Determination of thermomechanical ablation thresholds to sodium chloride irradiated by femtosecond laser pulses

A P Savintsev and Yu O Gavasheli
Kabardino-Balkarian State University, Chernyshevskogo Street 173, Nalchik, Kabardino-Balkaria 360004, Russia
E-mail: pnr@kbsu.ru

Abstract. We examine experimentally determined thresholds of thermomechanical ablation arising under the action of the 40 and 80 fs laser pulses on sodium chloride. We found that critical emission power in a pulse on the thermomechanical ablation threshold for these two cases differs not much approaching to the value of 1.3 GW.

1. Introduction
As part of our continued study of ionic crystals in the field of ultrashort laser pulses, we executed another piece of work, the aim of which was to study the characteristics of thermomechanical ablation of sodium chloride for femtosecond laser pulses of different duration. Such studies have not been performed before. The thermomechanical ablation leading to the removal of the surface layer as a result of the occurrence of power tensile stresses in the substance is the general mechanism of the surface damage in the case of femtosecond pulses: When irradiated by femtosecond laser pulses, the surface layer of transparent dielectric, which is heated as a result of multiphoton absorption under femtosecond impact, begins to be deformed and damaged [1–3].

The interaction of short laser pulses with solid targets, leading to ablation, is considered in papers [2, 4–9]. It is shown that the ablation of various materials [10–16] under the influence of femtosecond laser pulses has its own specificity [17–23].

To study the thermomechanical ablation thresholds ionic crystals the research of optical damage to sodium chloride by ultrashort laser pulses with duration of about $\tau_2 = 40 \pm 2$ fs was conducted [1]. This pulse duration is shorter than the other, used in similar experiments [24–27].

2. Experimental methods
The power density in performed experiments $I_{cr}$ attained 90 TW/cm$^2$, and critical electric field strength $E_{cr}$ attained 182 MV/cm.

Knowing $I_{cr}$ makes it possible to determine the lower pressure occurring with ablation (one of the fast phase transitions considered at the high-temperature phase diagram of sodium chloride [1, 28–32]).

Experiments were carried out using a terawatt titanium–sapphire femtosecond laser system of the Laser Femtosecond Complex Center of Collective Use of Unique Scientific Equipment of the Joint Institute for High Temperatures of the Russian Academy of Sciences (JIHT RAS) [33].
Laser pulses generated by the titanium–sapphire system at a wavelength of 800 nm with a duration of $40 \pm 2$ fs were focused on the crystal surface under an angle of $60^\circ$ by a lens with a focal distance of 20 cm.

The experiments described elsewhere [24–28], when the effect on surface of sodium chloride arising under the action of laser pulses with a wavelength of 1240 nm and a duration of $\tau_1 = 80$ fs was investigated, were carried out in the “Laser Femtosecond Complex” Center JIHT RAS on the terawatt femtosecond chromium–forsterite laser system.

The effect of the $p$-polarized laser radiation on the specimen surface was investigated.

The spatial energy density distribution in the focal spot corresponded to the Gaussian one. Relative error of measurement was 0.2%.

A femtosecond microscopy circuit [27,33] was applied for recording damage to a target surface after the effect of a laser, which allowed recording surface images before radiation, at the moment of radiation with a controlled time delay, and after radiation.

The image processing program determined geometrical dimensions $R_x$ and $R_y$ (dimensions of principal semiaxis) of damaged spots, which had an ellipse shape because of the oblique incidence of radiation on the target.

Spot dimensions were compared with laser pulse energy $G$ damaging the surface.

3. Results of measurements

The graph of the spot dimension (figure 1) versus $G$ was constructed to determine the threshold energy when the dimensions of the spot of radiation damage were reduced to zero (figures 2 and 3) [27,34].

