backup structure provided structural support and acted as fins that enhanced heat removal.[9] Early mirrors of this type utilized an array of pins individually placed in premachined holes and brazed to the backup structure and the mirror face; see Fig. 2(g). A variation of this concept was the use of a "ladder" of relatively thin sheet stock that is formed into a circle such that the long members are placed into grooves in the backup structure and the mirror face [Fig. 2(h)]. Suitable design of a set of concentric "ladders" allowed the simulation of an array of vertical posts. It is apparent that the spacing, between concentric rings and of the "rungs," can be tailored for a wide range of applications. While the "ladders" may be slightly more expensive than the equivalent number of pins, the installation cost was reduced dramatically.

As interest increased in lasers of shorter wavelength, demands for more efficient cooling of mirrors increased. Not only did this stimulate interest in more advanced materials for mirror construction, but it fostered attention to new heat exchanger concepts, the pin/post concept[10–12] as illustrated in Fig. 2(i), and the microchannel concept[13–15] in Fig. 2(j). A common feature is a short flow length that allows a high heat transfer coefficient to be obtained without an excessive pressure drop, although total flow of coolant usually increases as flow length decreases. Figure 3 illustrates the substantial improvement in performance provided by the newer heat exchanger concepts. The small geometric features of the newer concepts allow the use of thinner mirror faces than can be used with more conventional channel flow heat exchangers. The apparent complexity of the heat exchanger configuration is misleading. Very fine geometries of the pin/post configuration can be generated by ultrasonic machining or electric discharge machining depending on the particular material. The fine microchannels can be produced by differential etching in silicon, or by high-speed diamond sawing for a broad range of materials. In combination with a material like silicon a mapping coefficent of the order of 2 Å/W cm^{-2} can be obtained with a conventional coolant. With water as the coolant, configurations such as these can absorb heat fluxes in excess of a kilowatt per square centimeter.

A large number of heat exchanger configurations have been examined for cooled laser mirrors. The most suitable

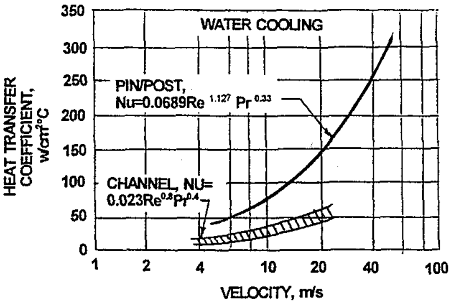

Fig. 3 Representative heat transfer coefficients.

configuration is highly dependent on the performance/cost trade-off for each particular application. Operational parameters such as the heat load to be absorbed, the magnitude and type of distortion that is allowable, and the characteristics of the cooling system including flow rate, pressure drop, and pumping power will affect not only the selection of the heat exchanger concept but the geometric proportions of the heat exchanger.

All of the heat exchanger designs discussed so far are used in convective cooling systems. Heat pipes have been considered for cooled mirror applications also. Porous wick-like structures carry the coolant to the mirror face where it evaporates. The vapor is subsequently condensed and liquid is returned through capillary action with or without auxiliary pumping.[16,17] The heat pipe concept is particularly attractive when extremely low jitter is required. The high heat of vaporization allows very low flow rates as compared to the much smaller caloric temperature rise of a single phase coolant; the ratio is usually greater than 10. However, the requirement for vapor space introduces some difficulties in implementing designs for high heat fluxes. Experimental evaluations for cooled laser mirror applications have not produced results that are competitive with the most effective of the convective cooling concepts. Details of such designs and experimental results are discussed in Ref. 18.

4 Manifolds

Supply of coolant to and removal from the mirror face heat exchanger can be a simple or a complex task depending on the design of the heat exchanger. As might be expected, heat exchangers with highest efficiency usually require the most complex manifolding. Figure 4 illustrates a number of manifolding concepts that have been used for cooled high-energy laser mirrors. Figures 4(a) and 4(b) illustrate two different approaches for achieving essentially uniform flow through all of the coolant passages. Such arrangements can be used for the heat exchanger concepts in Figs. 2(a) through 2(f). While the coolant line fittings are shown in the plane of the mirror face, they can be installed perpendicular to the mirror face. An arrangement such as that in Fig. 4(b) is particularly attractive for dither mirrors where the axis of rotation can be integrated with the coolant line connections.

