Single Shot Ablation Craters with Ultra-Short Laser Pulses: A Comparative Study

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INTRODUCTION

In femtosecond (fs) laser ablation, the entire pulse will strike the material surface before the plasma (that is created from the laser-material interaction) is dense enough to cause energy loss due to plasma shielding. Also, the pulse duration is shorter than the time required for the deposited energy to thermally conduct through the material[1].

In the nanosecond (ns) regime, deposited energy can thermally conduct because of the longer timescale. The material surface is subjected to a higher mechanical stress than in the fs regime due to thermal expansion and the force of the escaping material from the crater. This leads to rough edges and cracking of the material inside and around the crater[1].

The goal of this investigation was to observe the different dominating mechanisms for the two regimes on the surfaces of commonly used materials in manufacturing.

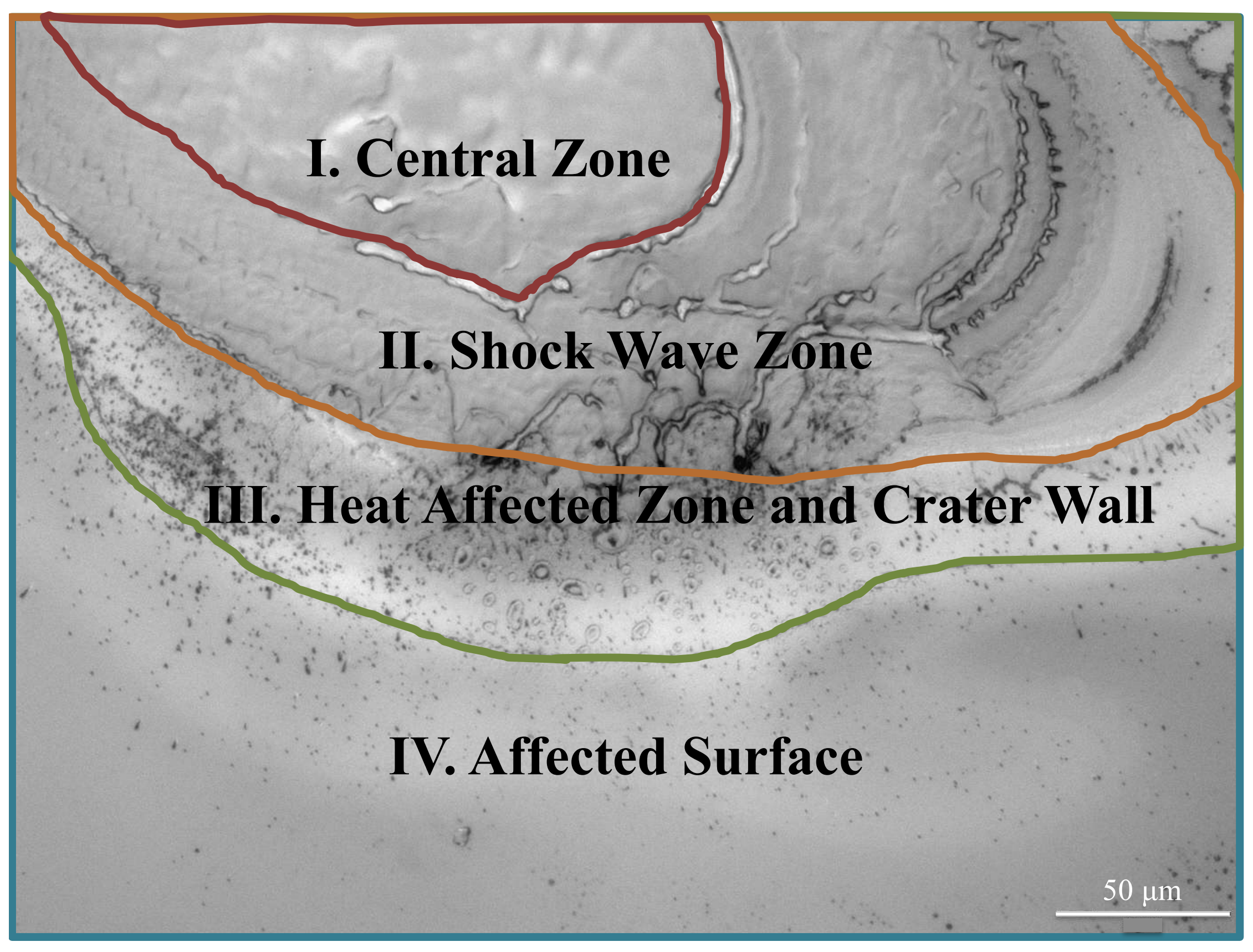

Fig. 1: Outlines of the four distinct ablation regions

In Figure 1, the ablation regions are classified as follows:

