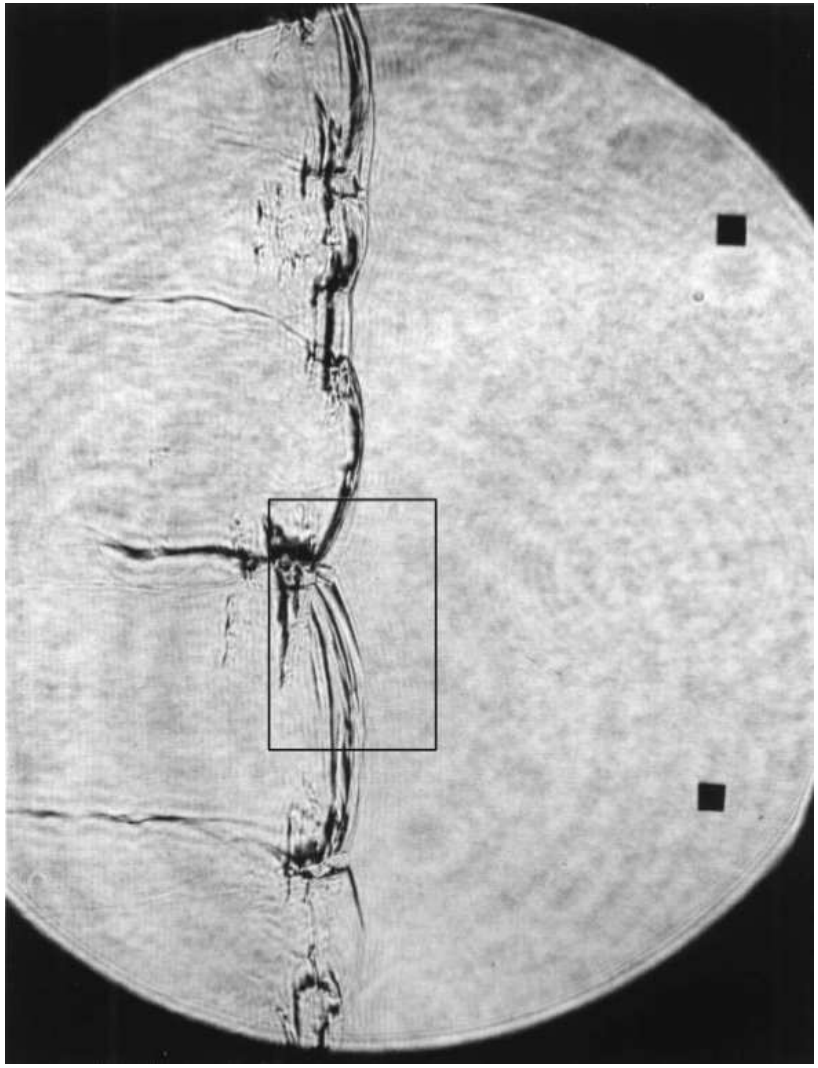
A Comparative Study of Detonability and Propensity to Sustain High-Speed Turbulent Deflagrations in Hydrogen and Methane Mixtures

Logan Maley, Rohit Bhattacharjee, and Matei Radulescu

University of Ottawa

Canada

The Detonation Wave

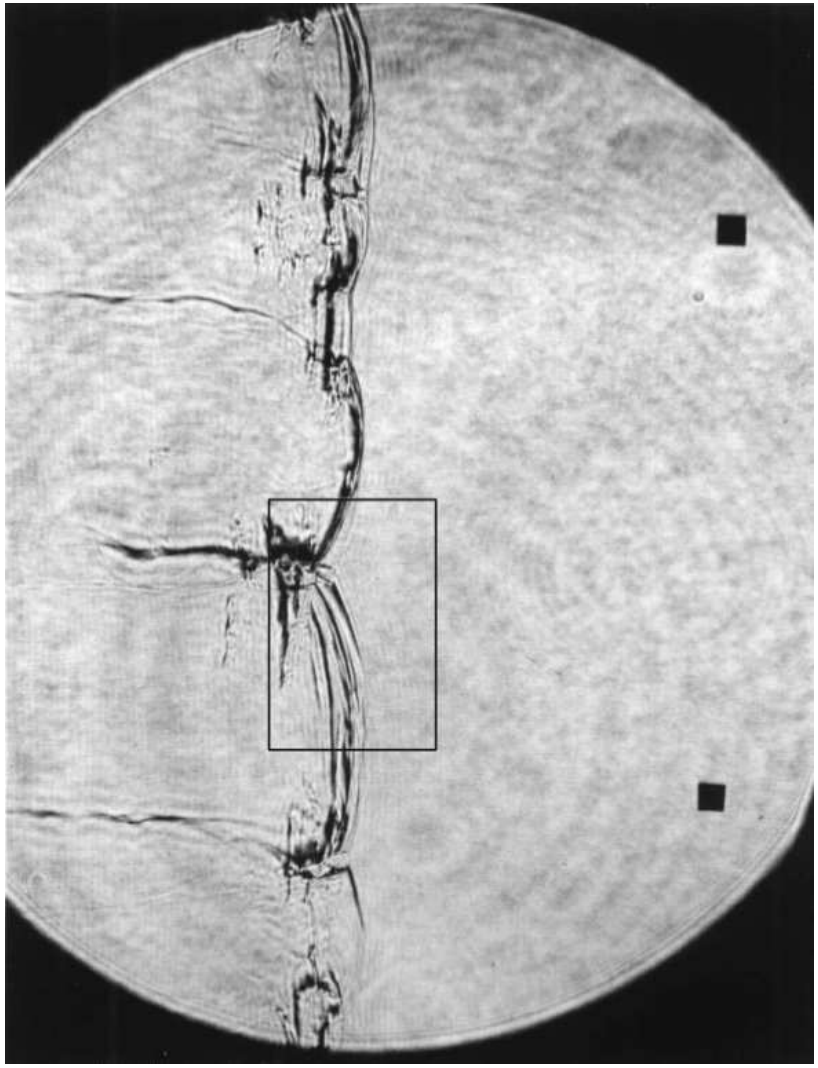


$2H_2 + O_2 + 3.5N_2$

- Supersonic combustions waves
- Very large over pressures
- Inherently unstable
- Complex Three dimensional structure

Austin PhD Thesis, CalTech 2003

The Detonation Wave

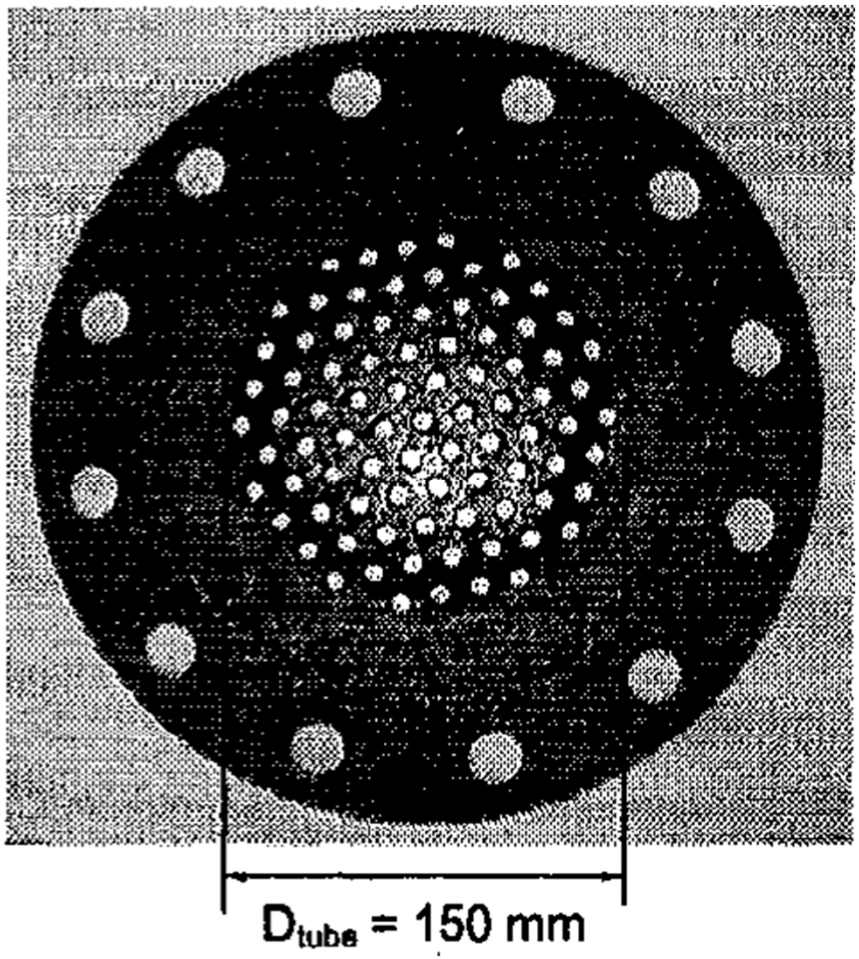


$2H_2 + O_2 + 3.5N_2$

To determine detonation limits, many researchers have used obstacle interactions to quench the detonation

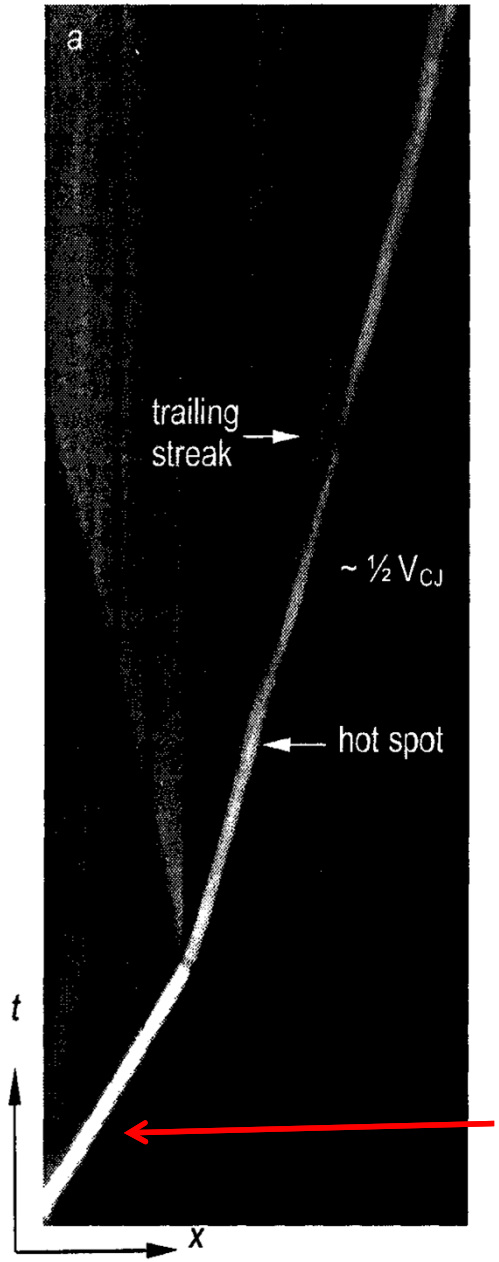
Austin PhD Thesis, CalTech 2003

Obstacle Interactions



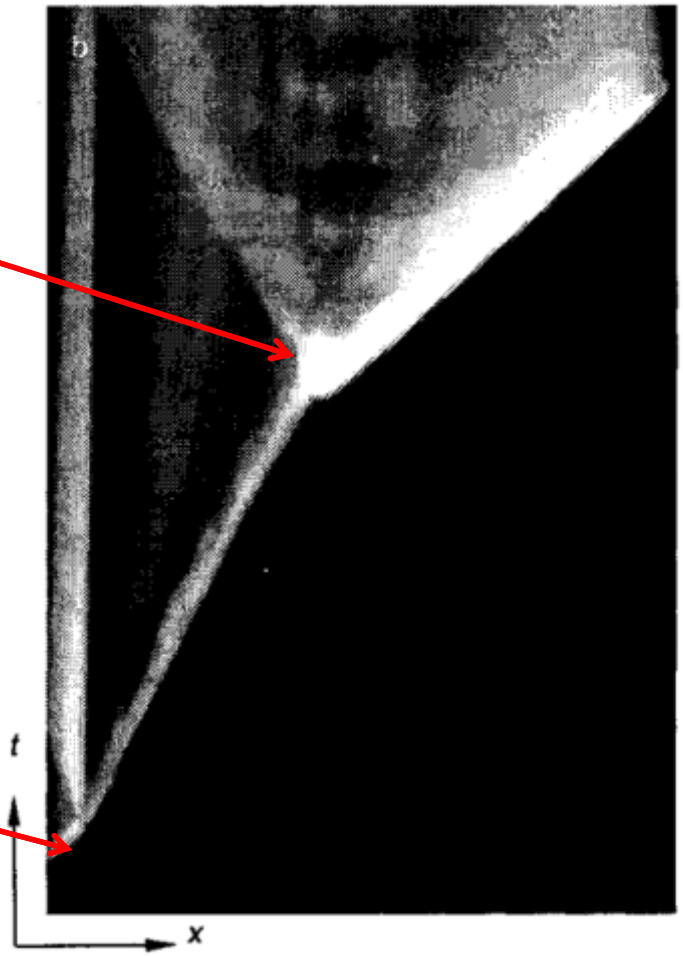
J. Chao – Ph.D. Thesis 2006

Flame Acceleration



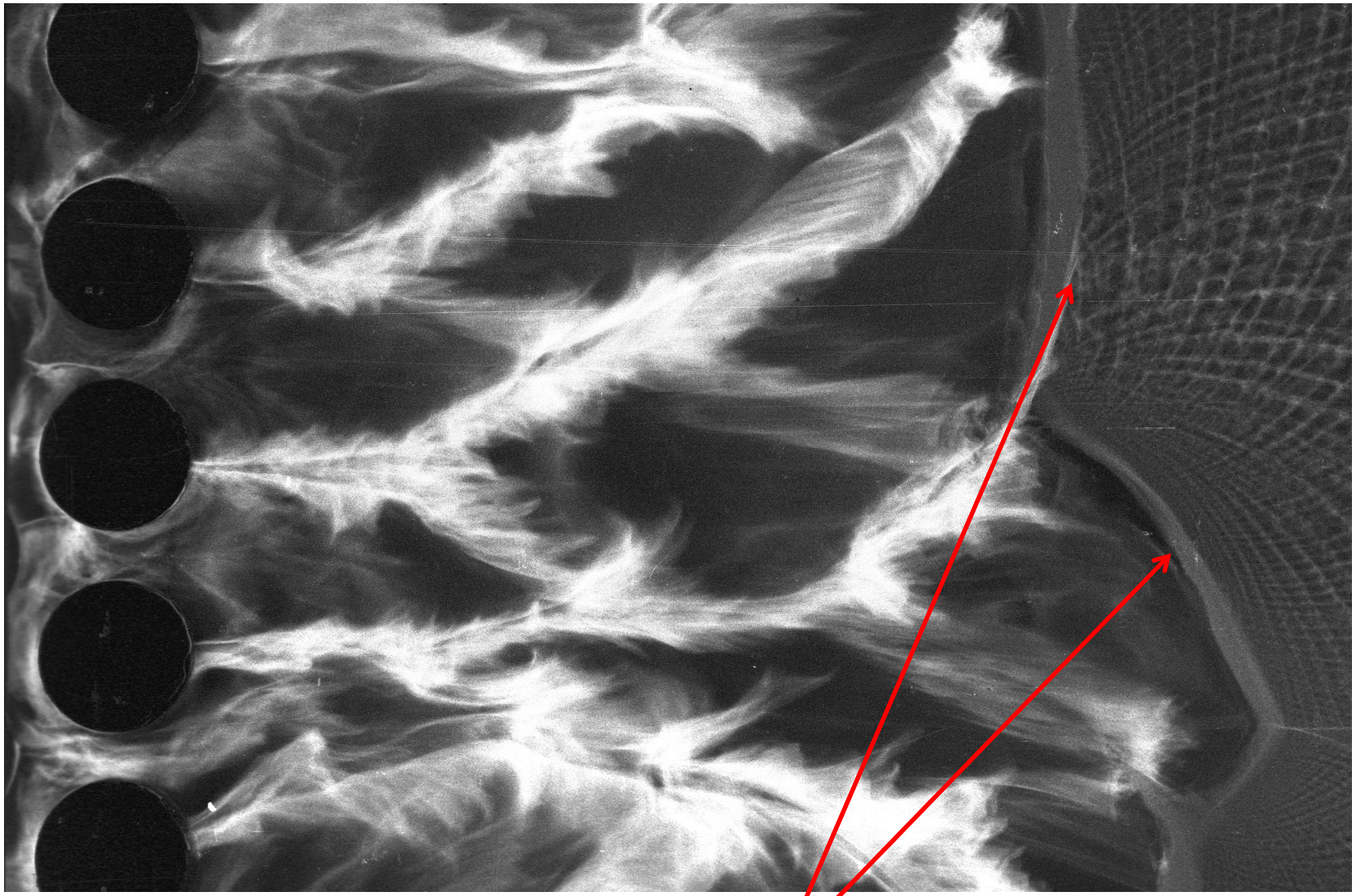
Detonation transition

Initial Detonation



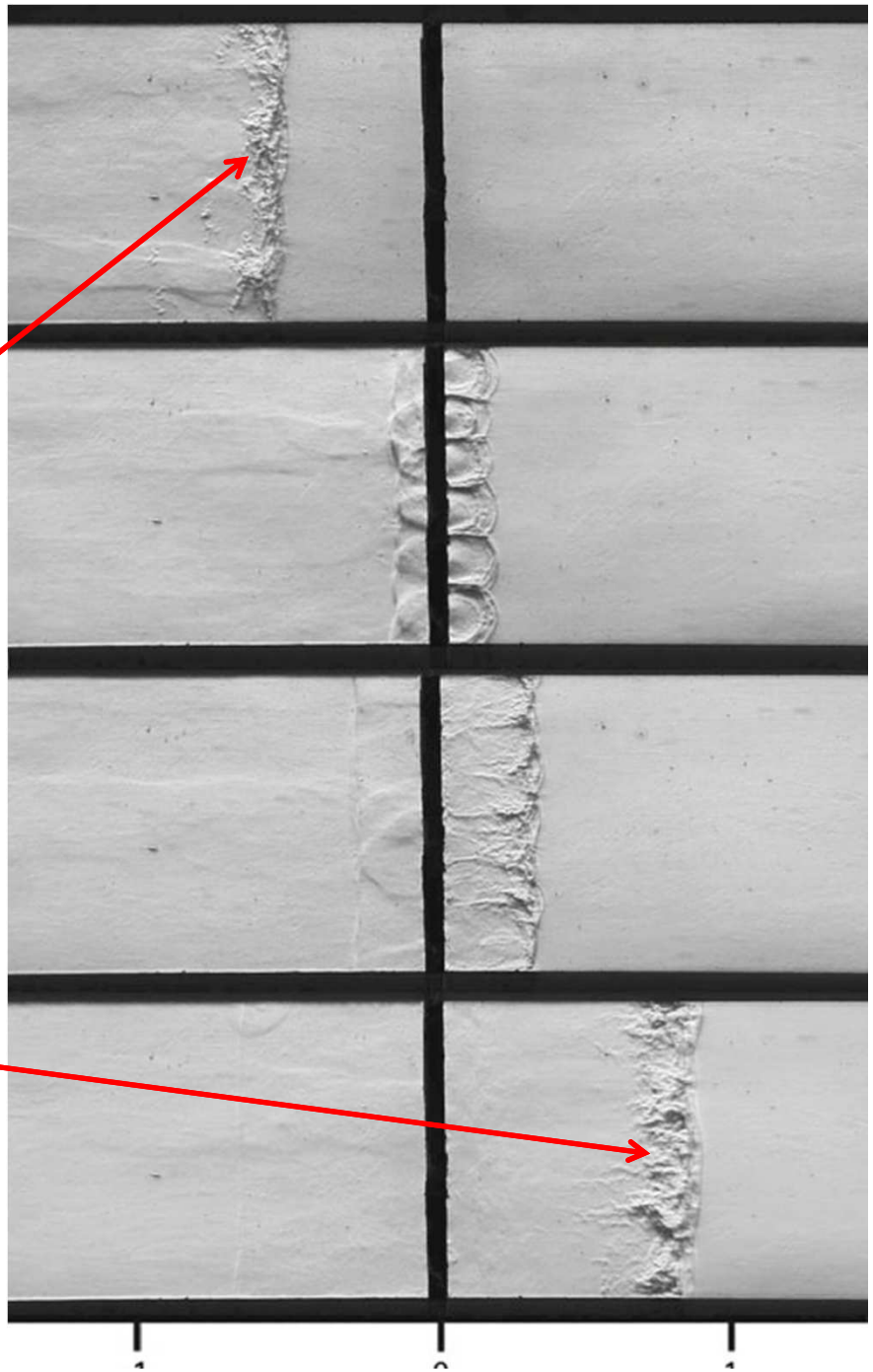
$C_2H_2 + 2.5O_2$ a) *Po* = 3 kPa 69% blockage b) *Po* = 6 kPa 87% blockage J. Chao – Ph.D. Thesis 2006