A counterflow coolant arrangement can be achieved by duplicating the manifolding and passages to provide two circuits in the mirror, as shown conceptually in Fig. 4(c). Such an arrangement is another way to eliminate the tilt associated with caloric temperature rise of the coolant. Longitudinal tilt is replaced by a lateral thermal ripple, see Fig. 1, of much smaller magnitude and of high frequency.

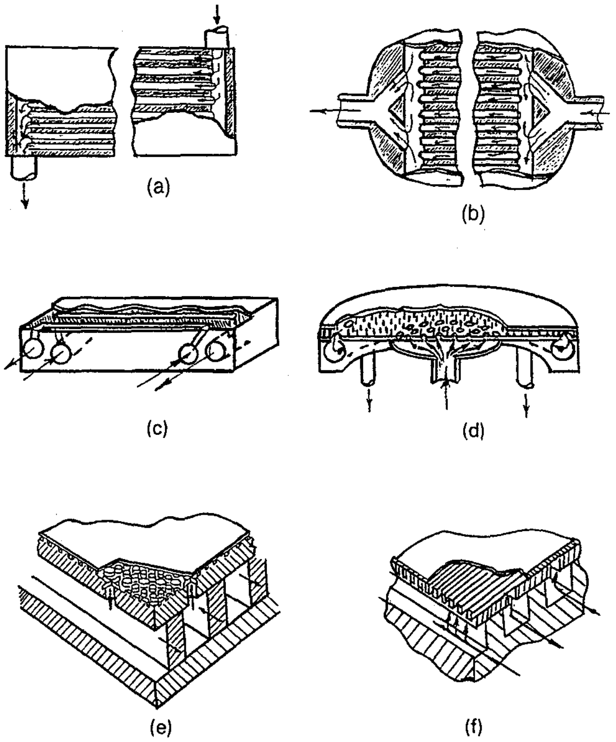

Fig. 4 Manifold concepts.

A showerhead type of inlet has been used for radially cooled mirrors as illustrated in Fig. 4(d). By properly sizing the holes it is possible to tailor the flow to approximate the heat flux input distribution. Such mirrors employ an annular collection ring, for the warmed coolant, which can be extended across part of the rear of the mirror or from which the coolant can be extracted directly at one or more coolant lines.

Distributed manifolding is required for the pin/post design. Figure 4(e) illustrates adjacent supply and return manifolds. Somewhat better thermal isolation can be obtained by distributing the supply and return manifolds in two layers parallel to the mirror face. Manifolding for the microchannel type of heat exchanger is similar.

Quite early in the development cycle, consideration was given to a manifold design that utilized the temperature rise of the coolant to heat the rear of the mirror and thereby reduce the thermal moment that causes bowing and slope error. This concept was investigated in Ref. 19 but was found to be unattractive. The complexity overshadowed the benefit for HEL applications but may be advantageous for synchrotron mirrors where slope error is the primary consideration. A first-order assessment suggests that the caloric temperature rise is too small to be a major benefit but clever engineering may amplify its effect.

5 Materials

Because of its high thermal conductivity and established fabrication technology, copper was one of the first materials to be used for cooled laser mirrors. Copper was adequate for use in early devices with a wavelength of 10.6 μm and modest power densities of a few hundred watts per square centimeter. Its low microyield strength led to permanent distortion when relatively small temperature differences were experienced, which motivated designers to seek other materials. For many years molybdenum was the workhorse material. The reason for this, despite higher material and fabrication costs, can be seen in Table 1 where a number of candidate materials are compared on the basis of performance parameters. Large values indicate superior performance except in the cases of coefficient of thermal expansion and density. The k/α parameter is most useful for assessing performance under steady-state conditions, thermal conductivity relates to temperature differences, and the coefficient of thermal expansion relates to distortions. The $k/\alpha\rho c_p$ parameter is useful in assessing performance under pulsed conditions. Note that a material that is superior for one situation is usually superior for the other. When mirrors are relatively small, material stiffness and density are not of much concern.