The linear approximation of obtained experimental data in coordinates $R^2$ versus $\ln G$ on the given graphs verifies the correctness of fulfilled measurements for the beam with the Gaussian spatial distribution. Approximation results (figures 2 and 3) made it possible to determine the pulse energy corresponding to the threshold of the surface damage ($G_{02} = 49 \mu J$).
Figure 2. The dependence of the size of the major semiaxis of the optical field of damage to the surface of sodium chloride from the laser pulse energy: points are experimental data, and the line is the linear approximation.

Figure 3. The dependence of the size of the minor semiaxis of the optical field of damage to the surface of sodium chloride from the laser pulse energy: points are experimental data, and the line is the linear approximation.

Taking into account laser beam dimensions $R_{0x} = 29 \, \mu m$ and $R_{0y} = 56 \, \mu m$ by level $e^{-1}$, it was found that the energy density of the threshold of the optical damage of the sodium chloride surface by laser pulses with a duration of $40 \pm 2 \, fs$ is determined by $J_2 = 0.97 \, J/cm^2$.

Recalculation gives $I_{cr} = (2.4 \pm 0.1) \times 10^{13} \, W/cm^2$ and $E_{cr} = (9.4 \pm 0.2) \times 10^7 \, V/cm$.

4. Discussion

In case of damage to the sodium chloride surface pulses at 800 nm on the pulse duration 40 fs at a surface densities of the power of the threshold of the optical damage of the surface $I = (2.4 - 9.0) \times 10^{13} \, W/cm^2$ calculation of ablation pressure gives the value $0.2 - 1.3 \, TPa$.

Previously, in [29,35], it was specified that it should be expected that $E_{cr} = 100 \pm 5 \, MV/cm$ at $\tau = 40 \, fs$ (relative error of measurement $\varepsilon_1 = 5\%$). In the case of $\tau = 40 \pm 2 \, fs$, will $\varepsilon_2 = 5\%$. Then, according to [36], for $E_{cr}$ at $\tau = 40 \pm 2 \, fs$ one obtains an ambiguous value $\varepsilon_n = (\varepsilon_1^2 + \varepsilon_2^2)^{1/2} = 7\%$, and have a value of $100 \pm 7 \, MV/cm$.

The obtained experimental results, with $\tau_2 = 40 \, fs$, gave a new reference point (figure 4) along with the data obtained at $\tau_1 = 80 \, fs$ on the installation [37] and allowed to come to the determination of thermomechanical ablation threshold values for the femtosecond laser pulses in a wide range of values of $\tau$.

Comparison of the results of experiments for $\tau_1$ and $\tau_2$ indicates that

$$I_{cr2}/I_{cr1} \approx J_1/J_2 \approx 1.5.$$  \hspace{1cm} (1)

However,

$$G_{02}/G_{01} \approx \tau_1/\tau_2 \approx 2.$$  \hspace{1cm} (2)

So that the critical power femtosecond pulse (leading to the birth of the crater [38]) for both is not much different and approaches in both experiments to the value of $13 \times 10^8 \, W$.

In experiments on the ablation of sodium chloride by laser pulses of 80 fs duration, only the dimensions of the optical damage spot were determined [27].

After irradiating of the samples with laser pulses of 40 fs duration, additional geometric parameters were determined: the depth and profile of the crater arising in the near-surface domain of sodium chloride by ablation [30].

At the first stage, estimating the depth of the crater ($h$), the fringe shift technique was used, which proved to be very useful for metals [39].
Figure 4. The dependence of the critical electric field (threshold of thermomechanical ablation) of sodium chloride on the pulse duration: experimental points at 80 and 40 fs.

Figure 5. Profile of ablation crater on Al surface.

Figure 6. Crater-profile in the near-surface region of sodium chloride.

However, observations showed that for sodium chloride the contrast of the interference fringes turned out to be quite low, and it could only be estimated that the depth of the crater exceeded 100 nm, in comparison with metals, where \( h \) is tens of nm (figure 5) [11].