Detonation Quenching



$C_2H_2 + 2.5O_2$

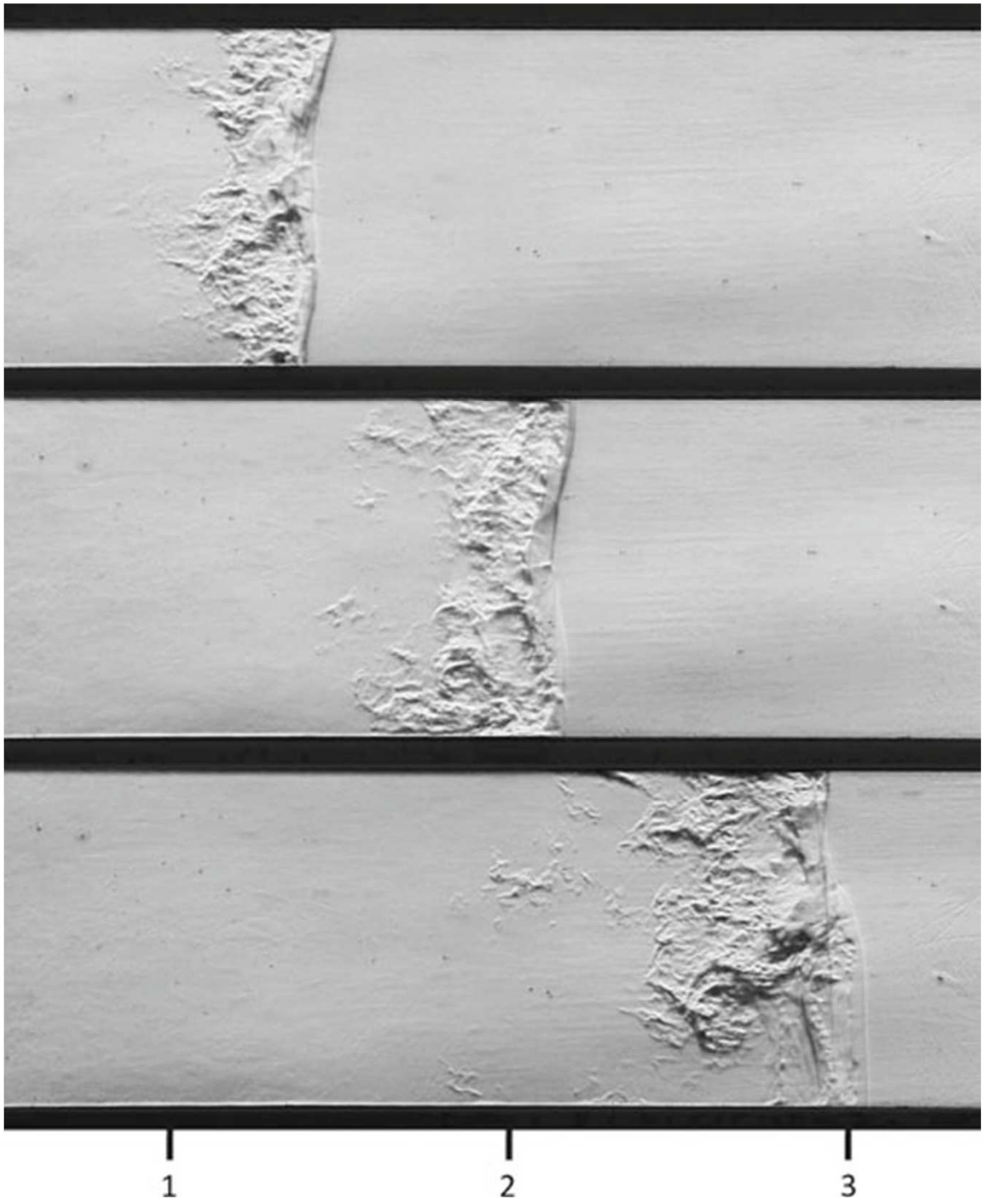
Radulescu & Maxwell JFM 2012



$C_3H_8 + 5O_2$

J.-S. Grondin
J. H. S. Lee, SW 2010

Turbulent reaction zone
structure closely coupled



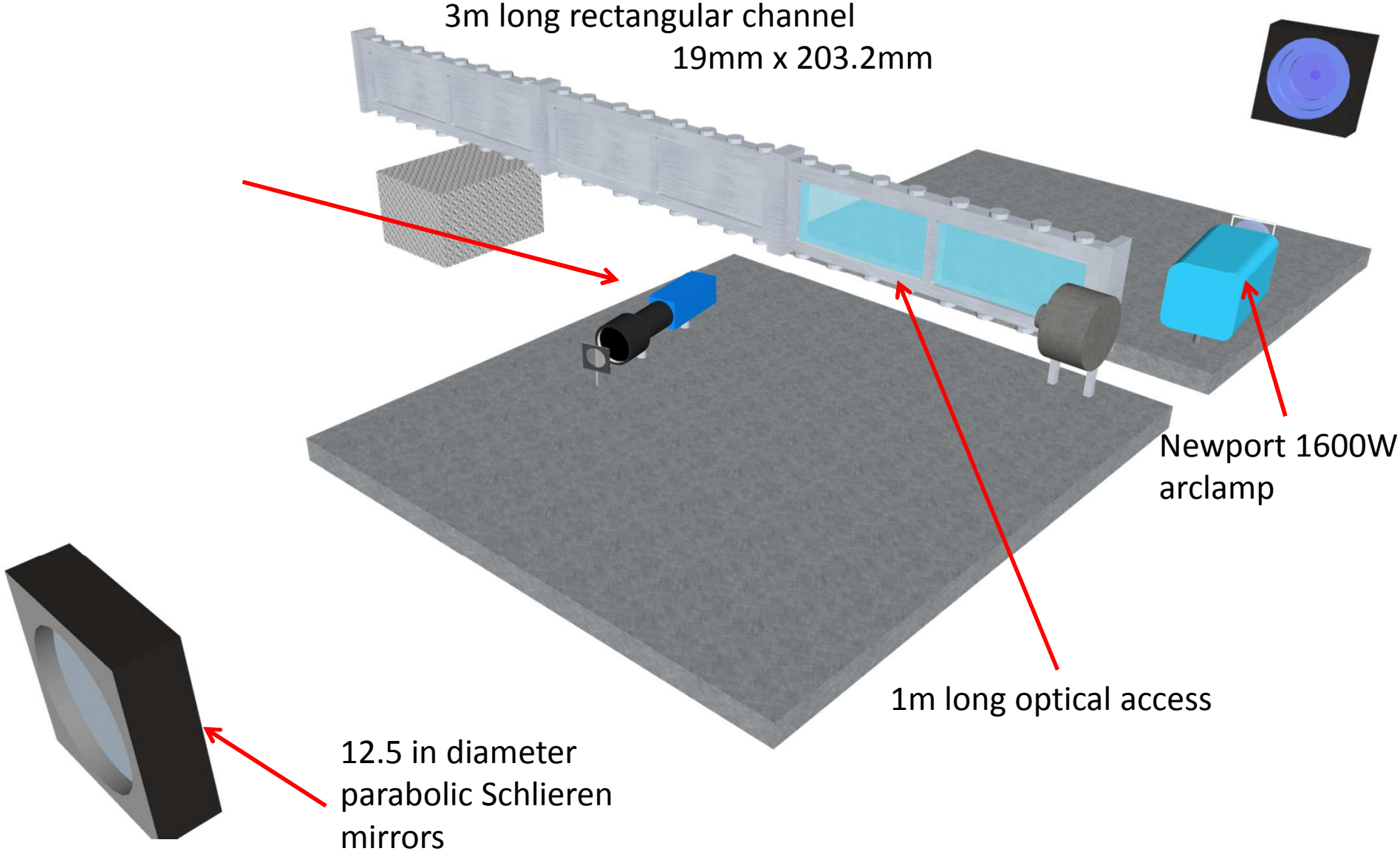
J.-S. Grondin
J. H. S. Lee, SW 2010

$C_3H_8 + 5O_2$

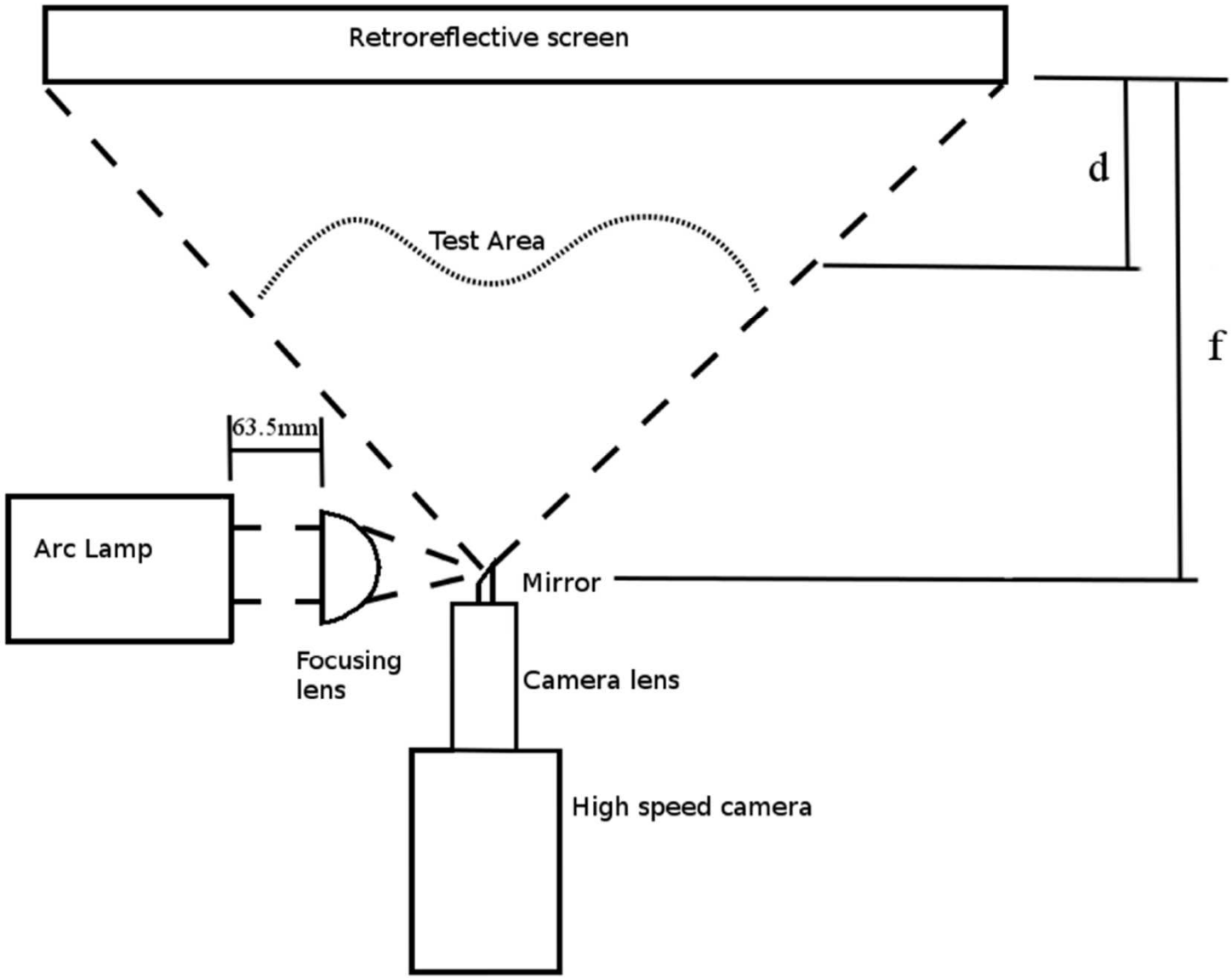
This Study

…attempts to isolate the structure of the fast flame in a well controlled and reproducible fashion to clarify the behaviour

Experimental details



Settles' Large Scale Shadowgraph



Mixtures Investigated

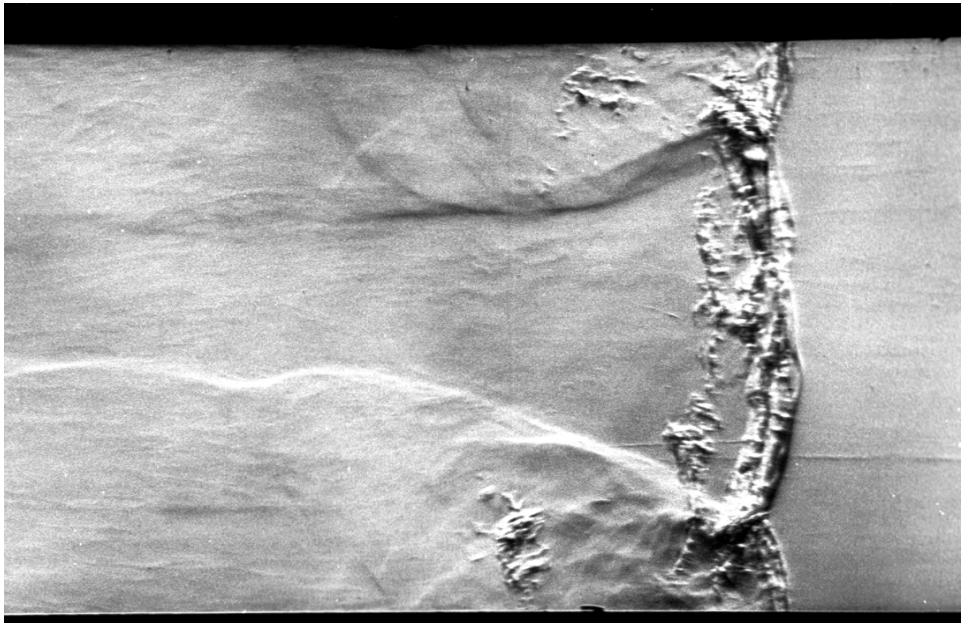
An unstable detonation

$CH_4 + 2\ O_2$

A more stable detonation

$2H_2 + O_2$

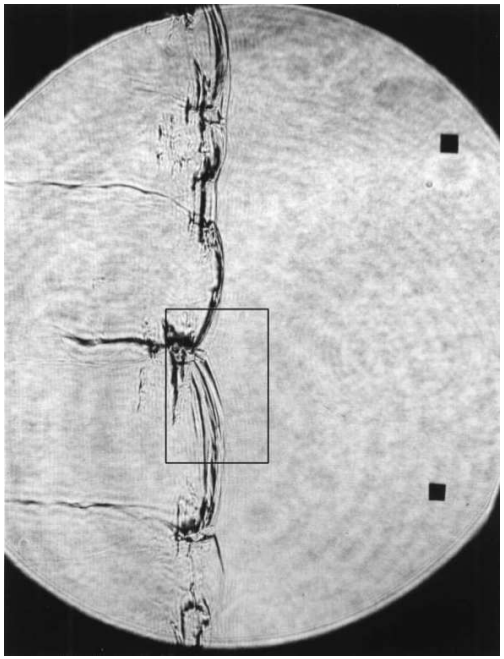
Seen here,



$CH_4 + 2\ O_2$

Radulescu PhD Thesis, McGill 2003

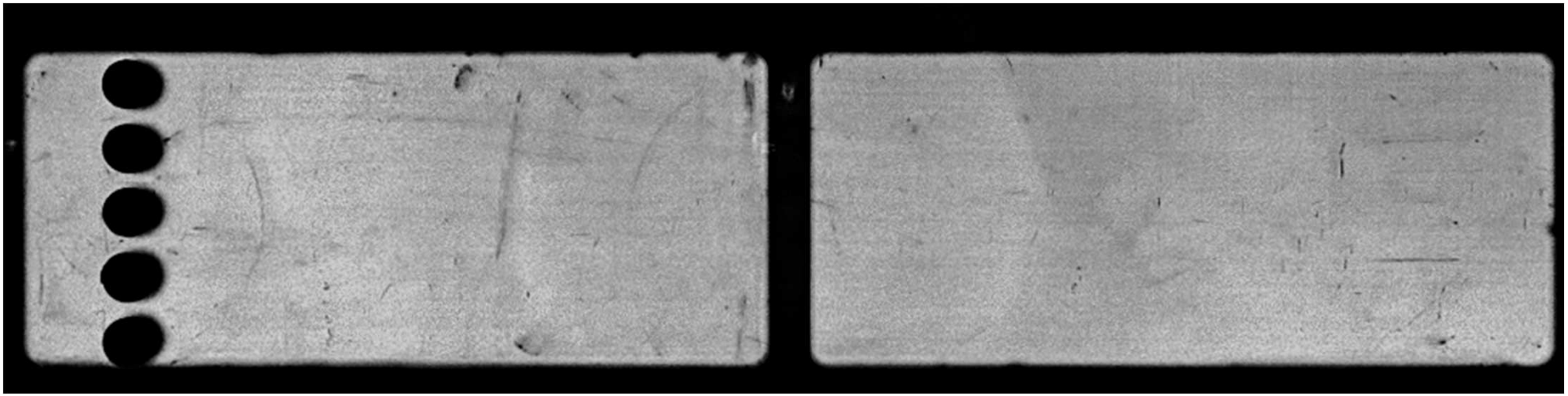
Similar to,



$2H_2 + O_2 + 3.5N_2$

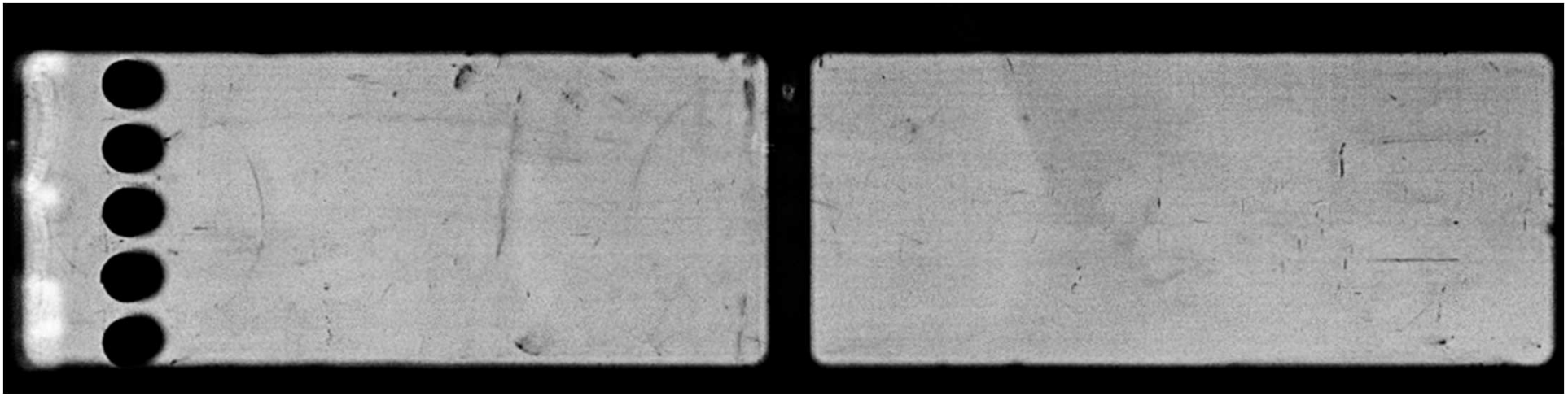
Austin PhD Thesis, CalTech 2003

Fast Flame Amplification



$CH_4 + 2O_2$ P_o = 6.9kPa

Fast Flame Amplification



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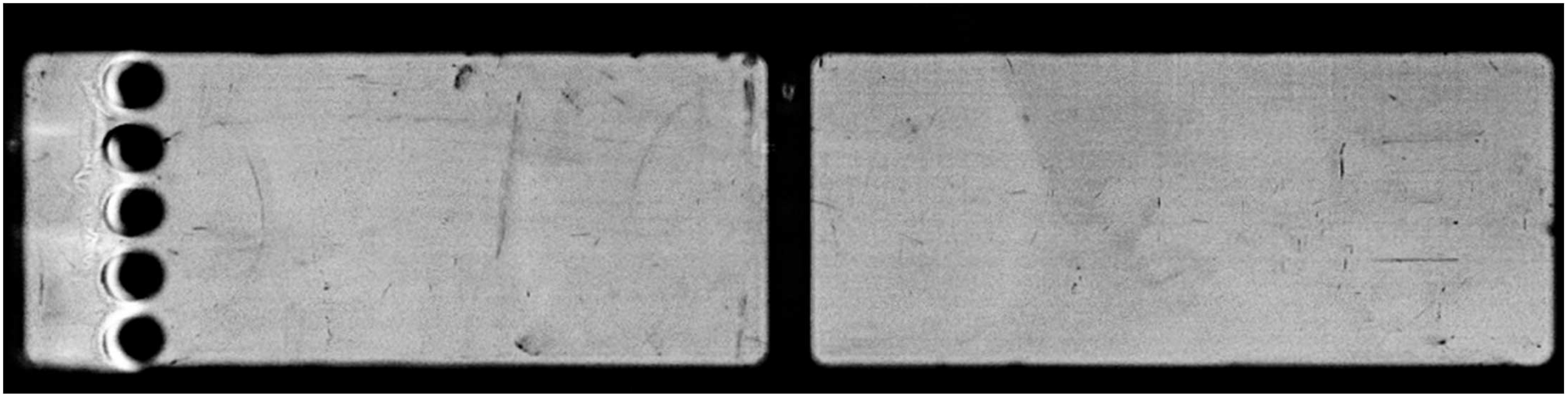