When HEL interest shifted from CO_2 to deuterium fluoride (DF) and hydrogen fluoride (HF) media, wavelengths decreased by a factor of 3 to 4. There was some interest in other materials but improvements in heat exchanger design and in reflective coatings were sufficient to limit the scope of such activities. It was not until the late 1970s when there was interest in free electron lasers with wavelengths in the 0.5- to 1.5-μm range that the need for improved materials as well as improved heat exchanger designs spawned developmental work to meet the new requirements.

It is obvious from Table 1 that silicon and silicon carbide were high on the list of potentially useful new materials. Funded efforts concentrated on these materials. Each material has its own group of advocates but in the author's opinion it is fair to say that the technology for cooled silicon mirrors has been developed more extensively.

One of the early efforts to develop technology for alternative construction materials focused on a carbon-carbon composite system. The objective was to take advantage of the low density of the basic materials and the versatility of designing a material system to meet specific property objectives. As shown in Table 1, excellent performance would be achieved if a suitable material system of fibers and matrix could be produced in a reliable manner. Unfortunately there were difficulties in adapting fabrication techniques suitable for uncooled mirrors to cooled configurations, which lead to the abandonment of this approach.

A number of other materials were considered for cooled laser mirrors and, in some instances, mirrors were actually fabricated. Copper alloys, such as beryllium copper, overcame the low microyield strength of pure copper without unduly sacrificing high thermal conductivity. Nickel mirrors were considered. While thermal conductivity was not as high as for copper, the microyield strength was significantly higher and high purity nickel has a respectable thermal conductivity. Bimetallic mirrors such as copper/stainless steel and nickel/stainless steel received attention. At least one cooled beryllium mirror was fabricated. Despite the investigation of many potential candidates, molybdenum was the construction material of choice for most laser mirrors. Only toward the end of the cooled laser mirror development effort did silicon[10–13,20–22] and silicon carbide,[23,24] become candidates.

Before leaving the materials aspects it is appropriate to indicate the performance potential associated with operation at cryogenic temperature. Figure 5 depicts the k/α parameter as a function of temperature. As temperature is reduced, note the significant increase in the parameter for all materials, silicon in particular. The performance benefits associated with operation at cryogenic temperature were recognized more than a decade ago but the complexity of cryogenic systems precluded experimental evaluation for laser usage.[21]

6 Fabrication

One point often overlooked, particularly when new materials are being introduced, is the importance of primary material fabrication. For the cooled metallic mirrors used so extensively during the HEL programs there was little concern for variability in the basic material. The primary materials, copper and its alloys and molybdenum, had been produced in tonnage quantities for many years so that quality control had been established for all of the primary material fabrication processes. This allowed the design and development effort to concentrate on adapting these particular materials to the configurations desired.

The lack of success of the carbon-carbon composite cooled mirror was due primarily to the fact that the material system was being developed concurrently with its intended usage. Similar composite materials had been under development for about a decade, but that is really quite a short span when

Table 1 Comparison of materials for cooled laser mirrors.

MATERIAL	k W/cm°C	α 10^6/°C	E GPa	ρ g/cm³	e_p cal/gm°C	E/ρ 10^6cm	k/α 10^6W/cm	$k/\alpha\rho c_p$ 10^6W cm$^{2\circ}$C/cal
Copper	3.91	17.7	126	8.92	0.092	126	0.22	0.27
Nickel	0.75	13.3	220	8.90	0.109	227	0.06	0.06
Molybdenum	1.45	5.0	350	10.2	0.065	324	0.29	0.44
Beryllium	2.00	11.6	290	1.85	0.45	1406	0.17	0.20
Carbon/Carbon	0.23	0.27	16	2.00	0.16	72	0.85	2.66
Silicon	1.53	2.1	190	2.33	0.18	739	0.73	1.74
Silicon Carbide	1.45/1.93	2.1/2.4	435/530	2.90/3.10	0.17	1355/1550	0.69/0.86	1.40/1.63