Central Zone: Characterized by a smooth surface with few ripples. This is where the most intense part of the beam hit.

Shock Wave Zone: This region is where most of the molten material was pushed towards. A combination of ejecting gasses/plasma and surface tension made the molten material rise up from the surface of the sample.

Heat Affected Zone: All material here was ablated, but some molten material was ejected from the inner regions forming droplets in this region and the next.

Affected Surface: This region is the area outside of the crater wall that has either been subjected to possible electron excitations from the neighboring irradiated areas, turning it into a brighter colored surface, the deposition of the droplets, or both.

ANALYSIS OF SURFACE MORPHOLOGY

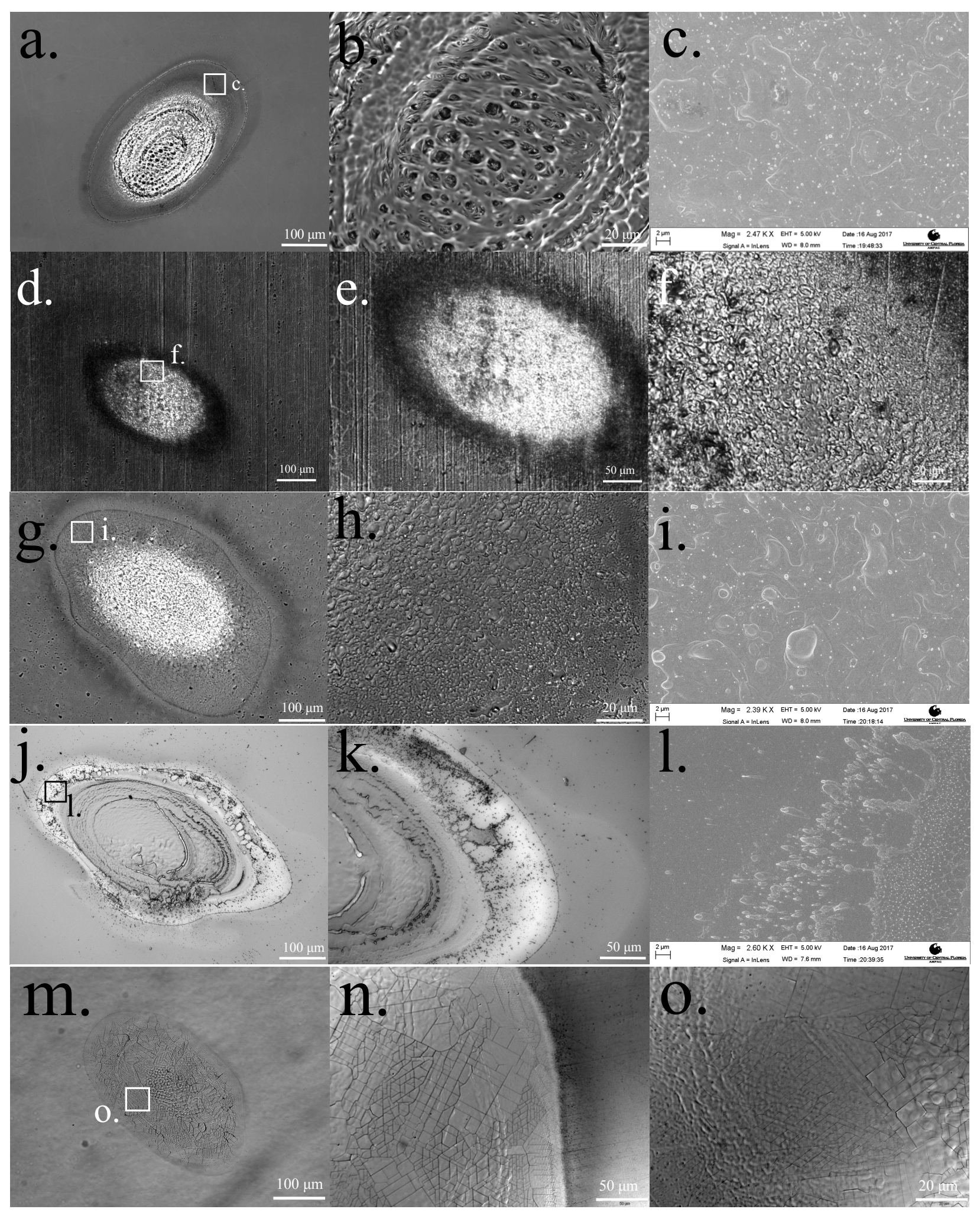

Fig. 3: Femtosecond ablation craters of a.-c.) Al, d.-f.) Cu, g.-i.) Ti, j.-l.) GaAs, m.-o.) ZnSe

Table 1: Measurements of the major surface features of each of the materials' craters from the femtosecond and nanosecond ablation

fs Regime	Central Zone Diameter (µm)	Total Crater Diameter (µm)	Depth (µm)	Height Above Surface of Ridges (µm)	Diameter of Nanodroplets (µm)
Al	105.723	326.175	0.25	0.30	0.460
Cu	-	507.955	0.15	0.25	0.783
Ti	128.357	390.765	0.15	0.20	0.395
GaAs	156.805	364.026	0.20	0.35	0.418
ZnSe	238.129	335.252	0.20	0.10	0.597