In the second stage, the area of optical damage on the surface of sodium chloride was studied using an atomic force microscope. On this microscope, the profile of the crater was scanned, and its depth was determined. The result is shown in figure 6. As can be seen, the crater profile turned out to be symmetrical.

According to the measurements, for a pulse with an energy density \( F = 3.5 \text{ J/cm}^2 \), the depth of the crater for sodium chloride was 1.45 \( \mu \text{m} \). In aluminum, according to [40], at the same value of \( F \), we expect \( h \) to be of the order of 100 nm. Thus, \( h \) sodium chloride is significantly (by an order of magnitude) higher than that of metals.

In table 1, the dependence of \( h \) in the near-surface domain of sodium chloride from \( G \) is presented. According to table 1, figures 2 and 3, in the studied domain \( F \), all dimensions of the...
Table 1. Dependence of the depth of the sodium chloride crater on the energy of a laser pulse with a duration of 40 fs.

| \( \ln G (\mu J) \) | 5.10 | 4.60 | 4.35 | 4.20 | 4.15 | 3.90 |
|----------------------|------|------|------|------|------|------|
| \( h (\text{nm}) \)  | 1410 | 1320 | 1160 | 1050 | 780  | 0    |

crater increase with increasing energy of the laser pulse. Also found that, with increasing \( G \), at small depths, the crater first grows linearly, and then, beginning with \( h \), of the order of 1 mm, growth follows a more complex power law.

5. Conclusions

Thus, it is possible to formulate following conclusions:

(i) There is good agreement between the predicted and found the critical electric field intensity for laser pulses with a duration of about 40 fs observed.

(ii) Critical emission power in a pulse near the thermomechanical ablation threshold for a pulse duration of 40 and 80 fs differs not much approaching to the value of 1.3 GW.

(iii) The depth of the crater of thermomechanical ablation in sodium chloride is an order of magnitude greater than that of metals.

Acknowledgments

This work was supported in the framework of the basic part of government task from the Ministry of Education and Science of Russia to KBSU for years 2017–2019 (project No. 3.8382.2017).