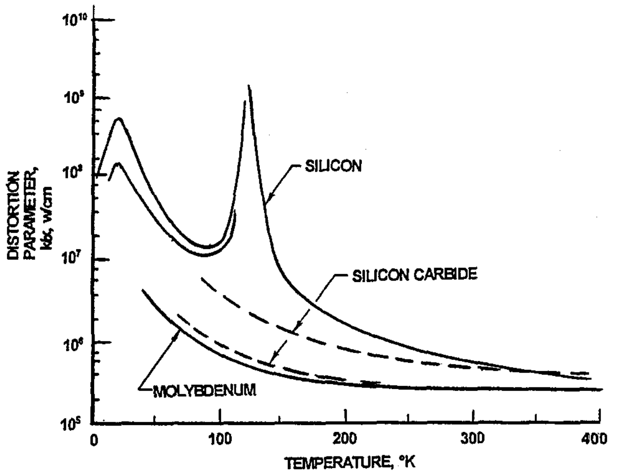

Fig. 5 Promise of cryogenic cooling.

compared with the several decades of molybdenum production and centuries of copper fabrication. There is definite value in utilizing a material that is produced in large quantity because of the high level of control exercised to achieve uniformity without undue expense.

In the normally considered context, fabrication of cooled laser mirrors involves processes of material removal and joining of component parts. For metallic construction materials, conventional machining practices are applicable with appropriate attention paid to the peculiarities of each material. Such processes are well established and involved little risk unless the geometries are complex. When heat exchangers are relatively shallow, wet chemical etching can be an effective process. For the more advanced candidate materials, silicon and silicon carbide, many conventional machining processes can be used if diamond-coated tools are substituted for the cutting tools used for metals. In addition, sophisticated shapes can be produced quite economically by ultrasonic machining.

Silicon carbide offers some unique processing opportunities. In one form, powder with a binder has been molded into unfired shapes that are relatively easy to machine and that have been fired, subsequently, to form the consolidated material of near net shape. Moldings have contained fugitive cores so that fired parts contained integral coolant flow passages. Machined unfired shapes have been joined during firing; mating surfaces were activated to ensure bonding. This is another technique that allows fabrication of substrate blanks with integral coolant passages without extensive machining of the hard silicon carbide and bonding of the densified fired material. Some types of silicon carbide are infiltrated with silicon, after sintering, to enhance properties. This can pose difficulties if coolant passages have small dimensions. Although many potentially useful fabrication processes have provided the types of shapes of interest for cooled mirrors there was not enough work done, in the opinion of the author, to demonstrate the consistency and homogeneity of material properties that are provided by materials produced in tonnage quantities such as copper, molybdenum, and silicon.

Both silicon carbide and silicon can be deposited from vapor onto premachined molds to produce parts at near net shape that require little or no subsequent machining. Application of such fabrication technology to parts for cooled laser mirrors has been less extensive than for other techniques.

Brazing techniques for copper and molybdenum parts are well established. Problems identified during the development of cooled laser mirrors, other than poor design or poor technique, were associated with blocking of coolant passages because of their fine geometry and the fluidity of the braze material at the joining temperature. Such problems were minimized or eliminated by carefully controlling the amount of braze material used, ensuring proper design of the joints, and providing gas flow through the coolant passage network during the braze cycle to minimize the likelihood of small passages and holes being blocked. Once a satisfactory joint was made, strength was rarely a problem. Samples of cooled molybdenum mirror configurations subjected to internal pressure have demonstrated burst pressures in the 5000- to 10,000-psi (gauge) range, well above design inlet pressures, which rarely exceed 500 psi (gauge).

Brazing, with gold-based alloys, was usually used to assemble silicon carbide parts when joining was not integral with the firing process. Burst pressure strengths ranged from about 500 psi (gauge) to more than 5000 psi (gauge) for the various joining procedures depending on the specifics of the silicon carbide material, heat exchanger design, and braze alloy or joining process.

Joining of silicon mirror parts has been accomplished by brazing and glass bonding; the latter has been used more extensively. Brazing studies focused on alloys that contain gold, to promote eutectic formation, or on metallization of the silicon prior to brazing. While all joining techniques require relatively flat mating surfaces, electrostatic bonding imposes the strictest demands. A thin layer of vapor-deposited glass promotes ionic transfer to achieve bonding. Strength of such joints may be adequate for some applications, equivalent to about 500 psi (gauge) of internal pressure in a well-designed mirror face heat exchanger. Joints of much higher strength, up to 5000 psi (gauge), have been achieved with less effort by glass frit bonding.[10]

Verification of the adequacy of the joints within the mirror required the use of a variety of nondestructive inspection techniques. These included radiography, ultrasonics, holography, and thermography. Although the basic processes are well established, some adaptation was required as new design configurations were introduced for cooled laser mirrors.