ns Regime	Central Zone Diameter (µm)	Total Crater Diameter (µm)	Depth (µm)	Height Above Surface of Ridges (µm)	Diameter of Nanopits (µm)
Al	122.055	453.468	0.30	0.70	2.199
Cu	-	231.281	0.12	0.20	2.120
Ti	292.504	600.148	0.15	0.20	2.858
GaAs	61.388	335.133	0.30	0.35	0.190
ZnSe	130.252	164.036	0.14	0.00	1.457

The craters that resulted on the Al in both regimes had nanopits that covered the entire Central Zone and Shockwave Zone (Fig. 3a, 3b, 4a – 4c).
The Cu craters did not have clear region separations (Fig 3d., 3e., 4d., 4e) which prevented clear measurements were not able to be taken of the Central Zone diameters. Also, the craters were randomly scattered with raised material.
The off-shaped structures in the ns regime craters (Figure 4) are due to the irregularity in the beam profile.

In both fs and ns regimes, Ti craters had the shallowest depths, the shortest ridges, but the largest total diameters (Table 1).

There was an abundance of nanodroplets along the fs GaAs craters (Fig. 3j – 3l). In the ns regime, very straight fracture lines appeared across the crater (Fig. 4j, 4k).
ZnSe craters had a very abrupt transition from the Affected Surface to the crater wall (3n., 4o.). There were, also, fracture lines throughout the craters, like in the GaAs samples, but in both regimes. Lastly, the craters were among the smallest of each regime.