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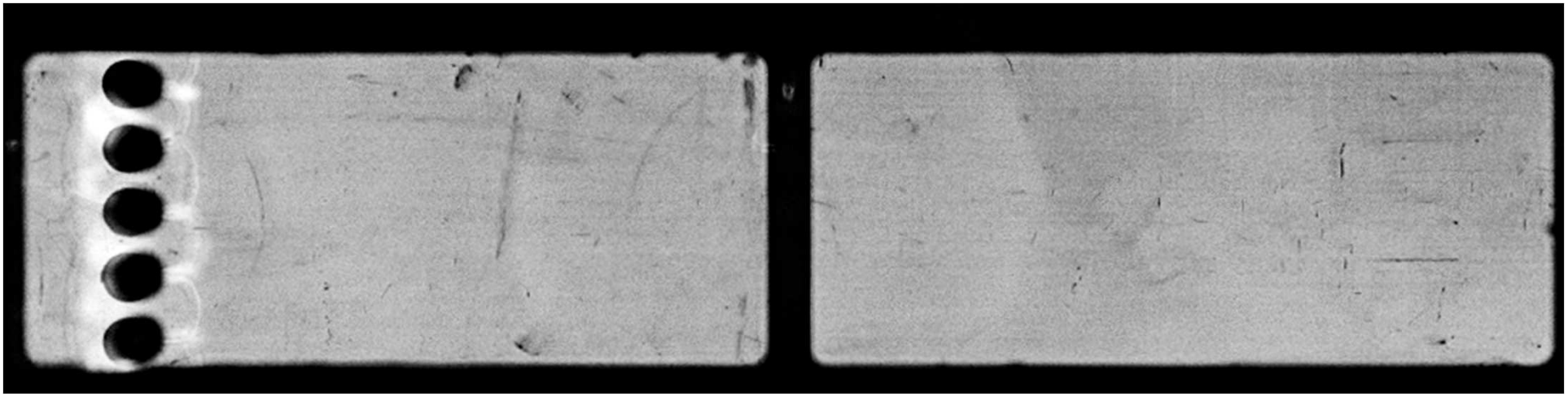

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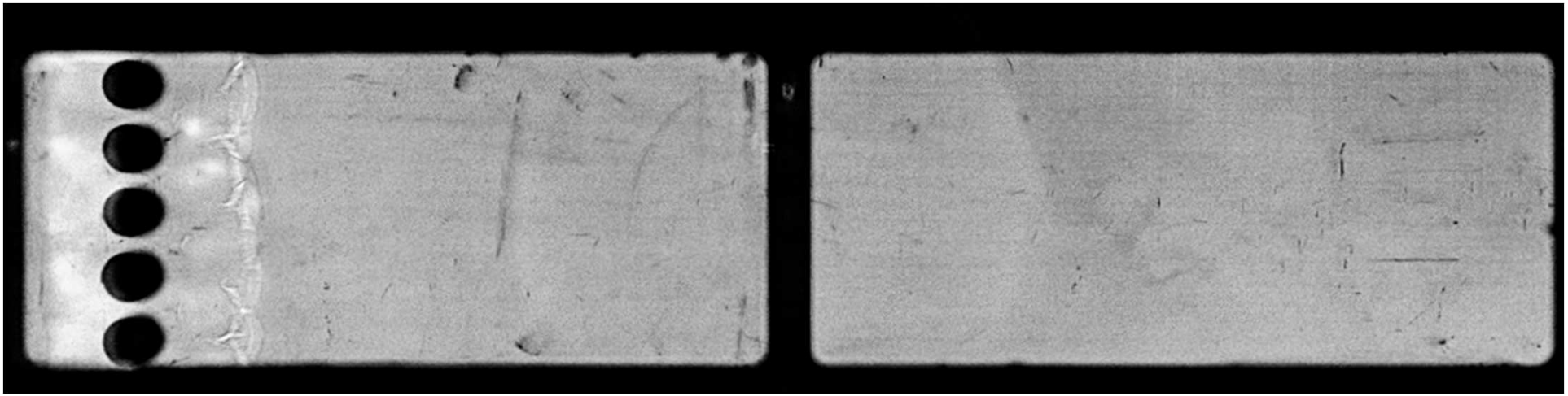

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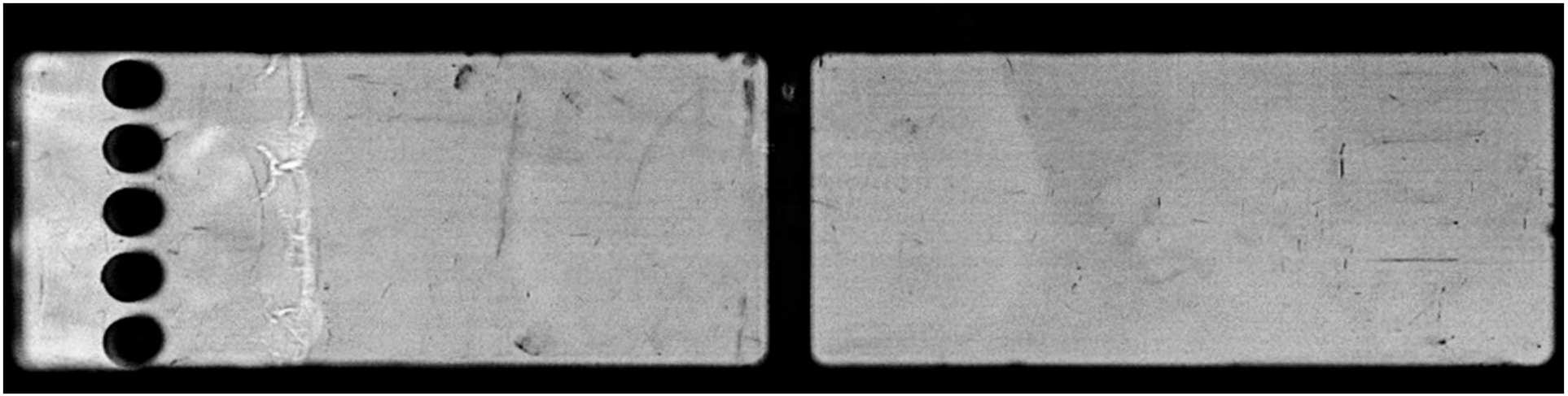

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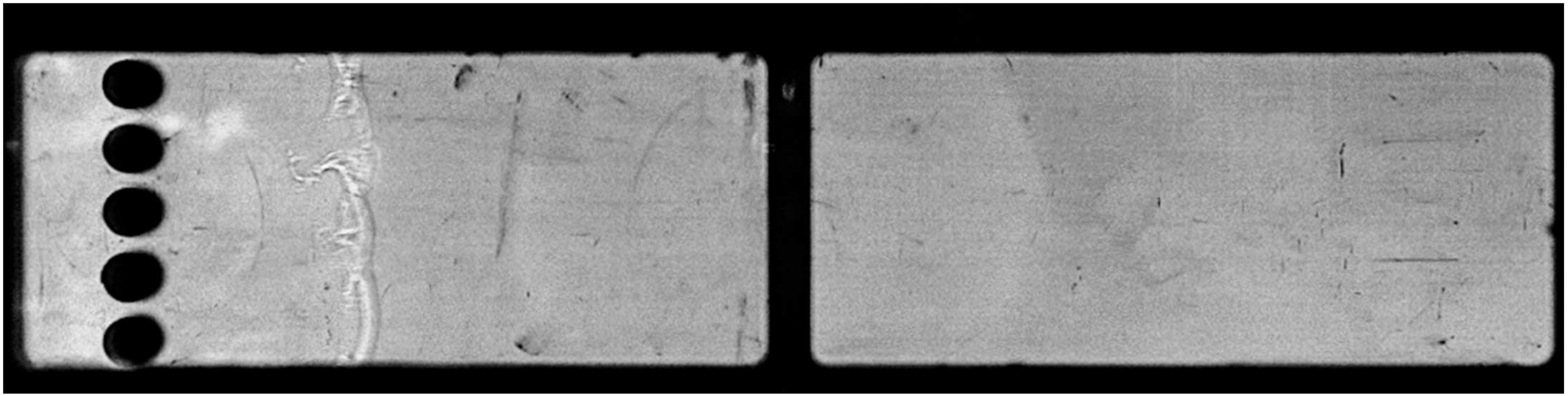

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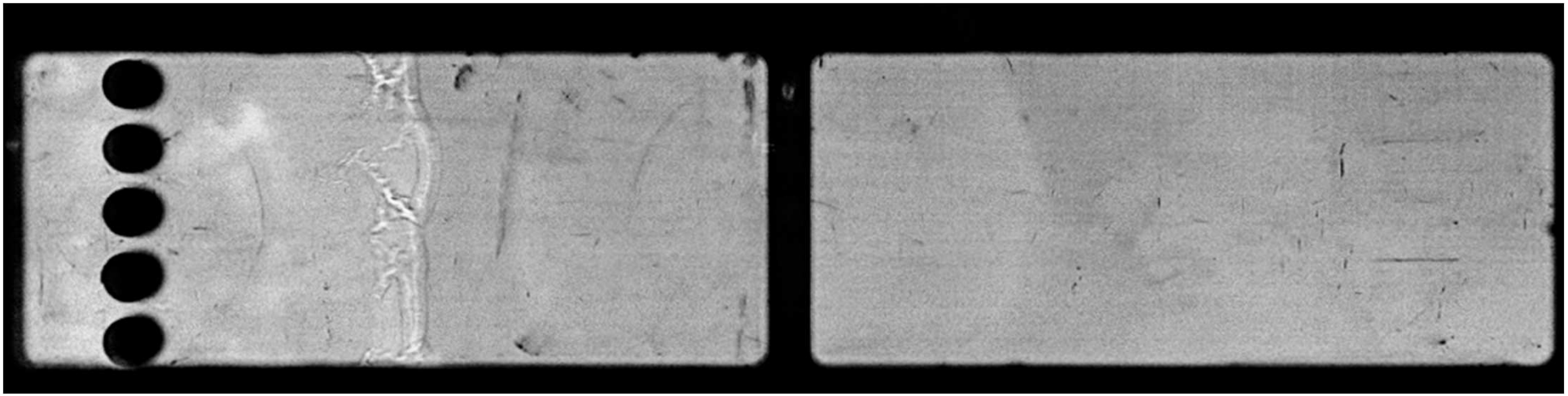

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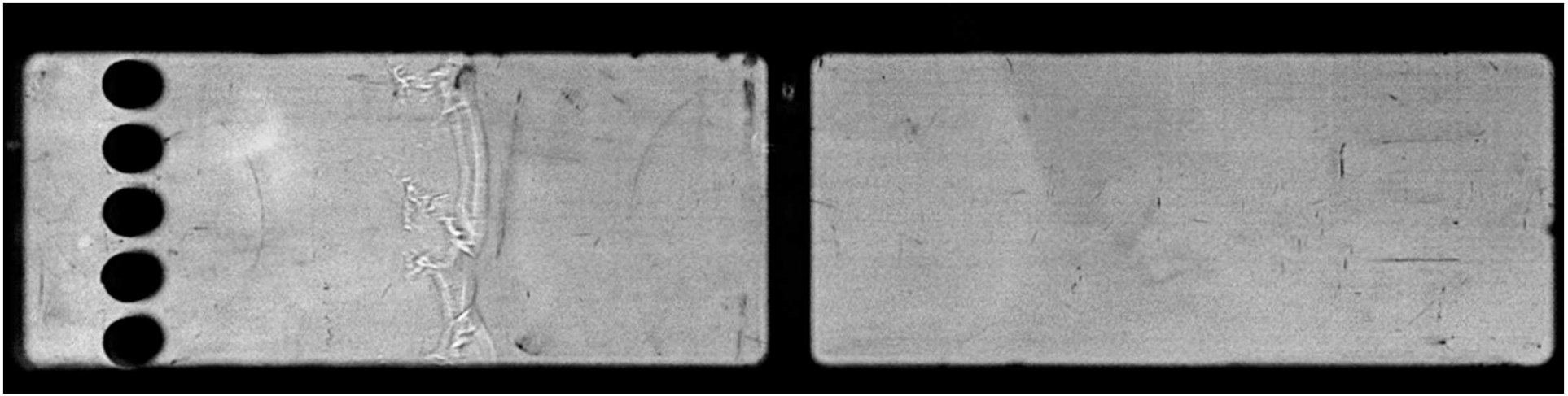

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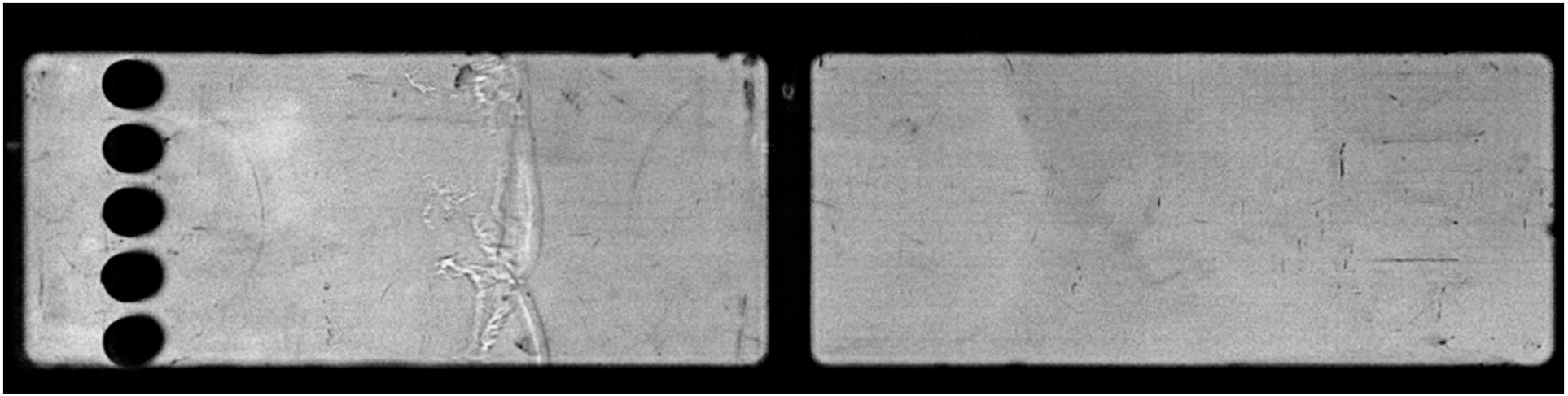

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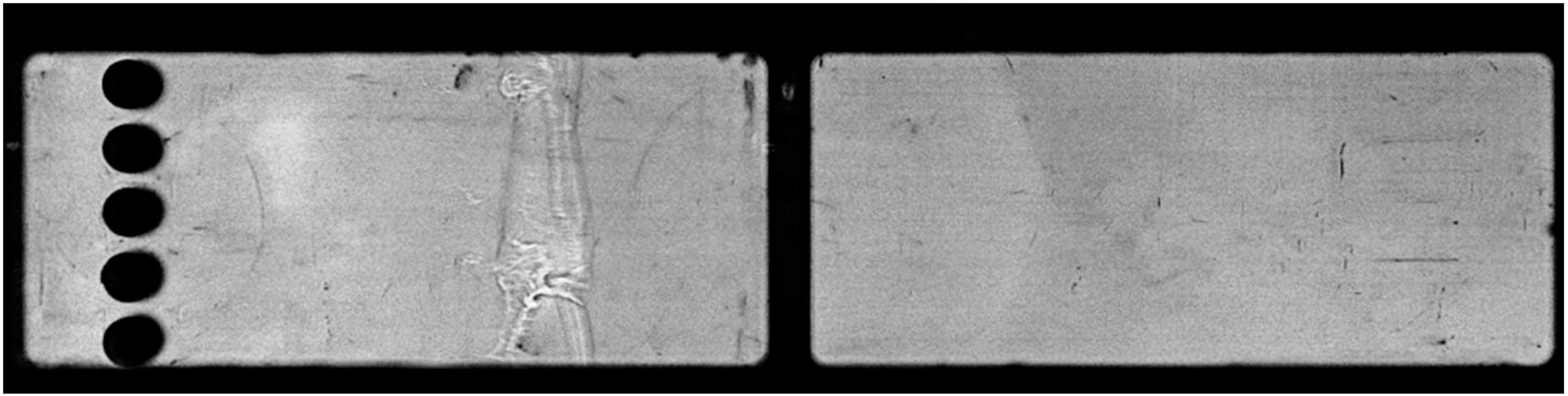

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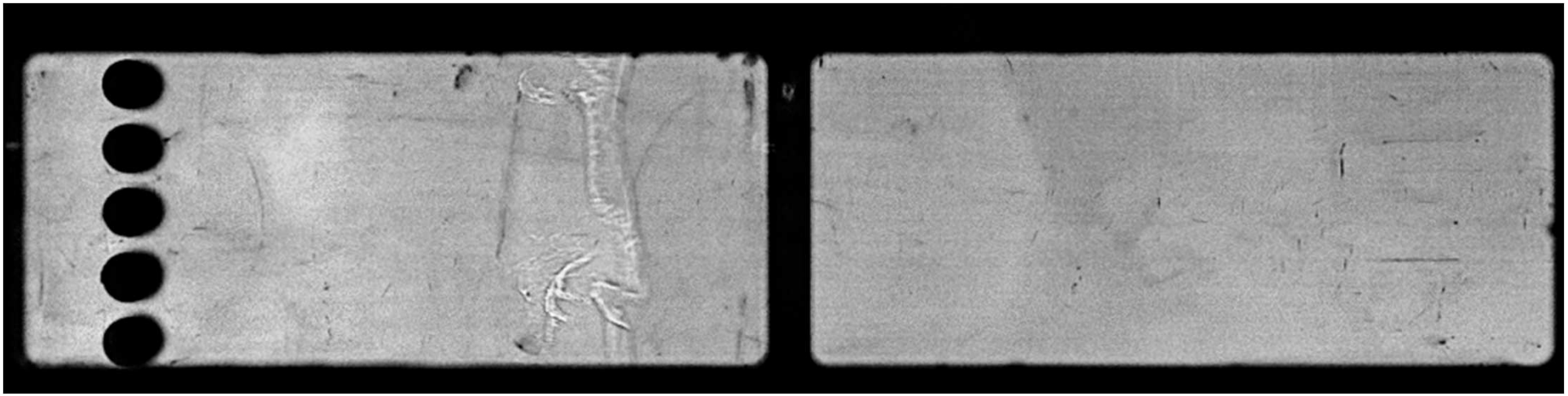

