Thin Solid Films 518 (2009) 1607–1613

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Laser damage thresholds of optical coatings

Detlev Ristau *, Marco Jupé, Kai Starke

Laser Zentrum Hannover, 30419 Hannover, Germany

ARTICLE INFO

Available online 28 July 2009

Keywords:
Laser damage
Optical thin films
LIDT measurement ISO 11254
Damage mechanisms

ABSTRACT

Since the very beginning of laser technology, Laser Induced Damage Thresholds (LIDT) of optical components were always an obstacle for the application of laser systems operating at high power levels. Also, further progresses in the development of new high power laser concepts are often directly limited by the availability of advanced optical components with high quality and LIDT-values. Nowadays, in the course of the development of optical materials with excellent quality and power handling capability, the problem of laser induced damage has shifted from the bulk to the surface of the optical component. The optical surface is objected to various production steps and environmental influences, which modify its structure and composition. Especially, the thin film coating, which is deposited on the optical surface to adapt its reflectance and transmittance to the application, contributes predominantly to the reduction of the LIDT-values. As a consequence, the measurement and optimization of the power handling capability of thin films is considered as one of the primary research areas in modern optics technology and is supported by an extensive scientific community.

In the present paper, a brief review will be given on selected fundamental damage mechanisms in thin films considering different operation conditions of modern laser systems. Also, the current standards for the measurement of LIDT will be described, and examples illustrating some practical aspects of high power optical coatings will be presented. Finally, recent trends in laser technology will be discussed in respect to research in laser induced damage.

1. Introduction

At the time of its invention by T. H. Maiman in the year 1960 the laser was considered as a solution seeking for the problem. However, only a few years later the enormous potential of the laser for ground-breaking innovations in many technical fields had been recognized, and the development of laser systems operating at high power levels in a variety of wavelength regimes moved into the focus of global research in optical technologies. Starting at a few milliwatts of output power in the pioneer times, many laser concepts have advanced to the multi Kilowatt range in cw-operation and to peak power densities on the Petawatt level for pulsed systems. These systems, which can reach a high reliability even in severe industrial environments, conquer an ever increasing variety of applications in material processing, medicine, or fundamental research. In the course of the corresponding research efforts, the power handling capability of optical materials and coatings was often encountered as a major factor which limits the output power of the laser systems. As a consequence, laser development has been always escorted by corresponding research activities in Laser Induced Damage Thresholds (LIDT) of optical components since its beginning [1].

The present review will give an introduction into the field of laser damage in optical components, which has matured to a vivid research field during the last 40 years. In the first section a brief summary will be given on typical laser induced damage mechanisms in optical materials and coatings considering also different operation regimes of modern laser systems. Reproducible and reliable measurement techniques for LIDT-values are an indispensable prerequisite for a comprehensive optimization of the power handling capability of laser components. Therefore, the following part of the review will be dedicated to the present state of the art in the measurement of LIDT-values under different operation conditions of the test laser systems. In this context, also current international standards and their development on the basis of round-robin tests will be described. In the final part, selected examples for investigations in the power handling capability of optical coatings will be presented. Major emphasis will be concentrated on current results for optical coatings optimized for laser pulses in the fs-regime. The review will be concluded with an outlook on selected trends in the future development of high power optical coatings.

2. Damage mechanisms in optical materials and coatings

In the early days of high power laser development, mainly inclusions in laser rod materials were discussed as a major complication for an improvement of the output power in solid state laser

---

* Corresponding author. Tel.: +49 511 2788 240; fax: +49 511 2788 100.
E-mail address: d.ristau@lzh.de (D. Ristau).

0040-6090/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.tsf.2009.07.150

systems. Nowadays, in the course of the development of optical materials with excellent quality and power handling capability, the focus of research has shifted from the bulk to the surface of the optical component. The optical surface has to pass through a complex production chain with various steps and different influences, which modify its structure and composition. For example, the polishing process is known for different types of microscopic defects introduced into the surface region by complex tribo-chemical processes. However, the thin film coating, which is deposited on the optical surface to adapt its reflectance and transmittance to the application, often suffers from even more severe structural deficiencies which can be attributed to coating process. Therefore, a clear ranking in the power handling capability of the constituents of a laser component can be expected for most laser operation conditions: The bulk material will often exhibit then highest LIDT-value which is followed by the surface with medium stability, and finally, the coating will possess the weakest power capability. As a consequence, the measurement and optimization of the power handling capability of thin films is considered as one of the primary research areas in modern optics technology and is supported by an extensive scientific community. In the following discussion of fundamental damage mechanisms, selected models conceived in more than forty years of research in laser damage of optical thin films and will be outlined and illustrated.

2.1. Thermal laser damage

In many practical cases laser induced damage can be attributed to an excess of thermal energy which is coupled into the optical structure by absorption of laser radiation and leads to a catastrophic failure by mechanical disruption or overheating. A typical example for such an effect is illustrated by the damage site depicted in Fig. 1. The morphology clearly indicates that the coating is delaminated from the surface of the optical component in the center of the laser beam area. Obviously, mechanical stress has built up in the coating by the thermal expansion of the materials which is driven by laser induced heating. At a certain thermal stress level exceeding the adhesion strength of the coating to substrate surface, the thin film cracks and may even delaminate from the component [2]. In other cases of this absorption induced damage effect, the film reaches its melting point prior to the delamination threshold and evaporates or changes its crystalline structure. A characteristic morphology for such a damage mechanism often displays a discoloration or an increased surface roughness in the center of the laser beam (see Fig. 2).