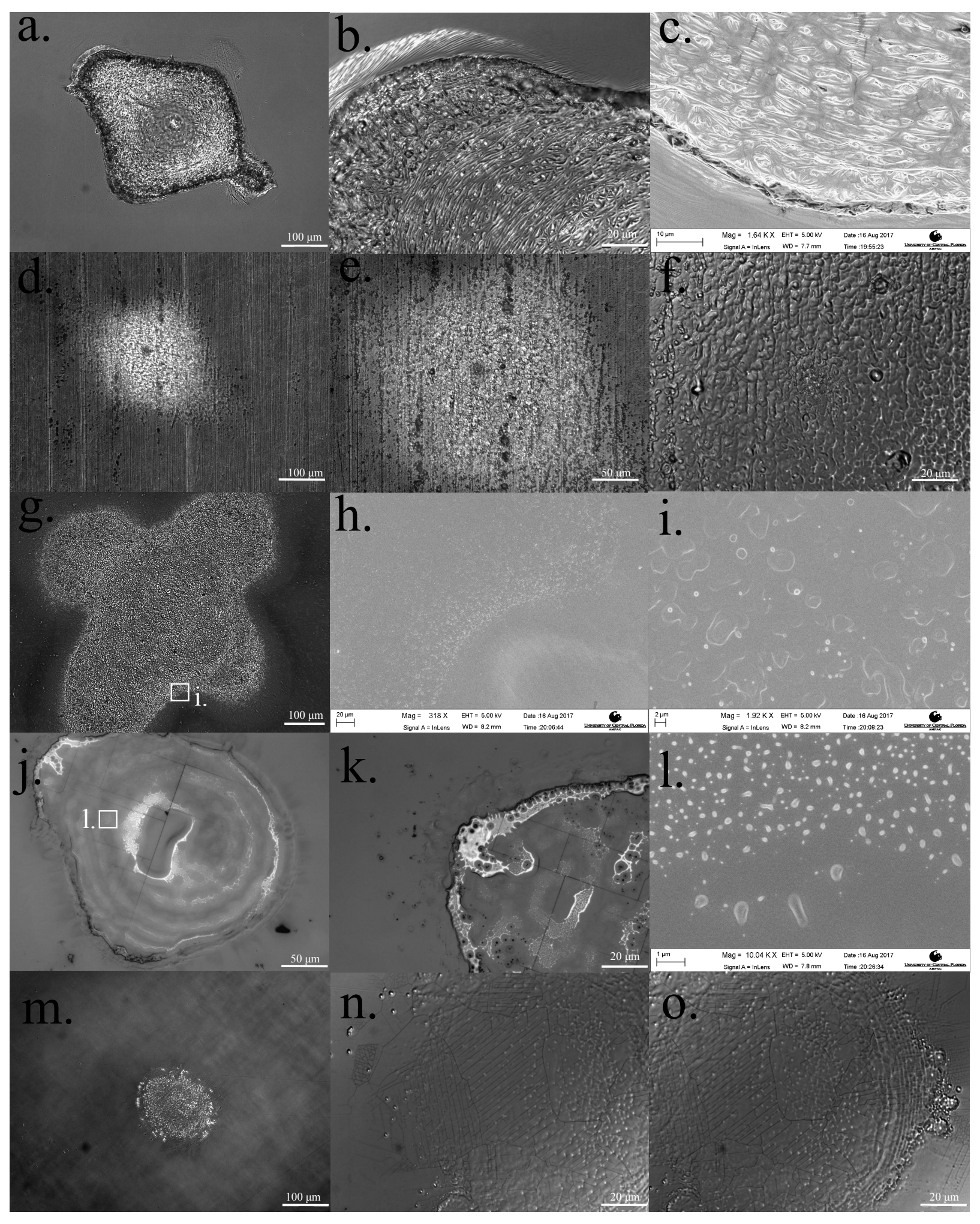

Fig. 4: Nanosecond ablation craters of a.-c.) Al, d.-f.) Cu, g.-i.) Ti, j.-l.) GaAs, m.-o.) ZnSe

CONCLUSIONS

Ejecting material through the surface caused the Al nanopits. The ambiguous regions of the Cu craters were a result of the sample's well known higher conductivity. The lack of significant material loss is consistent with similar investigations[2]. In both regimes, Ti had the largest and shallowest craters resulting from its lower energy conductivity, hardness, and lattice strength. In the ns regime, the GaAs fracture lines were due to thermomechanical stresses fracturing the crystalline structure of the sample. The nanodroplets of the fs regime were created from non-thermal phase change and recondensation[1,3]. The well contained ZnSe craters also showed the same crystalline fractures, but in both the fs and ns regimes, due to the energy from the heavy ablation regime [4].

In the ns regime, formation of a homogeneous and beam shaped crater of Ti (Fig. 3b, 5g) indicate a contribution from the beam/plasma interaction, most likely due to recoil pressure[5].

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This work is supported by the Summer Undergraduate Research Fellowship Program at Embry-Riddle Aeronautical University, ARO MURI "Light Filamentation Science", HEL/JTO and AFOSR MRI "Fundamental studies of filament interaction", and the State of Florida.