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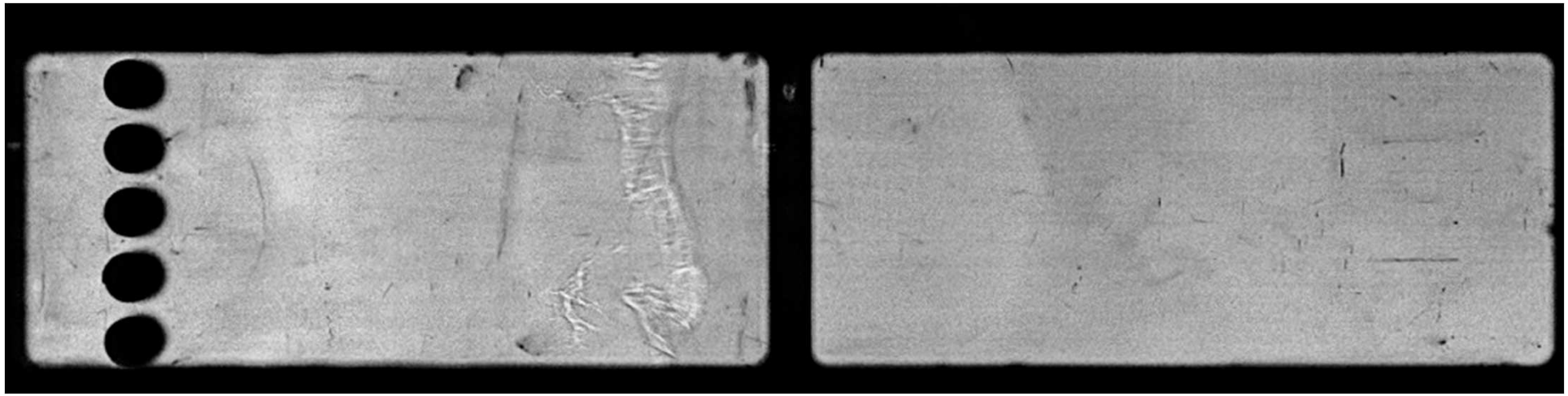

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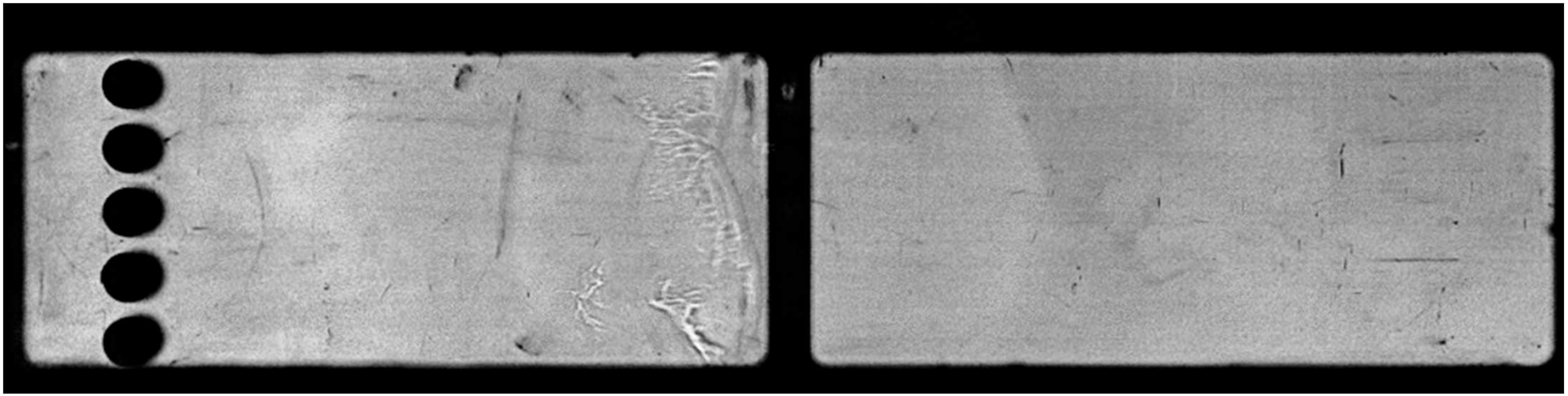

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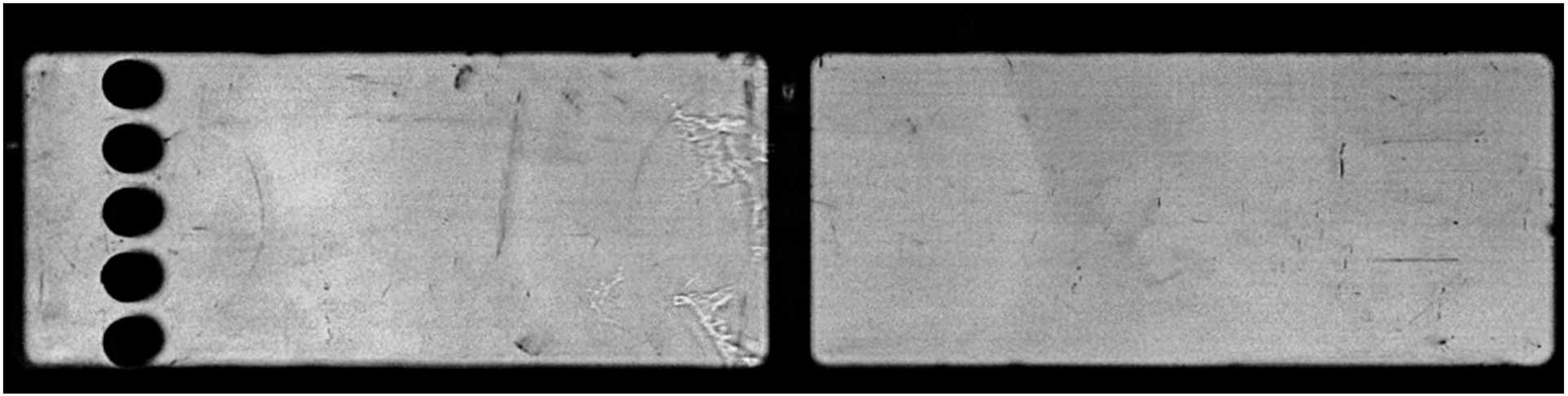

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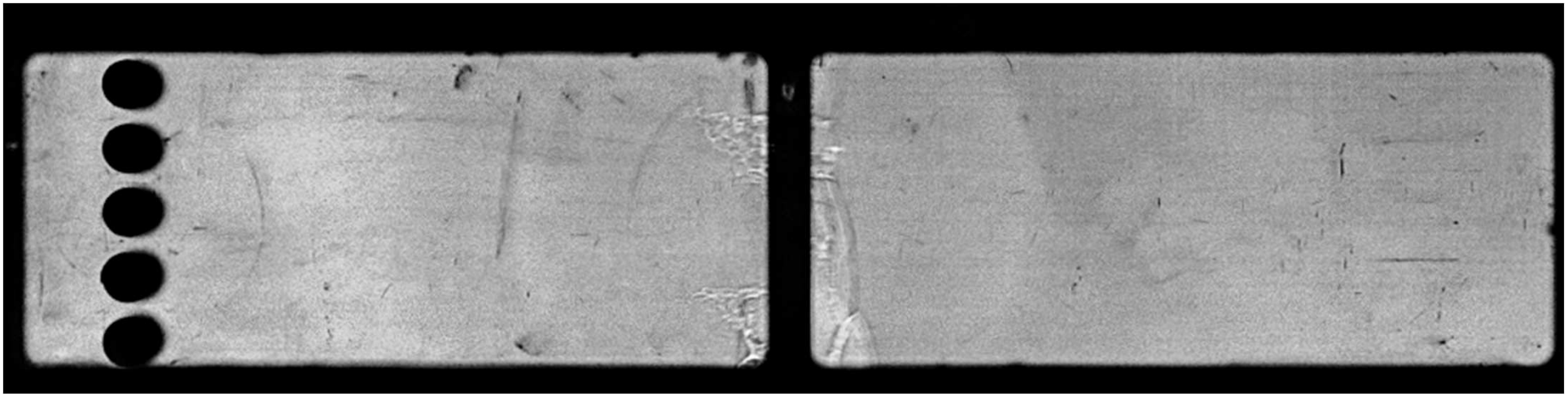

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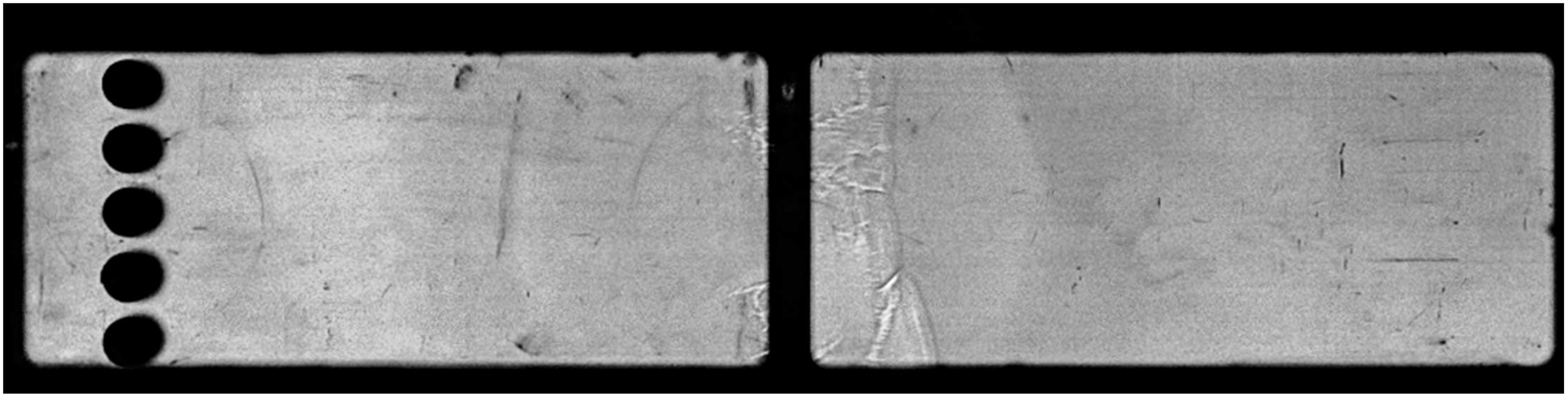

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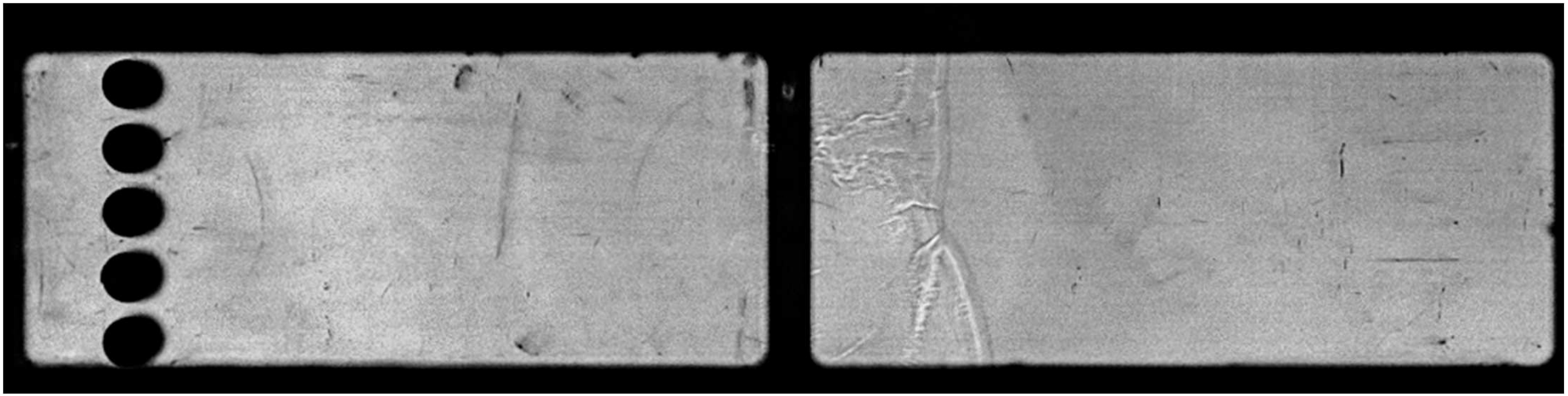

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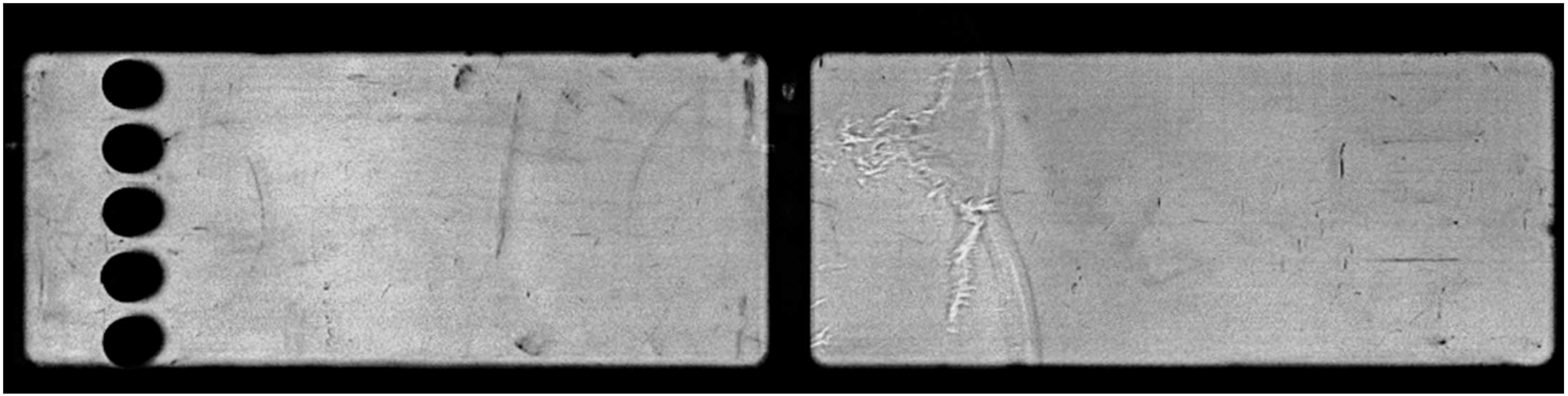

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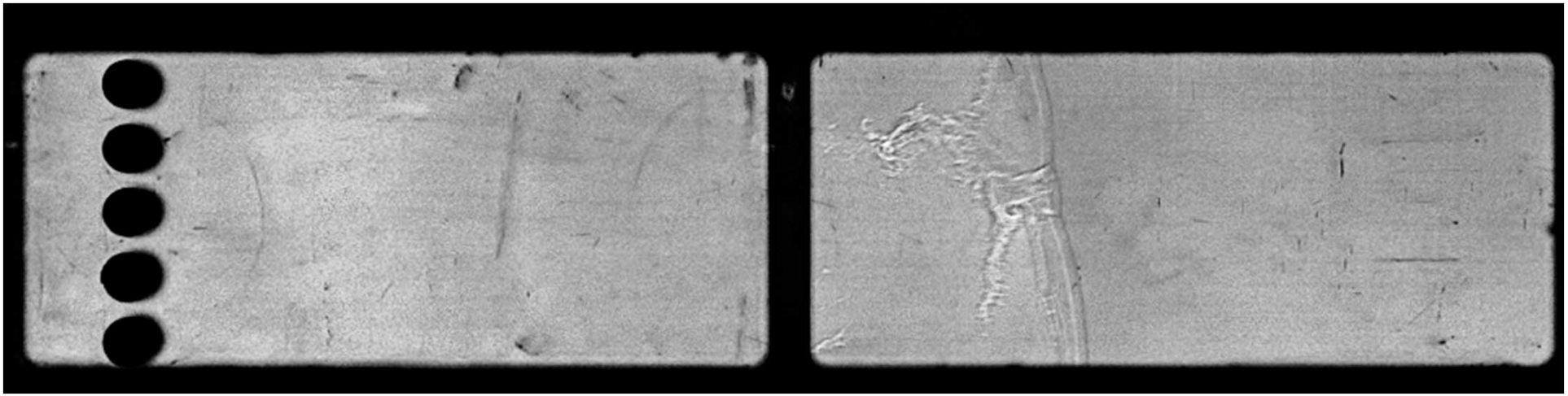

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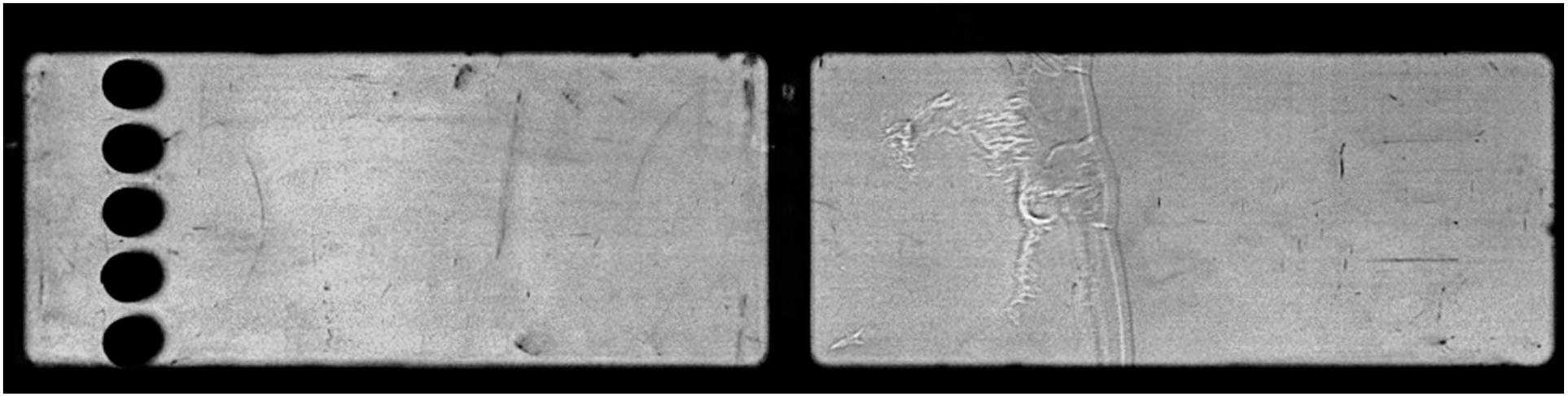

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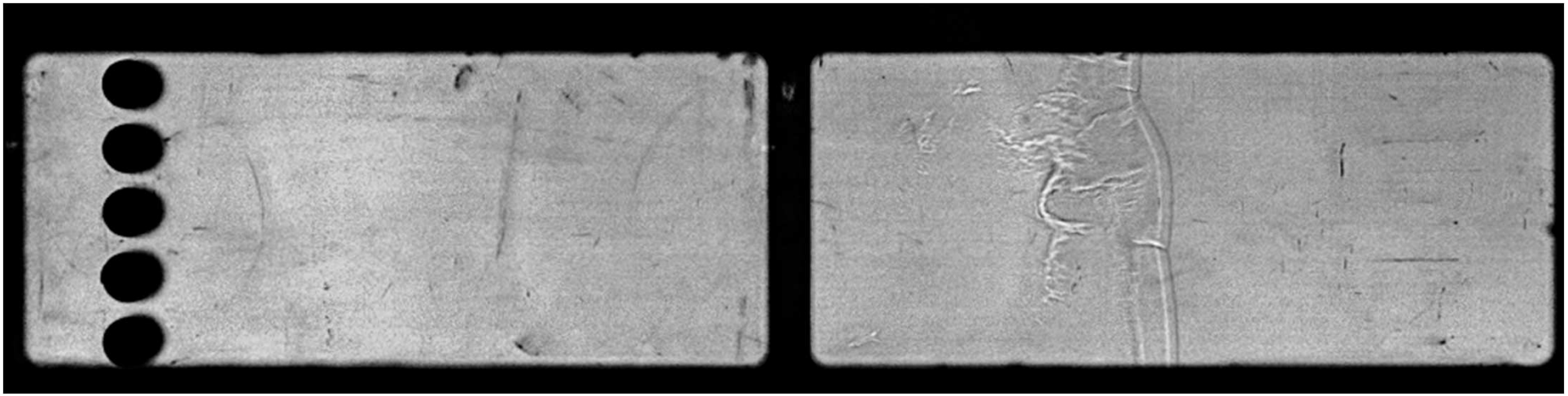