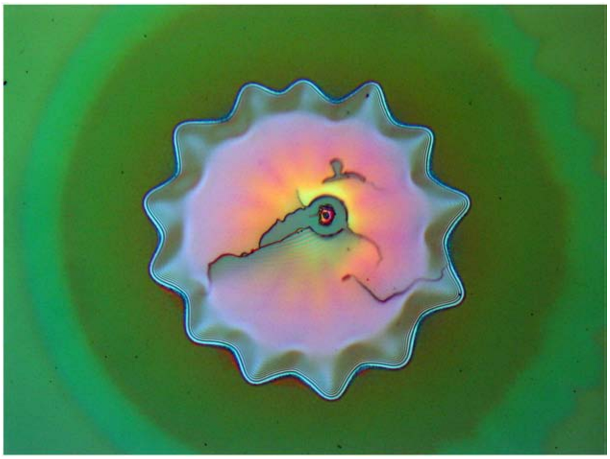

Fig. 1. Nomarski micrograph (magnification 200×, scale according to Fig. 2) of a damage site on a high reflecting mirror for the Nd:YAG-laser wavelength (damage after pulse 199 at a fluence of 143 J/cm^2, S on 1-test, beam diameter 200 µm, pulse duration 14 ns). As dominant damage mechanism a delamination of the coating by extreme mechanical stress is suggested.

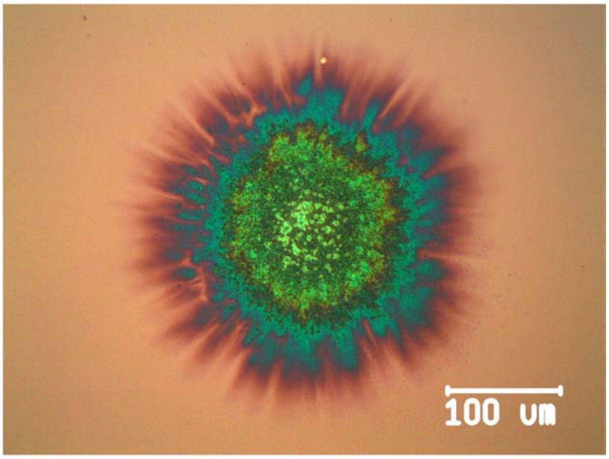

Fig. 2. Nomarski micrograph of a damage site on a single layer of Ta_2O_5 deposited by conventional evaporation. Damage occurred after one pulse (Nd:YAG-laser, wavelength 1.064 µm, beam diameter 200 µm, pulse duration 14 ns) at a fluence of 29 J/cm^2. The damage morphology indicates an absorption induced mechanism leading to melting and re-crystallization of the coating material.

The described absorption induced damage effects are dominated by an instantaneous heating of the coating material in the area of interaction with the laser beam. An approach for an analytical description of this phenomenon can be established on the basis of the heat diffusion equation. The corresponding source term is given by the spatial distribution of heat generated in the coating by absorbed laser energy, and the boundary conditions are determined by the geometry and the structure of the layer system as well as the heat dissipation into the environment. Apparently, absorption induced damage has to be considered only for components with significant absorptance at their operation wavelength. For example, even modern deposition processes cannot avoid residual absorption in fluoride coating materials for the DUV/VUV-wavelengths where absorption induced damage of laser components is occasionally observed. Also, laser induced breakdown in optical materials for the wavelength 10.6 µm of the CO_2-laser including ZnSe, ZnS, and fluorides for the coating systems is often dominated by absorption. Since CO_2-lasers may reach an output power of several ten KW under cw- and long pulse operation conditions and some of the employed optical materials may be severely toxic, damage effects for cw-irradiation were studied in some detail [3]. For these conditions, the laser induced temperature rise in the component can be calculated by numerical methods involving finite elements or differences. Also, an analytical expression can be derived for the temperature rise ΔT in the center of an irradiated circular component and a Gaussian beam profile (beam diameter w, power P),

$$\Delta T = \frac{2\beta_s P}{\pi^{3/2} k w} \tan^{-1}\left(\frac{16\kappa t_I}{w^2}\right)^{1/2}. \tag{1}$$

In this basic two-dimensional model the temperature rise is dependent on the thermal properties (k: thermal conductivity, κ: thermal diffusivity), on the surface absorption of the component (β_S), and on the beam diameter, respectively. For a time scale of t_1 high compared to typical heat diffusion time w^2/κ, Eq. (1)is reduced to an asymptotic dependence:

$$\Delta T \rightarrow \frac{\beta_s P}{\pi^{1/2} k w} \qquad t_I \rightarrow \infty. \tag{2}$$

In this straightforward model for long irradiation times, the temperature rise ΔT scales with the ratio P/w which has to be compared to