References

[1] Gavasheli Yu O, Komarov P S, Ashitkov S I and Savintsev A P 2016 *Tech. Phys. Lett.* **42** 565
[2] Anisimov S I and Luk’yanchuk B S 2002 *Phys. Usp.* **45** 293
[3] Stuart B C, Feit M D, Herman S, Rubenchik A M, Shore B W and Perry M D 1996 *Phys. Rev. B* **53** 1749
[4] Makarov G N 2013 *Phys. Usp.* **56** 643
[5] Krasyuk I K, Pashinin P P, Semenov A Yu and Khisluchenko K V 2016 *Laser Phys.* **26** 094001
[6] Chichkov B N, Momma C, Nolte S, Von Alvensleben F and Tünnermann A 1996 *Appl. Phys. A* **63** 109
[7] Bulgakova N M, Bourakov I M and Bulgakova N A 2001 *Phys. Rev. L* **63** 046311
[8] Bulgakova N M, Bulgakova A V, Bourakov I M and Bulgakova N A 2002 *Appl. Surf. Sci.* **197–198** 41
[9] Arakelyan S M, Itina T E, Kutrakovskaya S V, Kucherik A O, Shirkin L A, Mahalova E Yu, Volkova A Yu and Povarnitsyn M E 2014 *Izv. KBSU* **4(3)** 104
[10] Bulgakova N M and Bourakov I M 2002 *Appl. Surf. Sci.* **197–198** 96
[11] Ashitkov S I, Komarov P S, Ovchinnikov A V, Struleva E V, Zhakhovsky V V, Inogamov N A and Agronat M B 2014 *Quantum Electron.* **44** 535
[12] Starinskii S V, Shukhov Yu G and Bulgakov A V 2016 *Tech. Phys. Lett.* **42** 411
[13] Koldunov M F, Manenkov A A and Pokotilo I L 1998 *Quantum Electron.* **28** 269
[14] Winkler S W, Burakov I M, Stoian R, Bulgakova N M, Husakou A, Mermillod-Blondin A, Rosenfeld A, Ashkenasi D and Hertel I V 2004 *Appl. Phys. A* **86** 413
[15] Inogamov N A *et al* 2011 *J. Opt. Tech.* **78** 473
[16] Grehn M, Seutha Th, Hfner M, Griga N, Theiss Ch, Merillod-Blondin A, Eberstein M, Eicher H and Bronze J 2014 *Opt. Mater. Express.* **4** 689
[17] Wollershoff S S, Hohlfeld J, Geise J and Matthias E 1999 *Appl. Phys. A* **69**
[18] Babkin A A, Kiselev A M, Pravdenko K I, Sergeev A M, Stepansov A N and Khazanov E A 1999 *Phys. Usp.* **42** 74
[19] Mao S S, Quere F, Guizard S, Mao X, Russo R E, Petite G and Martin P 2004 *Appl. Phys.* **79** 1695
[20] Anisimov S I, Zhakhovsky V V, Inogamov N A, Nishihara K, Petrov Yu V and Khokhlov V A 2006 *JETP* **103** 183
[21] Ashitkov S I, Agronat M B, Kanel’ G I, Komarov P S and Fortov V E 2010 *JETP Lett.* **92** 516
[22] Corbari C, Champion A, Gecevius M, Beresna M, Bellouard Y and Kazansky P G 2013 Opt. Express 21 3946
[23] Bellouard Y, Champion A, McMillen B, Mukherjee S, Thomson R R, Pépin C, Gillet P and Cheng Ya 2016 Optica 3 1285–93
[24] Savintsev A P 2005 Ionic dielectrics in the field of femtosecond laser pulses Physics of Extreme States of Matter—2005 ed Fortov V E et al (Chernogolovka: IPCP RAS) pp 32–4
[25] Savintsev A P 2006 Sodium chloride in the field of femtosecond laser pulses Physics of Extreme States of Matter—2006 ed Fortov V E et al (Chernogolovka: IPCP RAS) pp 175–7
[26] Karpenko S V, Savintsev A P and Temrokov A I 2008 Dokl. Phys. 53 128
[27] Savintsev A P 2008 Tech. Phys. Lett. 34 122
[28] Savintsev A P and Gavasheli Yu O 2015 J. Phys.: Conf. Ser. 653 012011
[29] Savintsev A P and Gavasheli Yu O 2013 Dokl. Phys. 58 411
[30] Gavasheli Yu O, Komarov P S, Ashitkov S I and Savintsev A P 2016 Dokl. Phys. 61 577
[31] Savintsev A P and Gavasheli Yu O 2011 Tech. Phys. Lett. 37 1027
[32] Savintsev A P and Gavasheli Y O 2014 Dokl. Phys. 59 393
[33] Agranat M B, Anisimov S I, Ashitkov S I, Ovchinnikov A V, Kondratenko P S, Sitnikov D S and Fortov V E 2006 JETP Lett. 83 501
[34] Liu J M 1982 Optics Lett. 7 196
[35] Savintsev A P 2015 Izv. KBSU 5(4) 95
[36] Zaidel A N 1974 Errors of Measurement of Physical Quantities (Leningrad: Nauka)
[37] Agranat M B, Ashitkov S I, Ivanov A A, Konyashenko A V, Ovchinnikov A V and Fortov V E 2004 Quantum Electron. 34 506
[38] Savintsev A P and Gavasheli Yu O 2016 J. Phys.: Conf. Ser. 774 012118
[39] Ashitkov S I, Ovchinnikov A V and Sitnikov D S 2006 Dynamics of the expansion of the surface layer of the target under the action of femtosecond laser pulses Physics of Extreme States of Matter—2006 ed Fortov V E et al (Chernogolovka: IPCP RAS) pp 156–7
[40] Colombier J P, Combis P, Bonneau F, Le Harzic R and Audouard E 2005 Phys. Rev. B 71 165406