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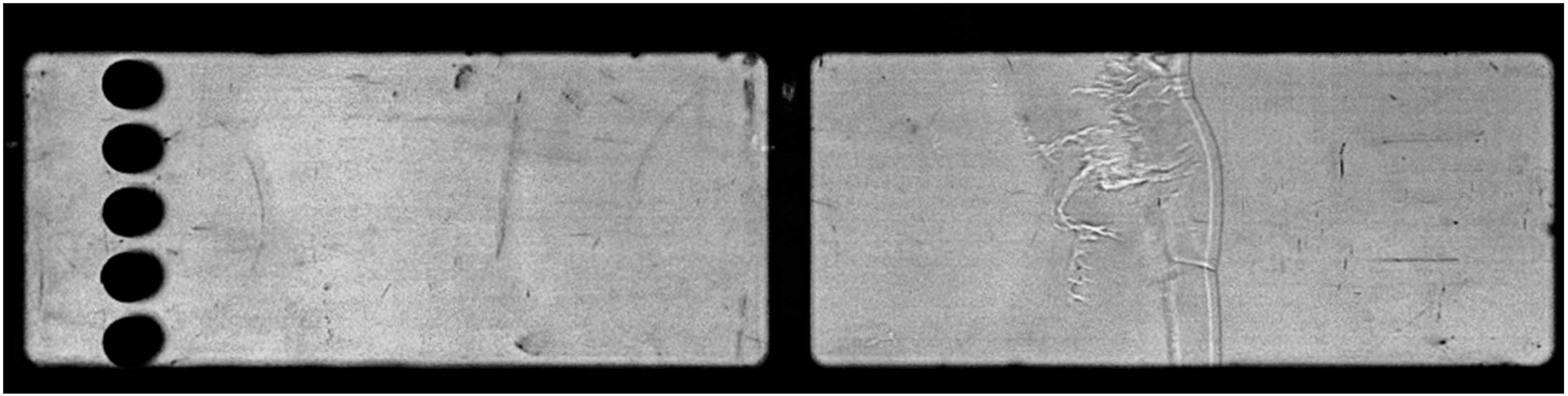

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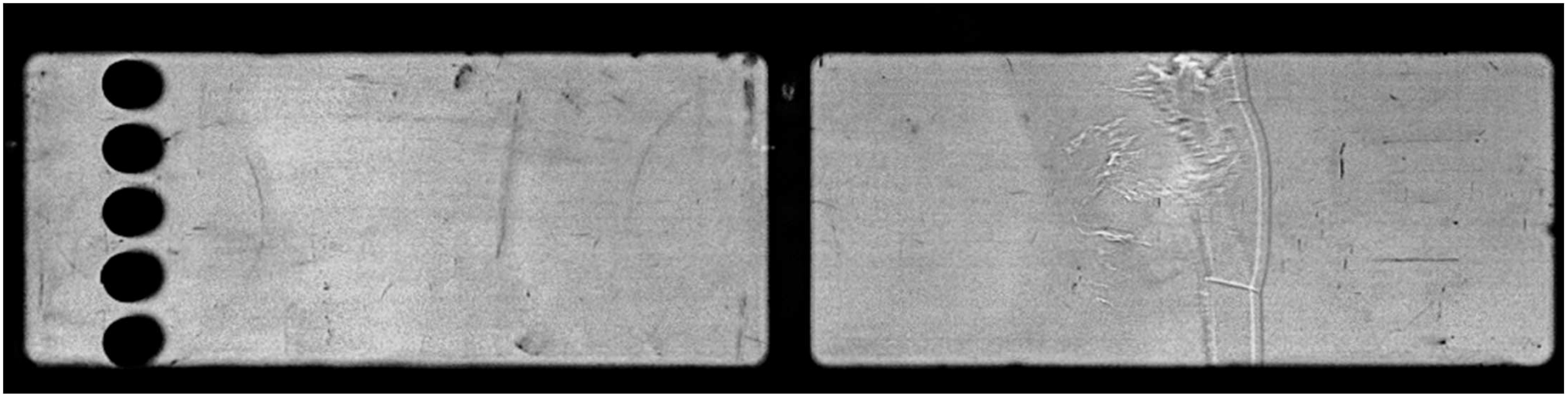

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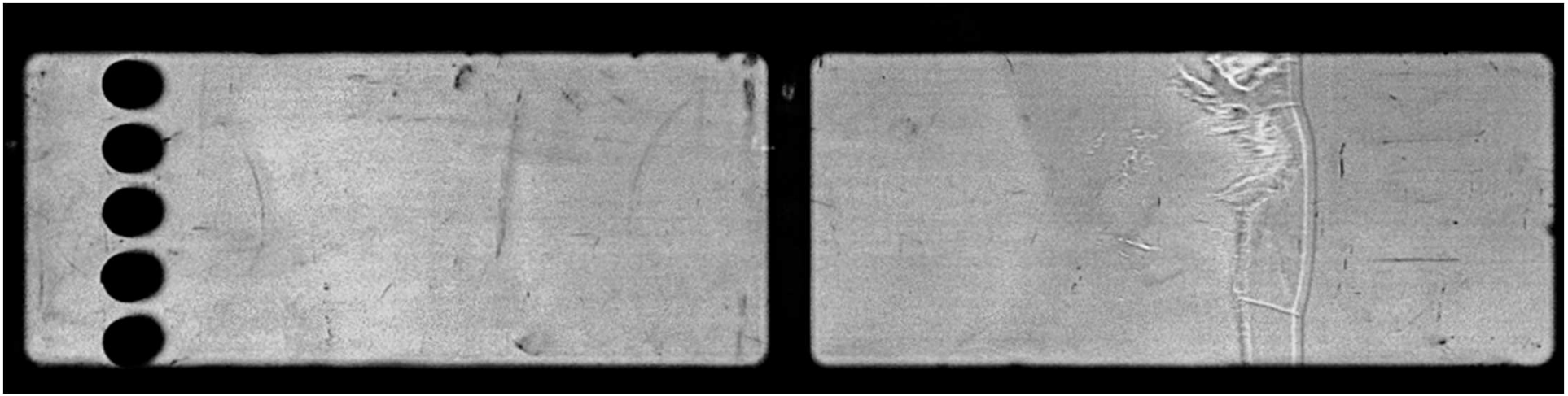

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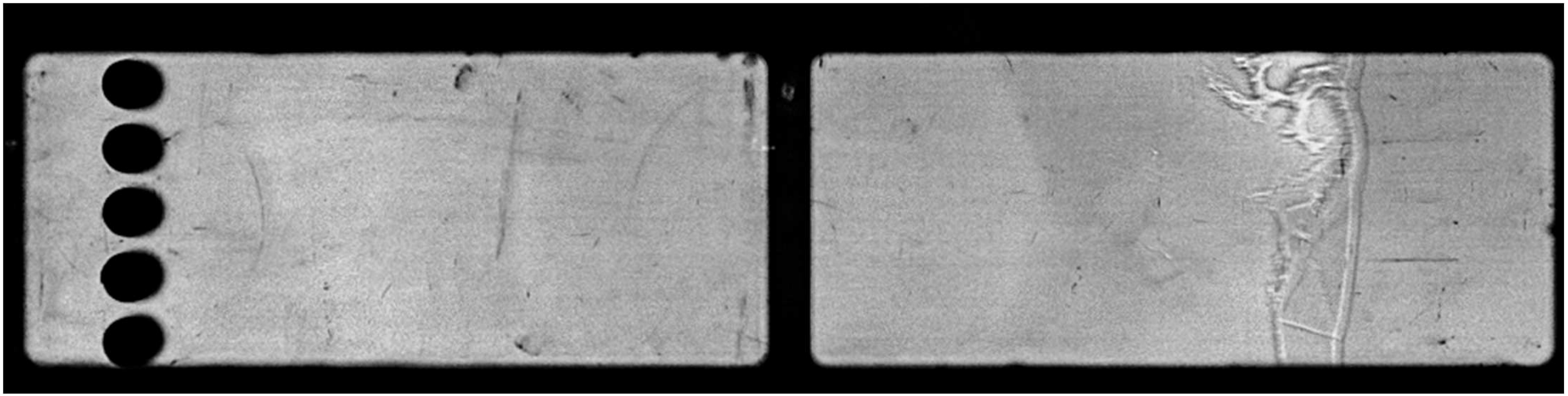

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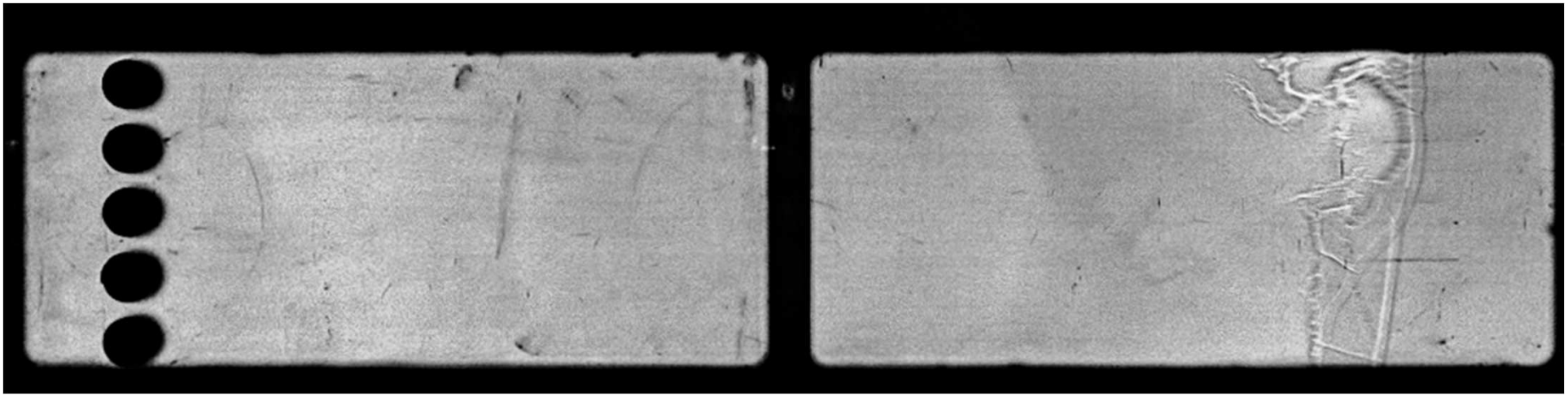

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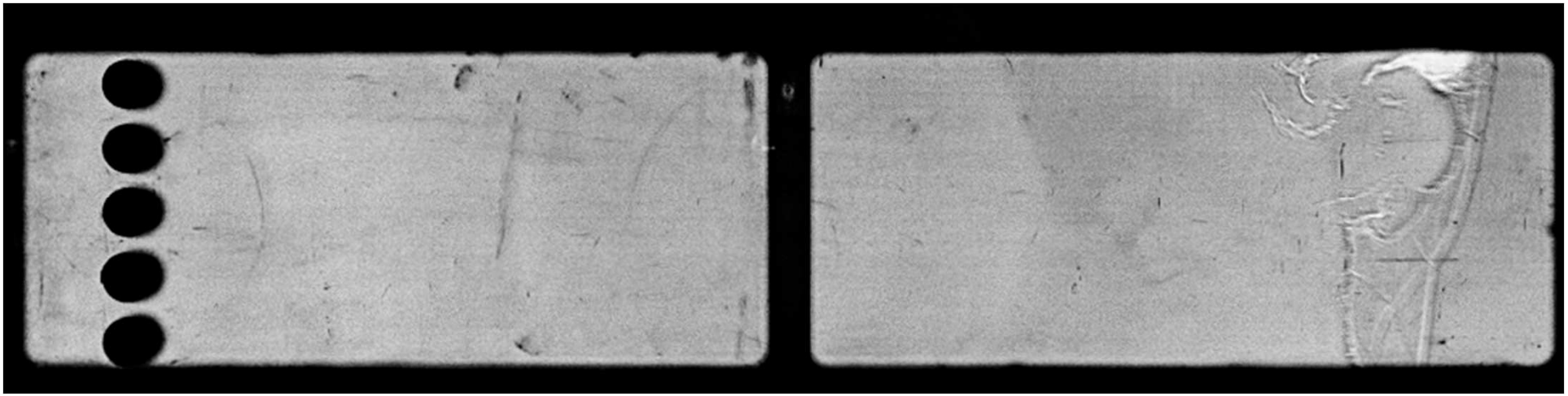

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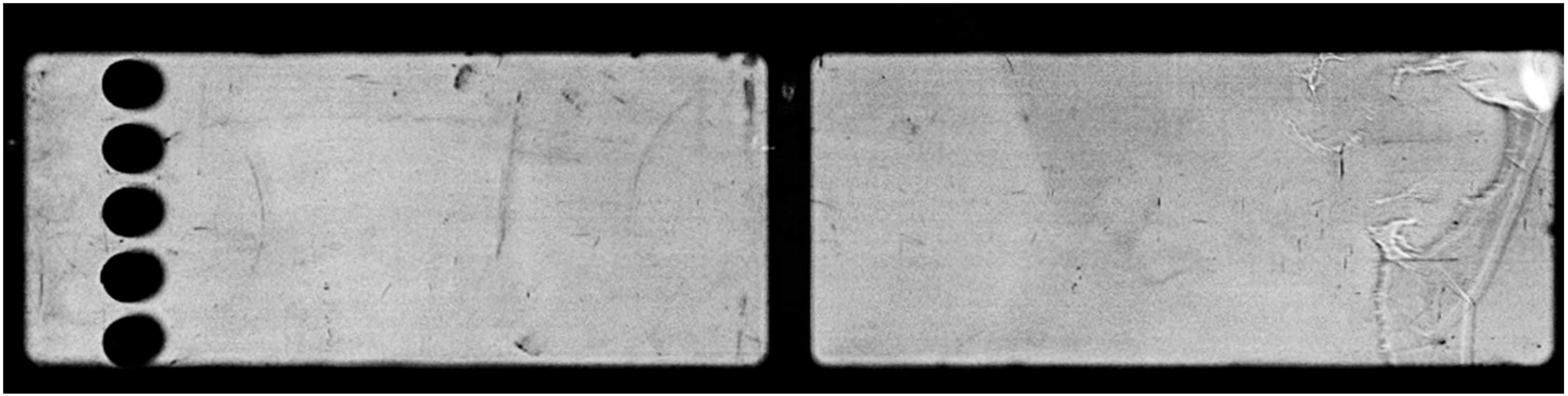

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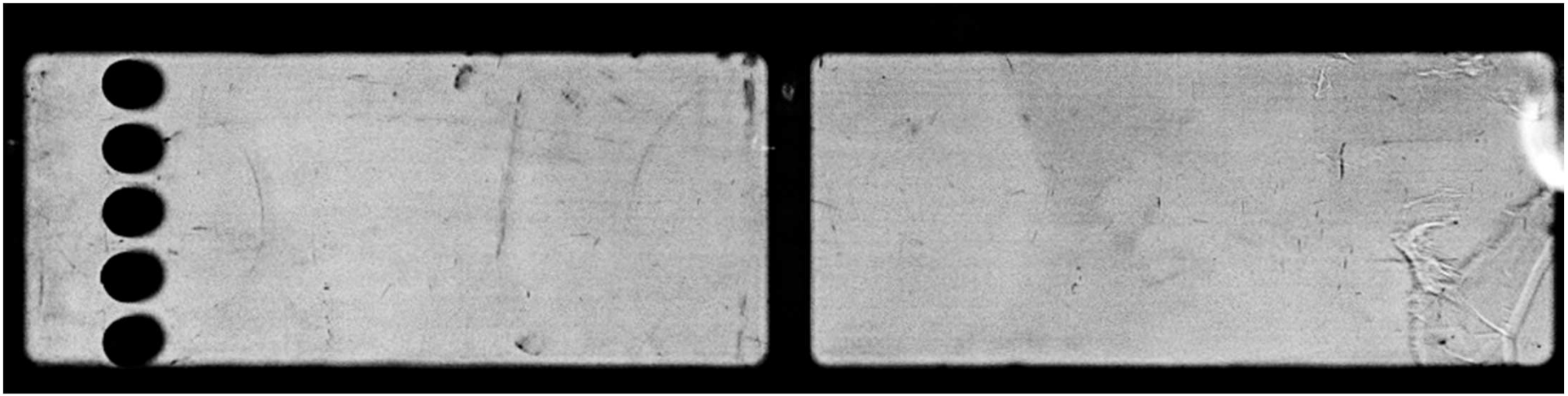

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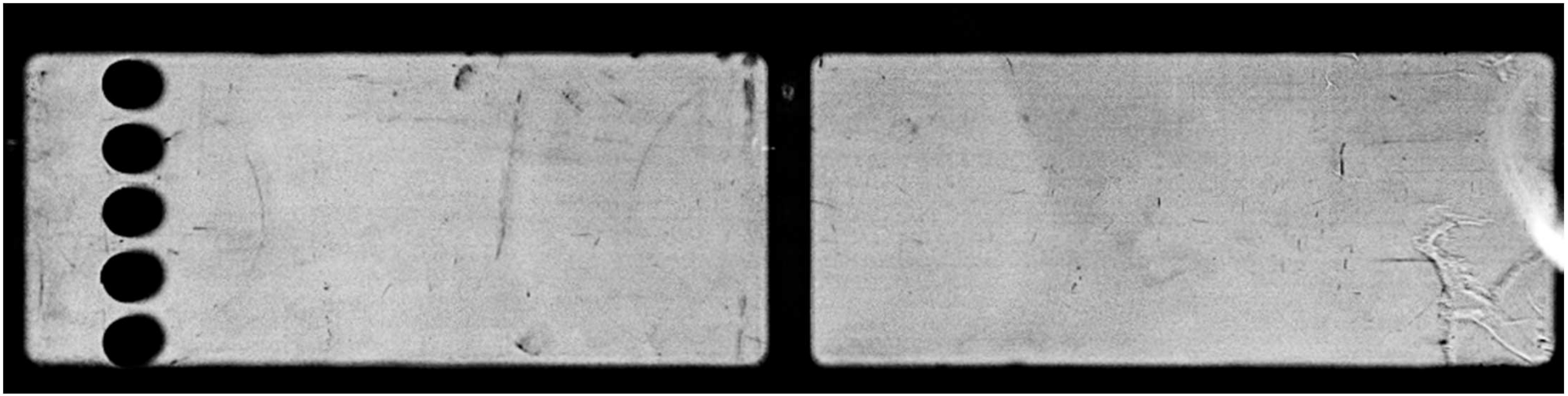