7 Operational Considerations

While there is extensive documentation of heat exchanger concepts, materials of construction, and fabrication methods, operational considerations receive relatively little attention. Actively cooled mirrors tend to be relatively small, within the total spectrum of mirrors, so that methods of mounting them are not considered to be as technically challenging as the mounting of large optics such as telescope mirrors. The cooling system, though critical for heat removal, is usually viewed as a collection of pipes, valves, etc.—a standard fluid flow problem. Nevertheless, a few comments on these subjects are appropriate.

The unusual aspect of mounting of cooled mirrors is the flow-induced vibration, associated with the cooling system, which can excite response modes of the mounted mirrors that can degrade optical performance.[25–28] Reference 29 discusses flow-induced vibration in considerable detail. Here, it is sufficient to indicate that the characteristics of the inlet and outlet lines at the mirror and the initial flow manifolding within the mirror are much more important than the detailed design of the heat exchanger region. The former tend to generate vibration forces of low frequency that can induce motions of large amplitude. The latter involve finer geometric sizes that produce vibration forces at higher frequency and of lower magnitude. When the velocity in the inlet and outlet lines is less than 3 m/s for water, or coolants of similar properties, few problems should be expected from flow-induced vibration forces. Another rule of thumb is to provide a mirror and mount combination whose fundamental response mode is above 200 Hz.

Corrosion of the cooled mirror system is another aspect that warrants consideraion. Not only must the initial composition of the coolant meet requirements but its composition must be controlled during the life of the system. Minor traces of elements introduced through the piping, valves, and/or pump can accelerate corrosion. Rates can change from tolerable levels to intolerable ones when only parts per million of the wrong ions are introduced. Such a problem was experienced in the optical system of a HEL when algae formed in the cooling water and changed its pH. Iron and chrome ions accelerated the corrosion within the heat exchanger sections of the molybdenum mirrors. This led to significant degradation of optical performance and required replacement of a number of mirrors. In addition to corrosion inhibitors, a biocide in the cooling water is desirable and the character of the water should be monitored.

8 Test Facilities

During the development of cooled optics for high-energy lasers, it was desirable to evaluate performance without actual operation in a costly laser device. The Thermal Distortion Test Facility at the Air Force Phillips Laboratory evolved as an extremely useful, cost effective, and versatile resource from one that utilized high-intensity lamps to one that employs a rastered electron beam. Local heating intensities in the thousands of watts per square centimeter can be achieved by rastering the beam over a small area; larger areas can be heated to lesser intensities. Mirrors of up to 24 in. in diameter can be evaluated for distortion, by means of holography, and with regard to surface temperature, by means of thermography. Reference 30 describes the facility in detail. Mirrors of many different designs and construction materials have been evaluated in this facility; the results constitute the largest body of experimental data for cooled HEL mirrors obtained in a single facility.

Another interesting test facility is available at the MIT Lincoln Laboratory.[31] A 2-kW CO_2 laser is used as the energy source. The beam can be expanded to about 10 cm in diameter. Distortion is measured interferometrically. Temperature levels and distributions can be measured thermographically. A special coating is used to absorb at 10.6 μm and reflect in the visible. After testing, this coating is stripped and the optic is recoated.

9 Conclusions

The differences in the performance requirements for HEL and synchrotron high heat load optics are relatively small when compared to common aspects. The extensive technology base developed for cooled laser mirrors should be of significant value to the synchrotron community.

References/Bibliography

This listing of documents related to cooled HEL mirrors was prepared to preserve these resources from being lost to future technical communities. While far from complete it can provide a starting point for design specialists. A few other pertinent references (Refs. 32 through 43) have been included to support comments made in the technical paper.

A particularly valuable set of reports is the proceedings of the topical meetings on High Laser Optical Components that were held from about 1979 through 1992. Only those for which report numbers were available are listed.

Many of the references are government reports with limited distribution. For those that are not available from the U.S. Department of Commerce, National Technical Information Service, please contact the agency of origin.

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