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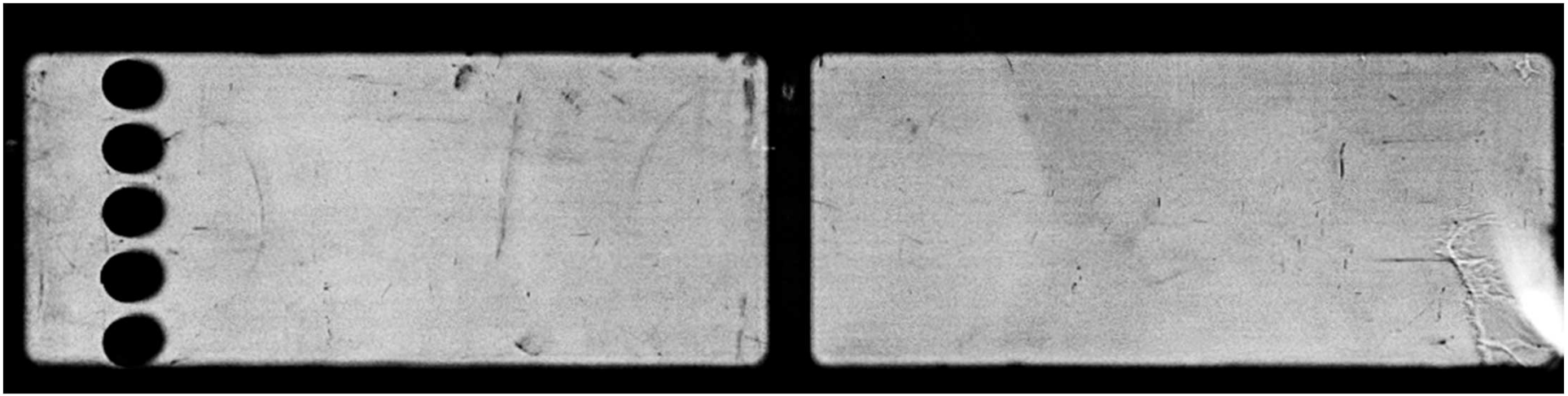
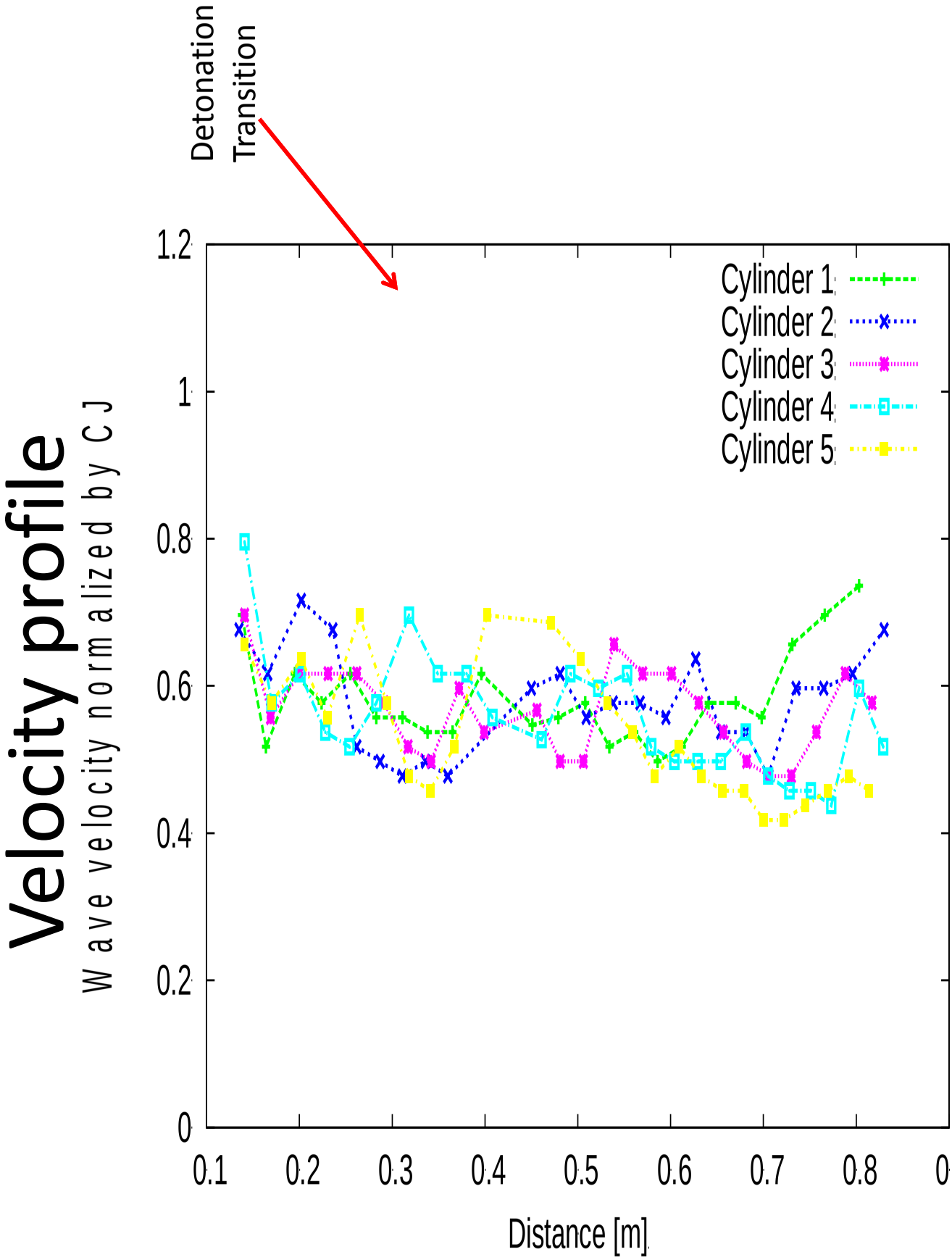
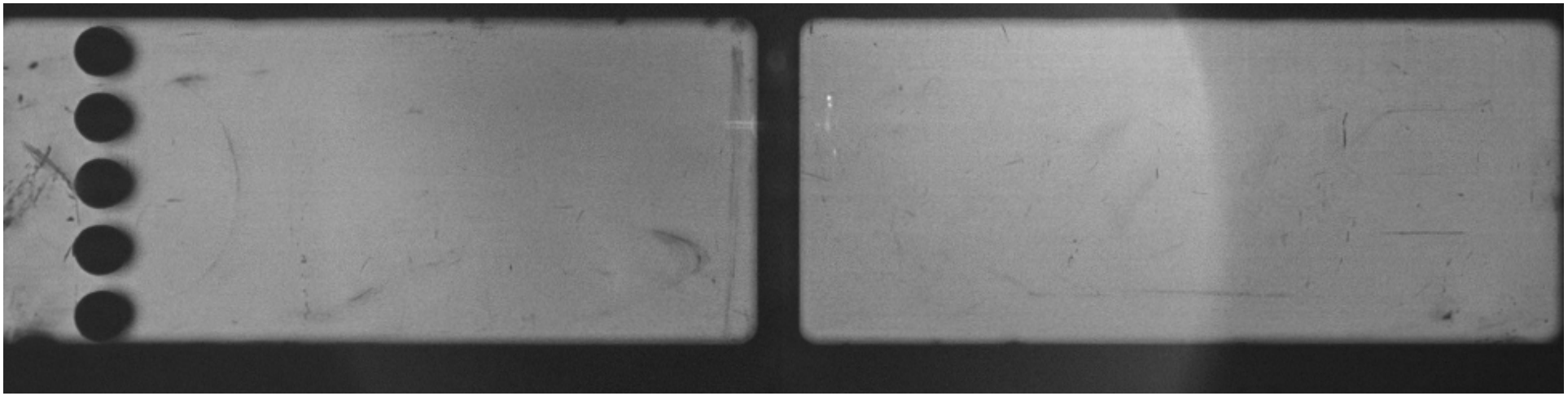


$CH_4 + 2O_2$ P_o = 6.9kPa

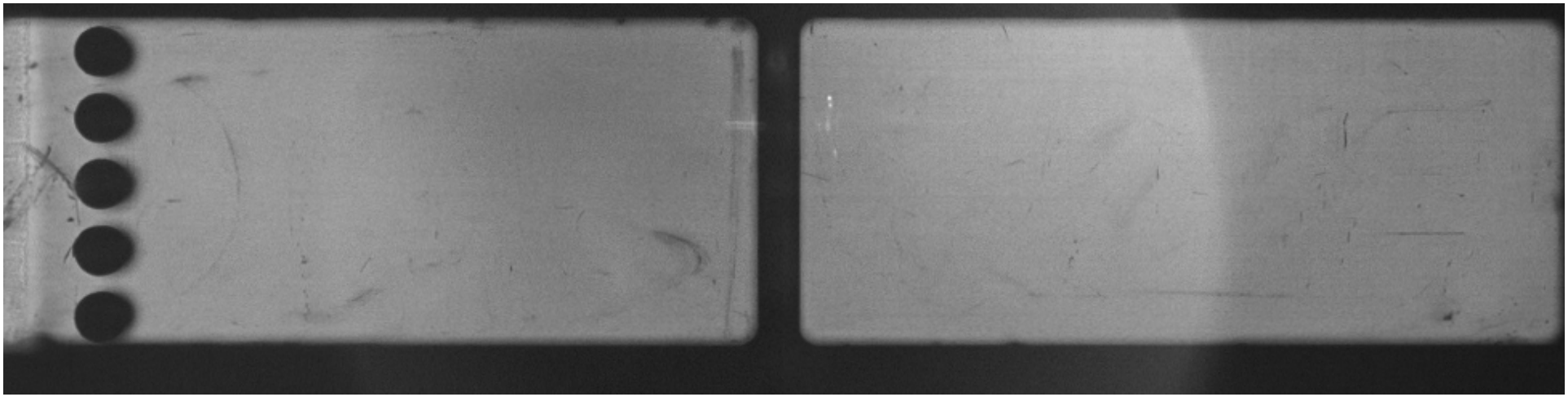

Velocity profile
Wave velocity normalized by CJ
Detonation
Transition
Cylinder 1
Cylinder 2
Cylinder 3
Cylinder 4
Cylinder 5
1.2
1
0.8
0.6
0.4
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Distance [m]

Oxy-Hydrogen Behavior



$2H_2 + O_2$ P_o = 17.2kPa

Oxy-Hydrogen Behavior



$2H_2 + O_2$ P_o = 17.2kPa

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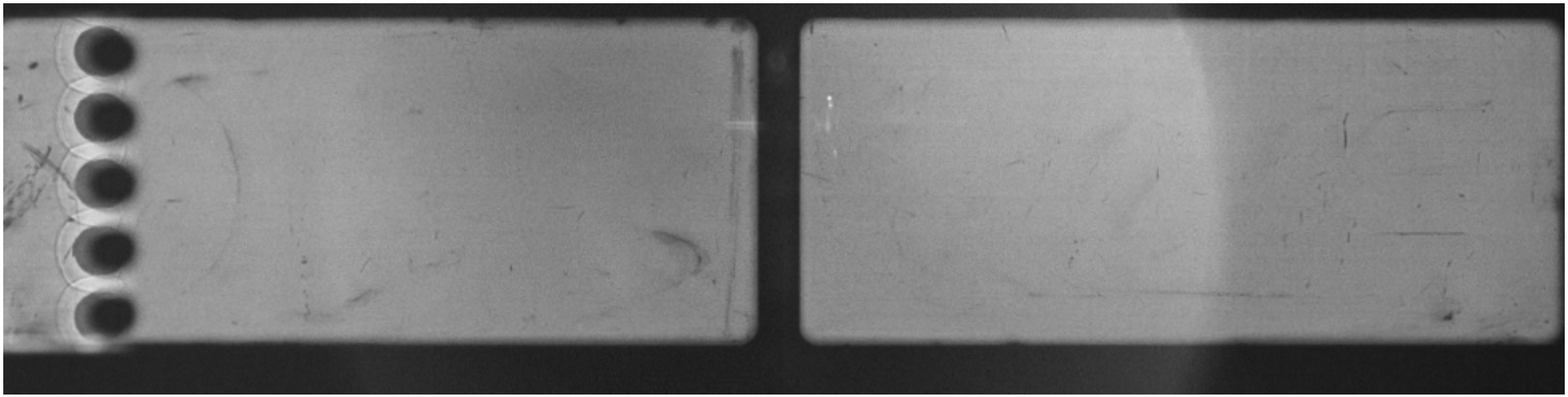

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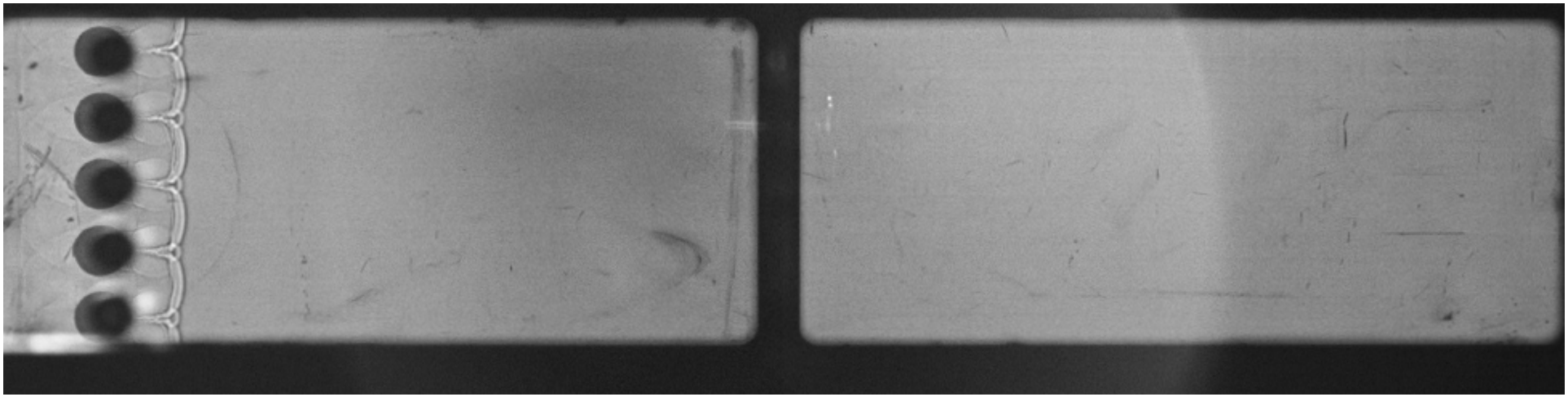

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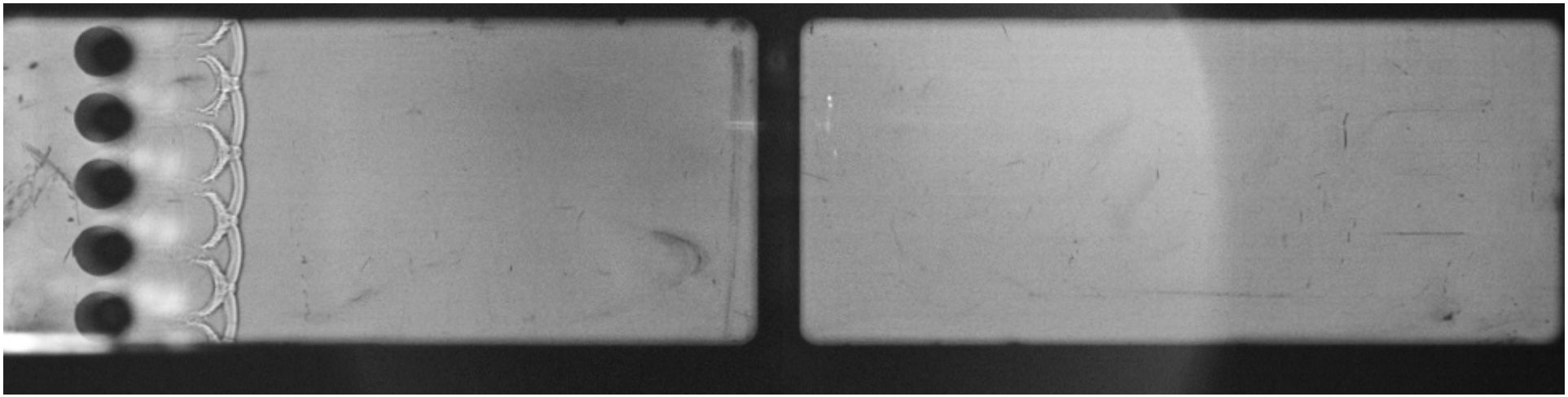

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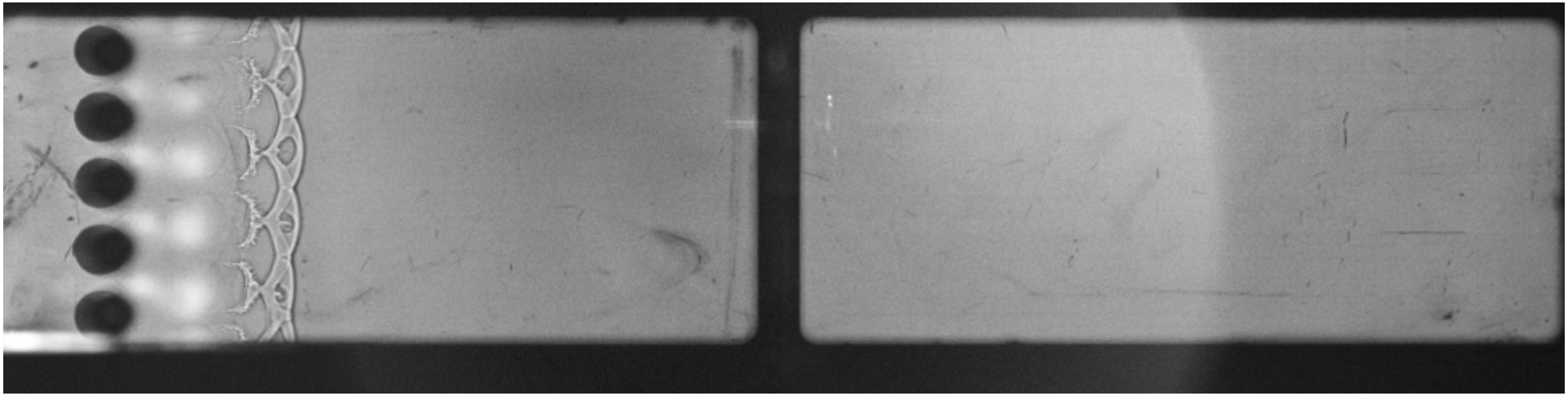

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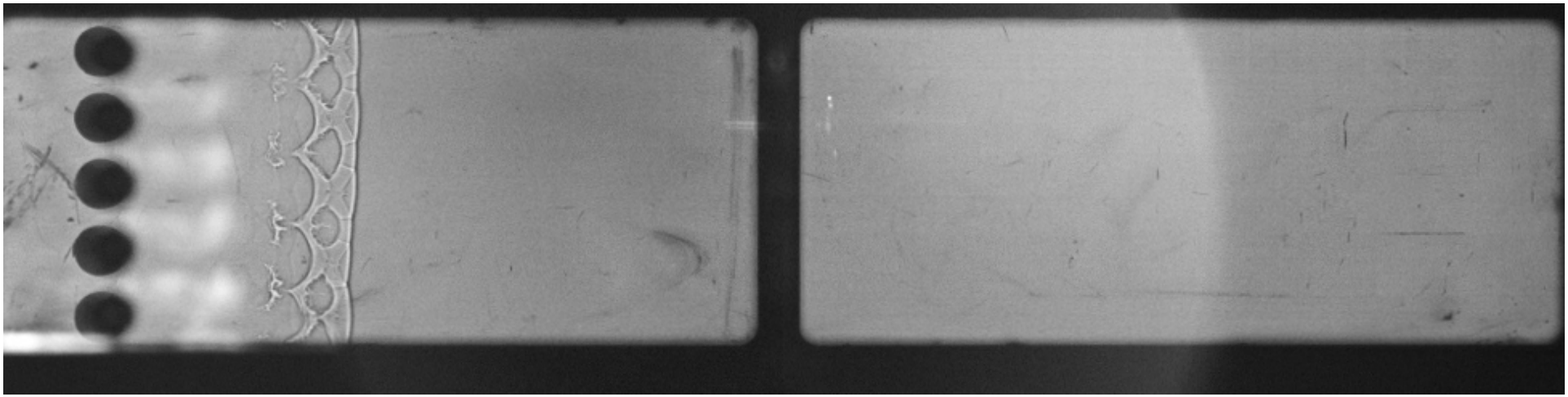

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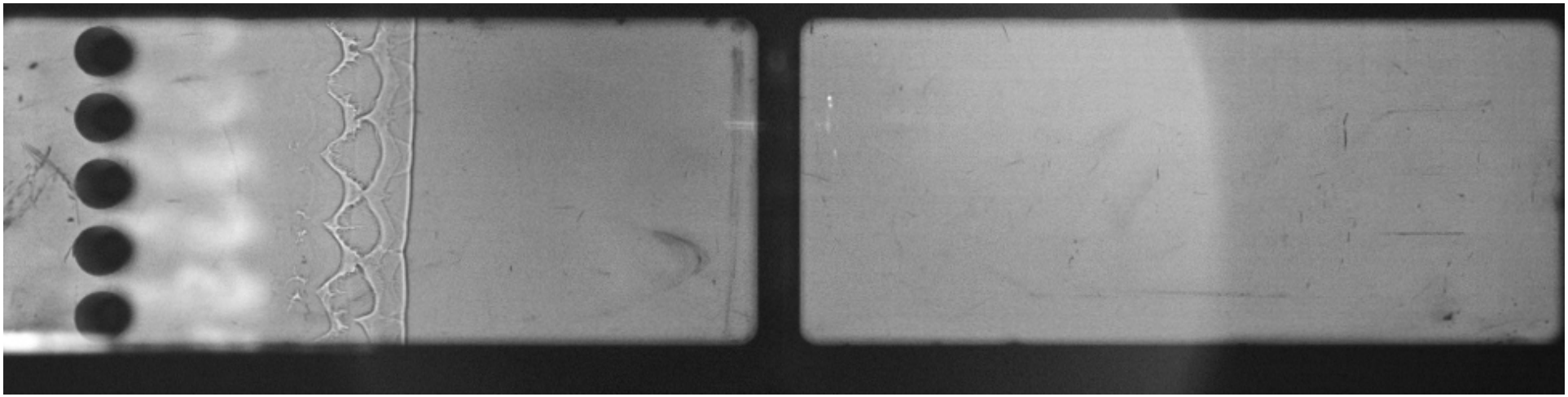

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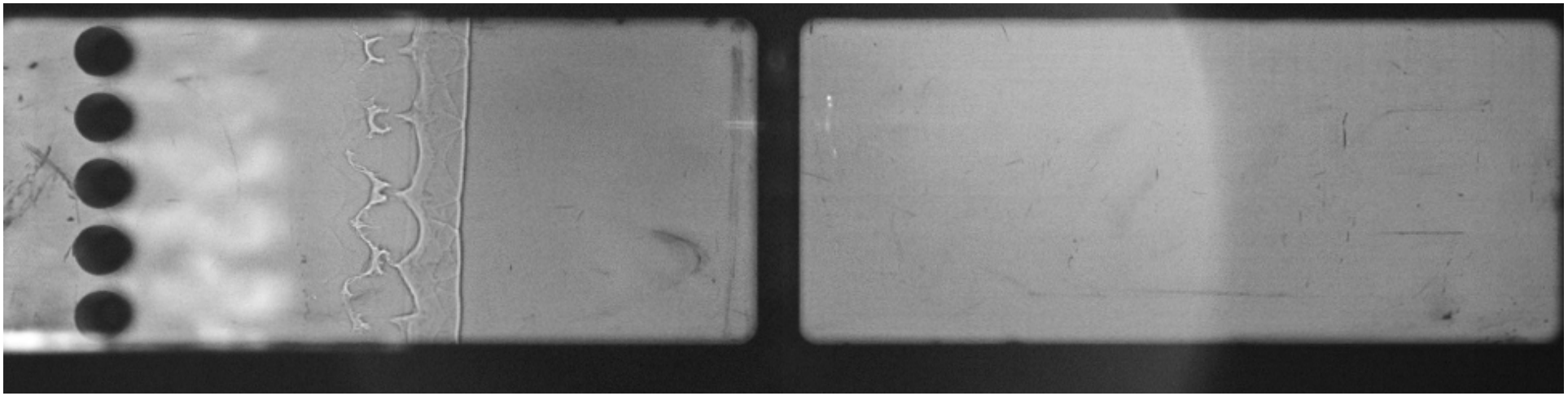

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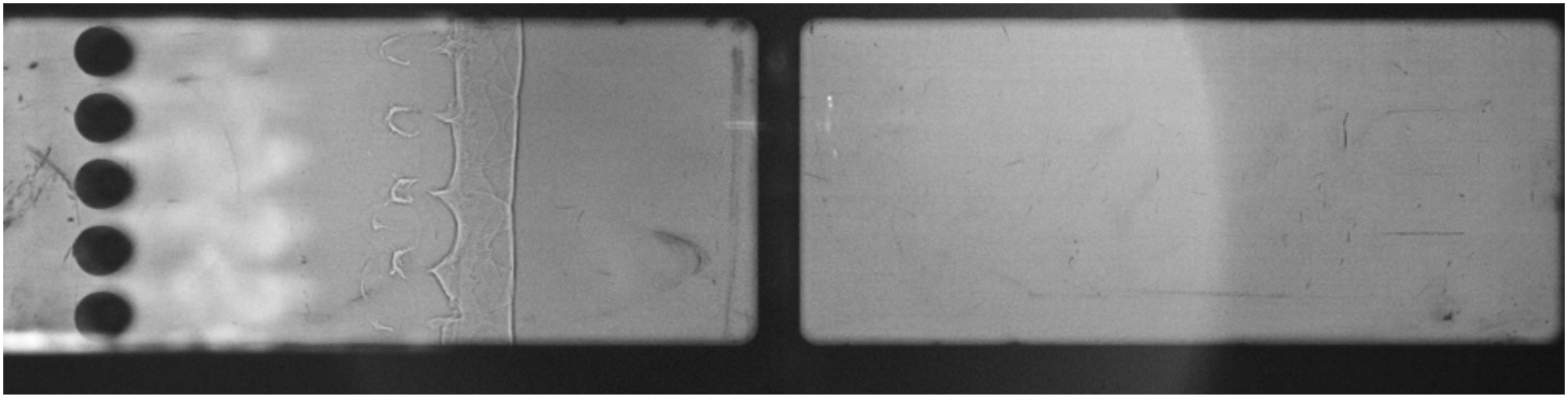

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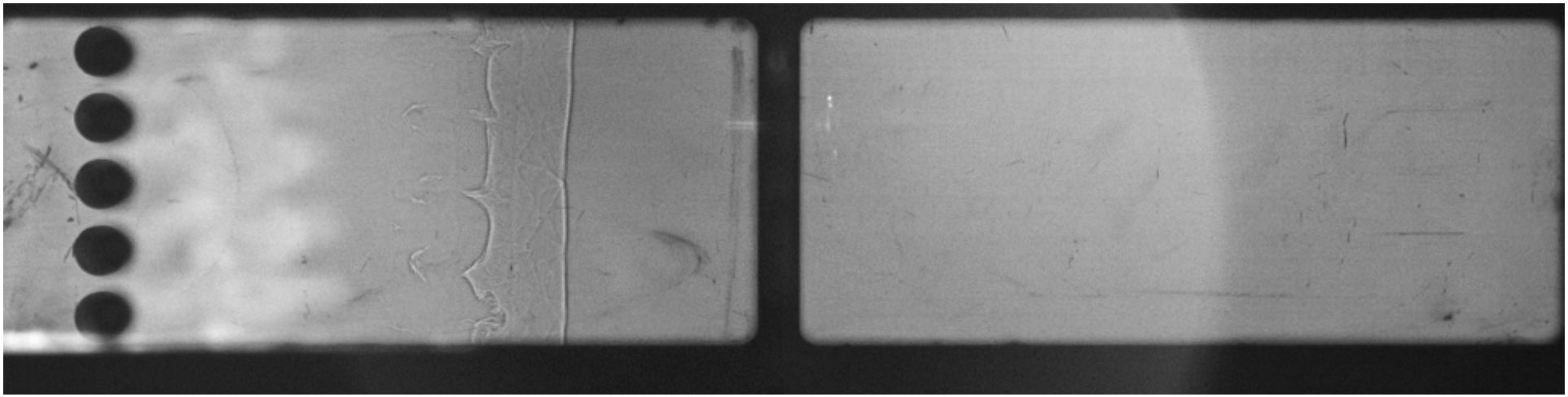

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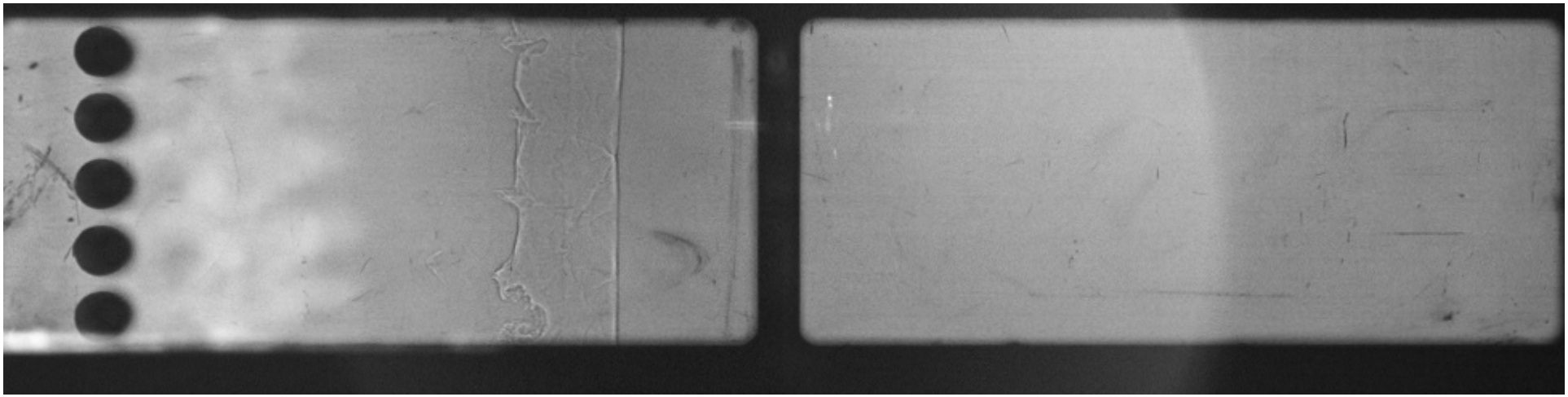

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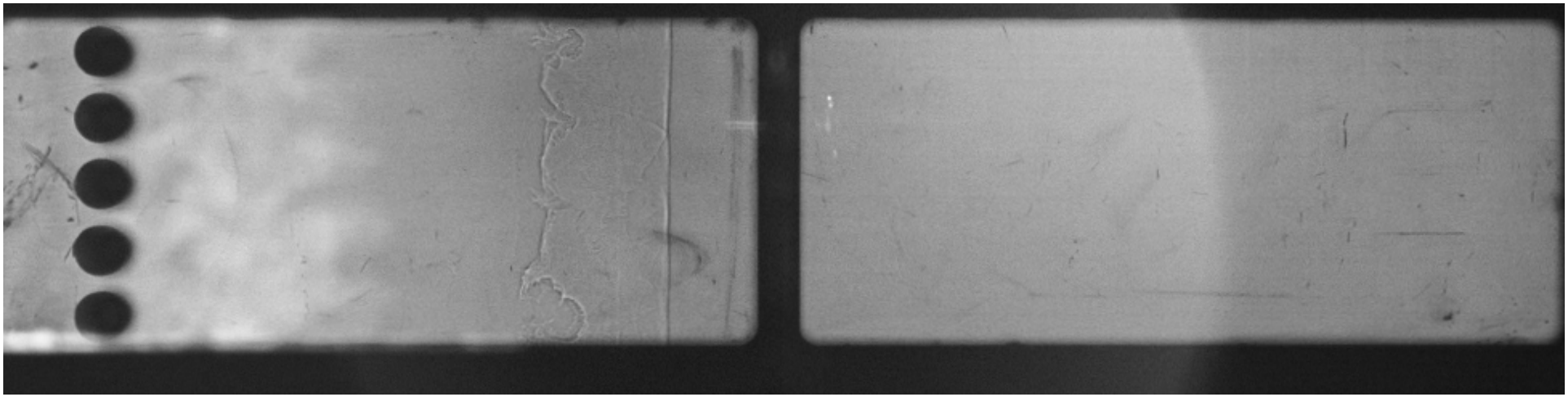

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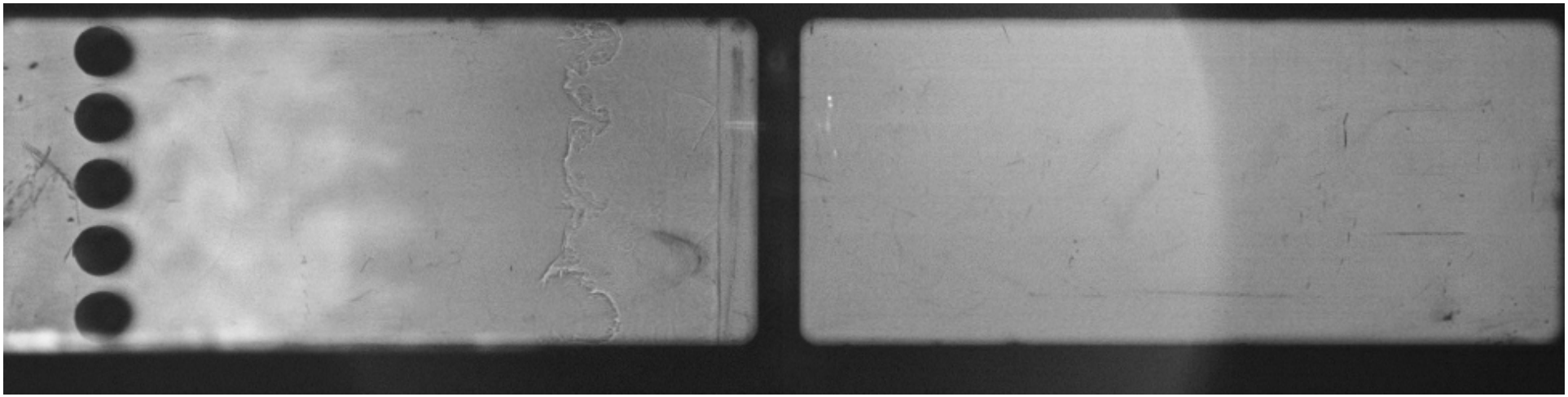

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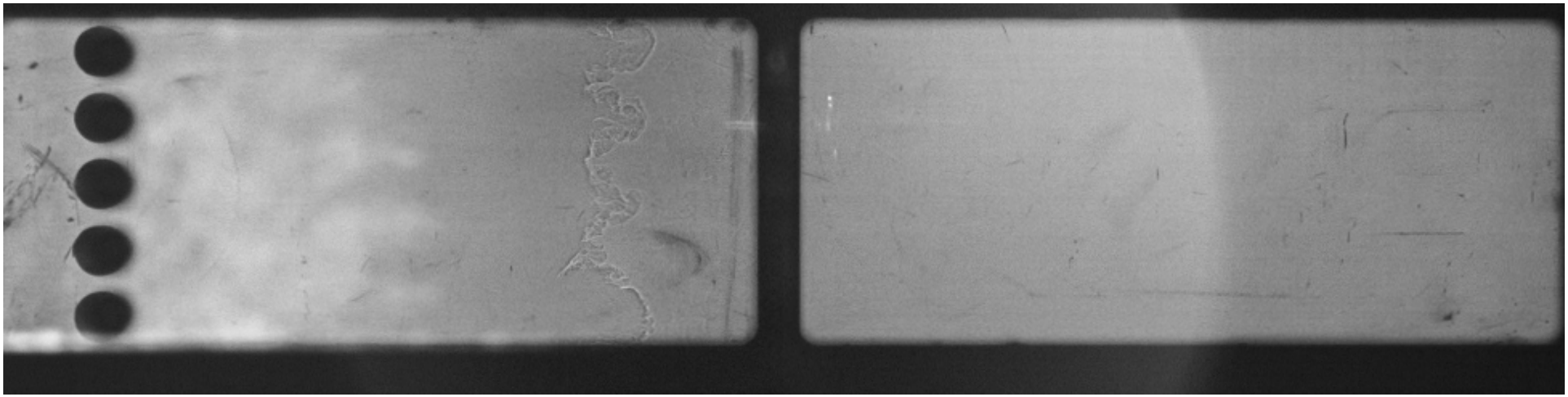

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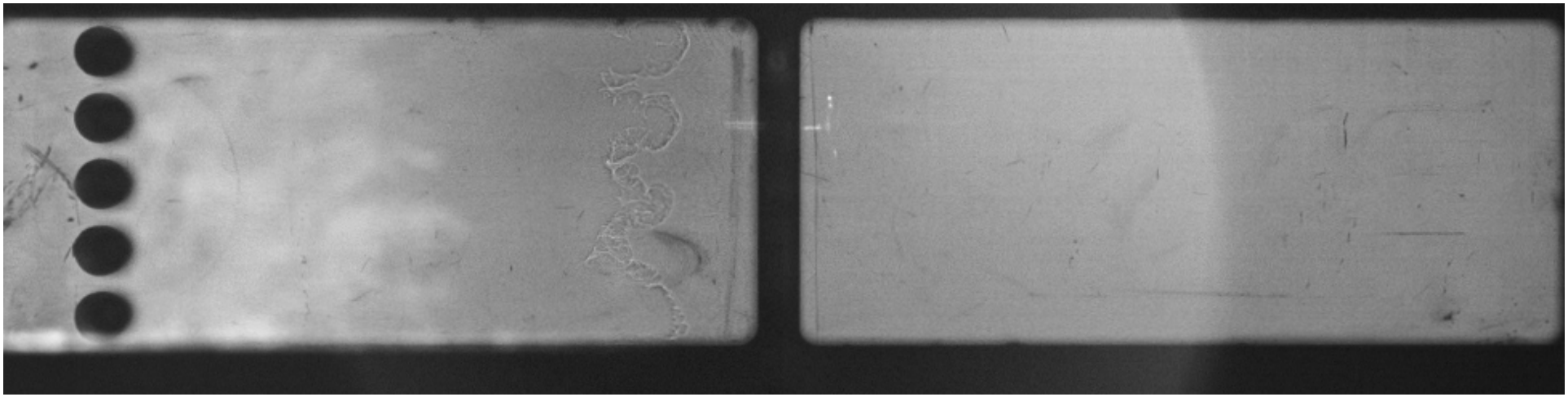

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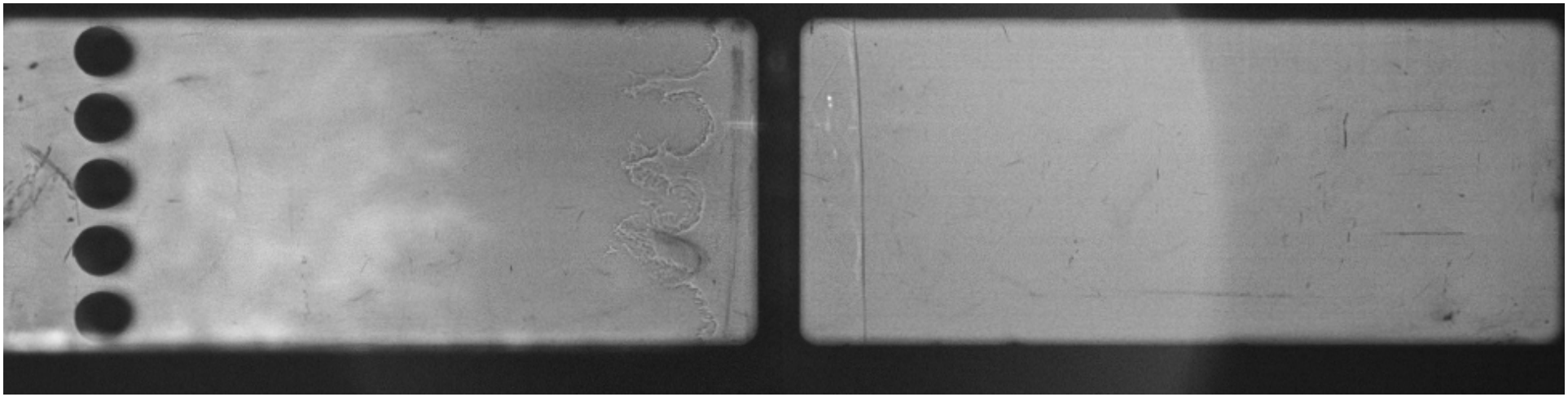

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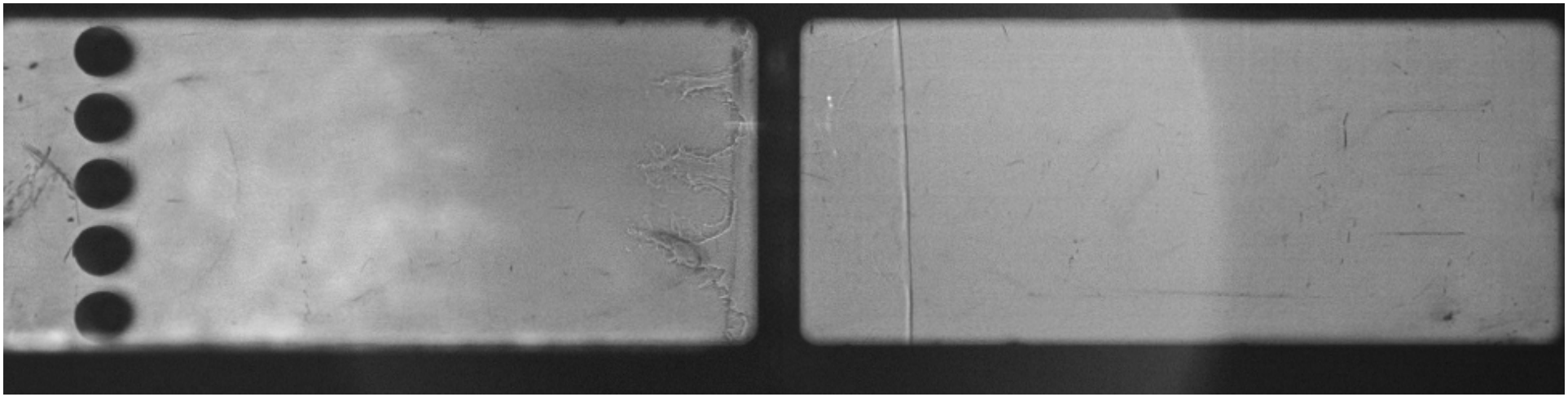

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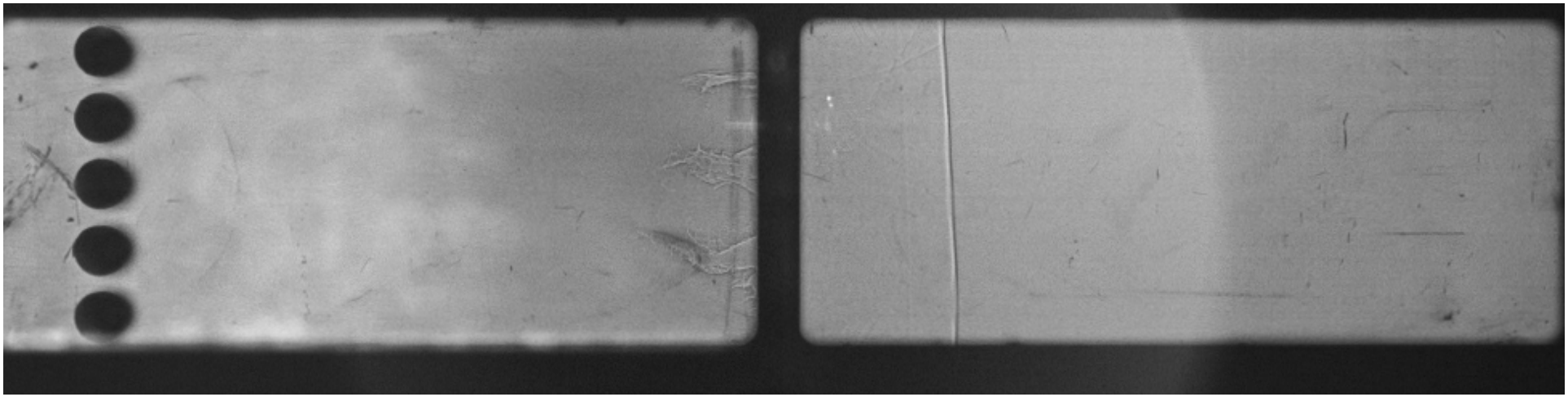

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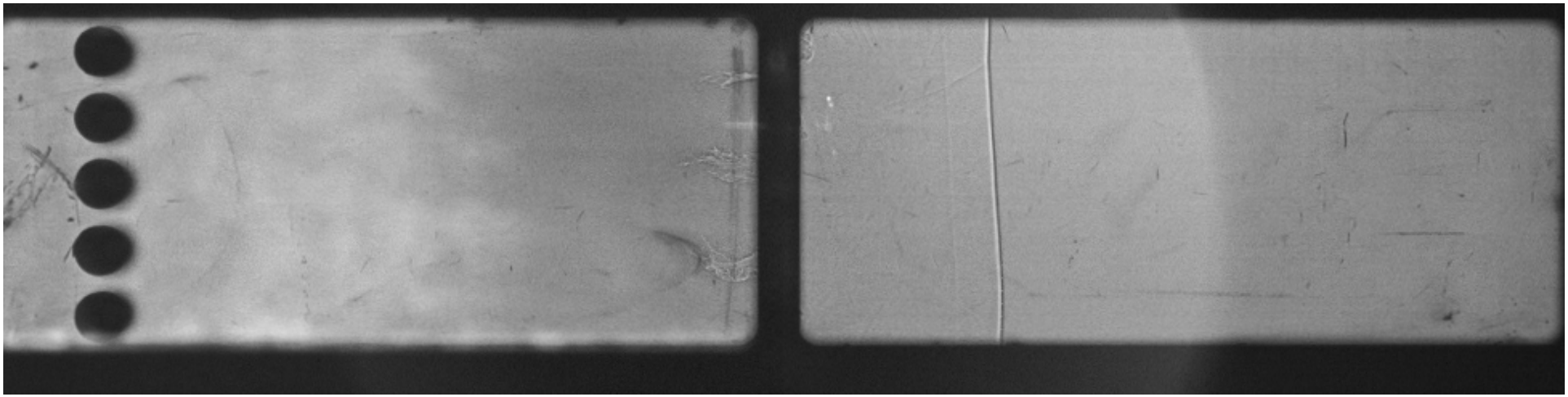

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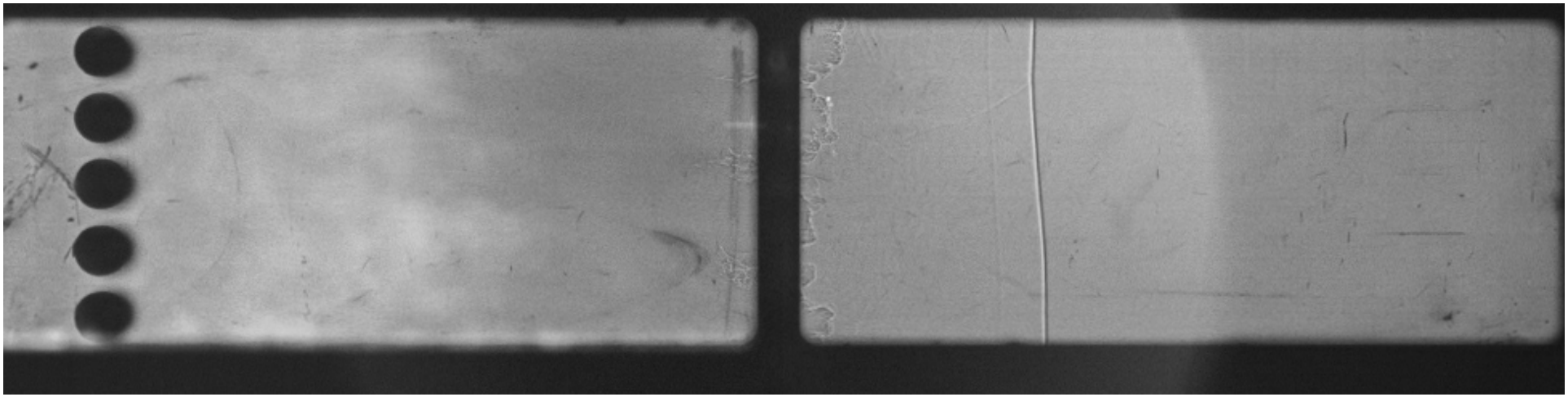

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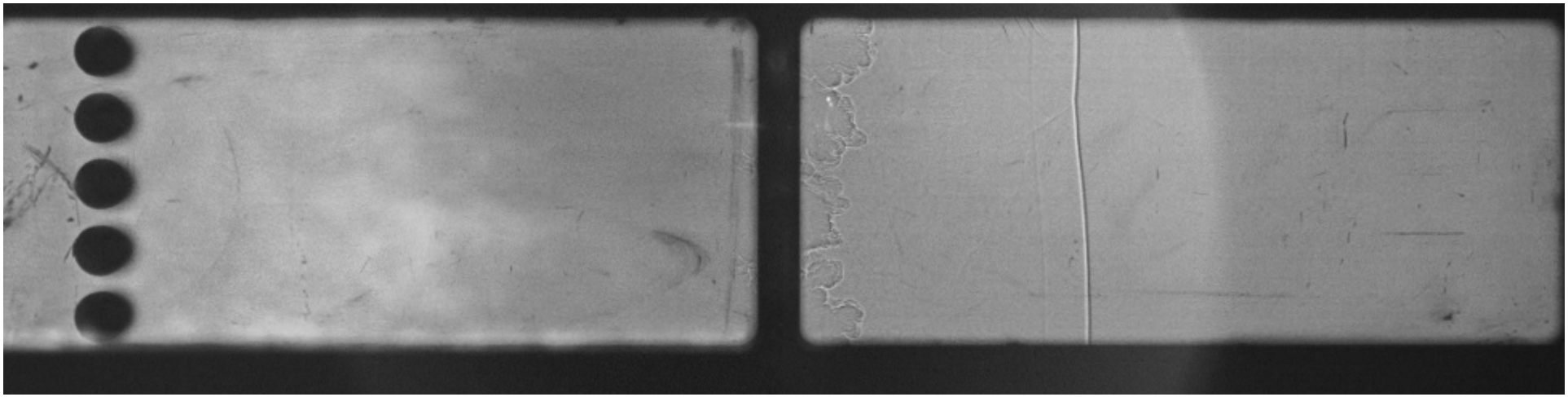

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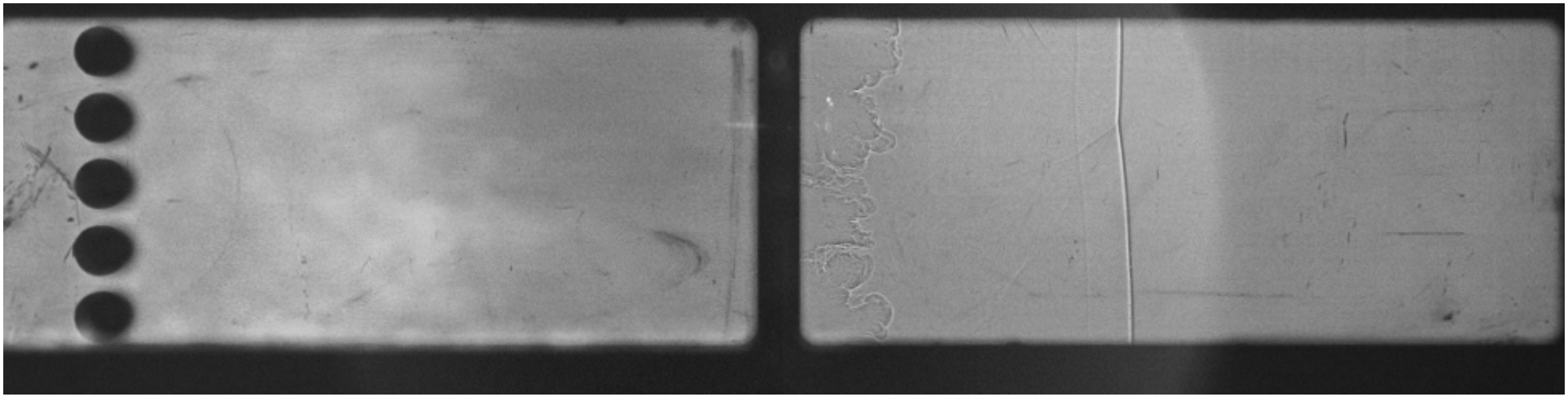

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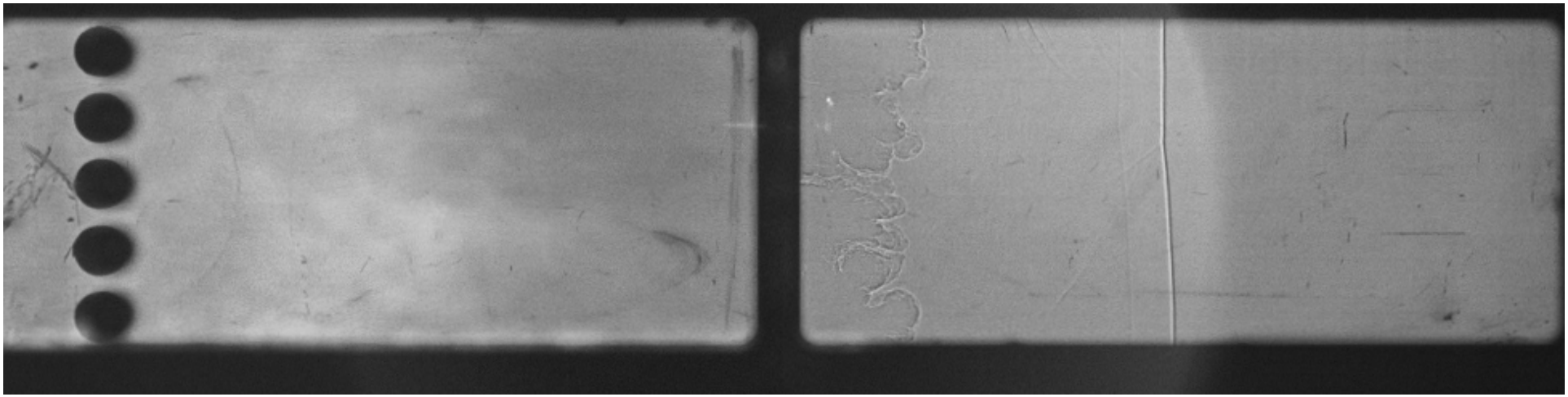

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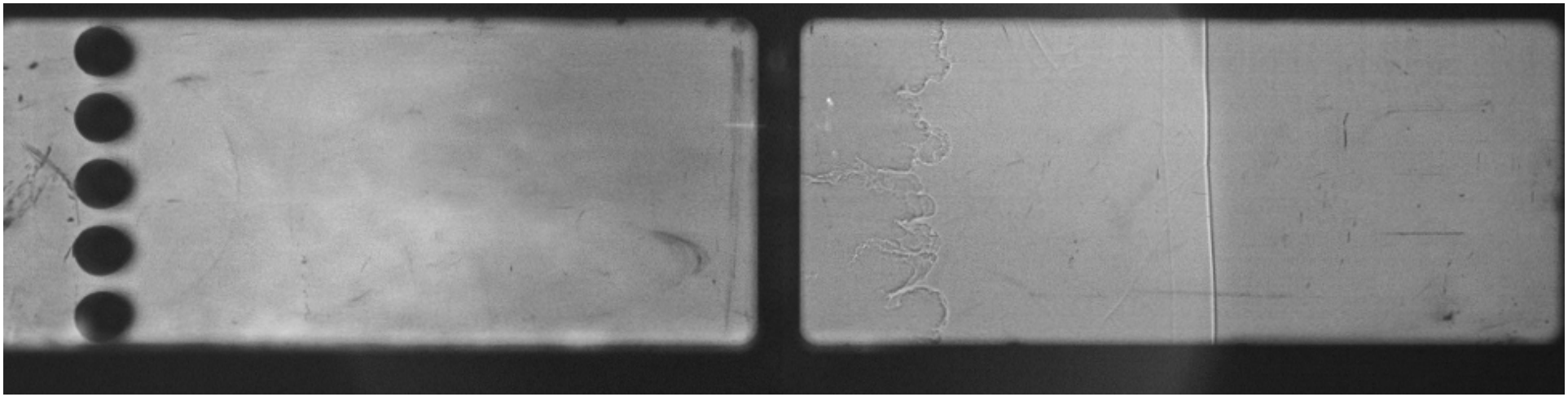

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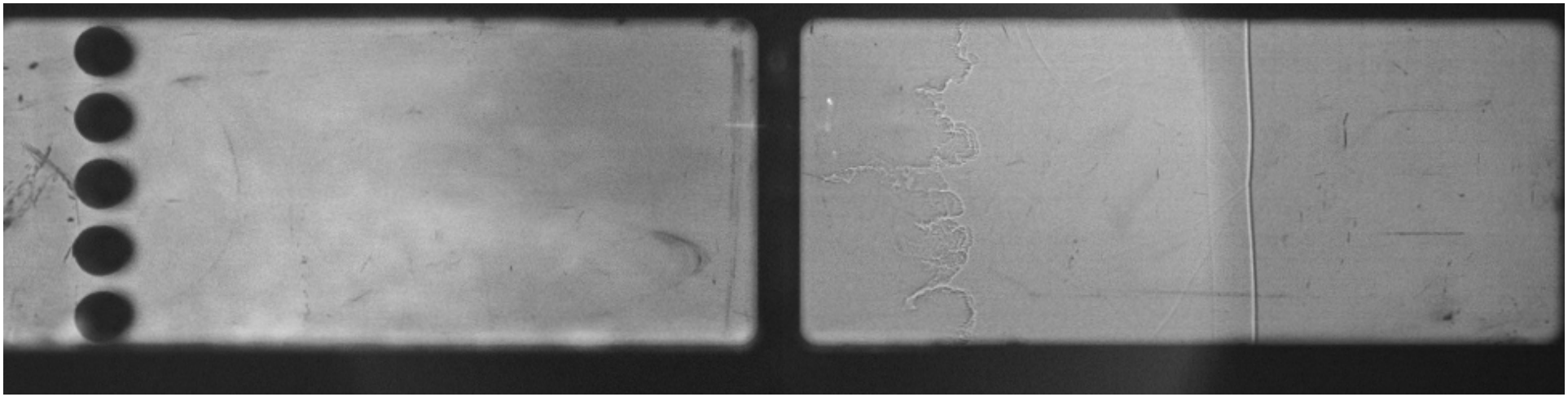

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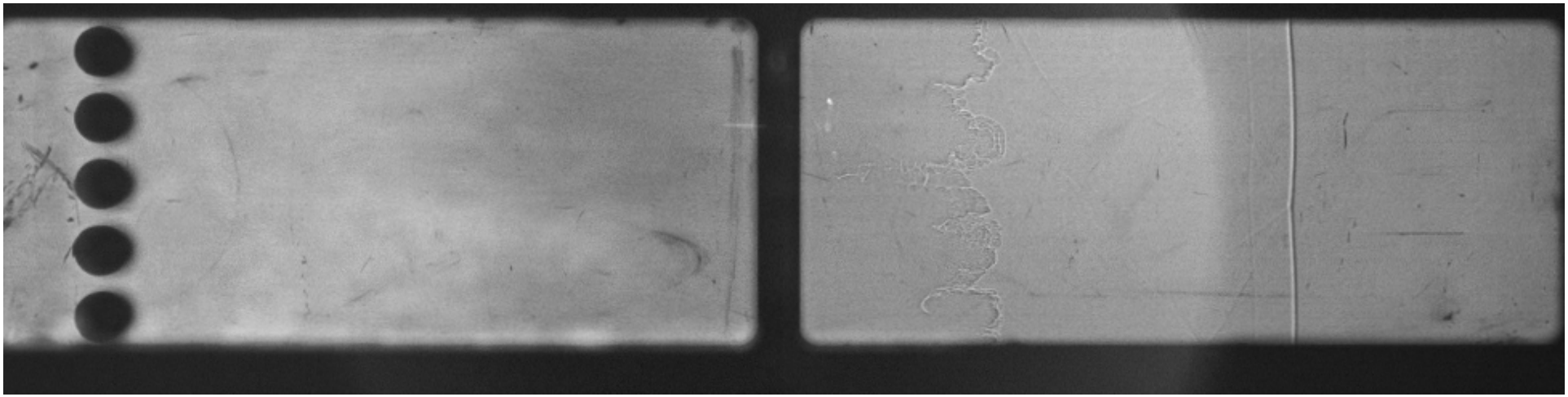

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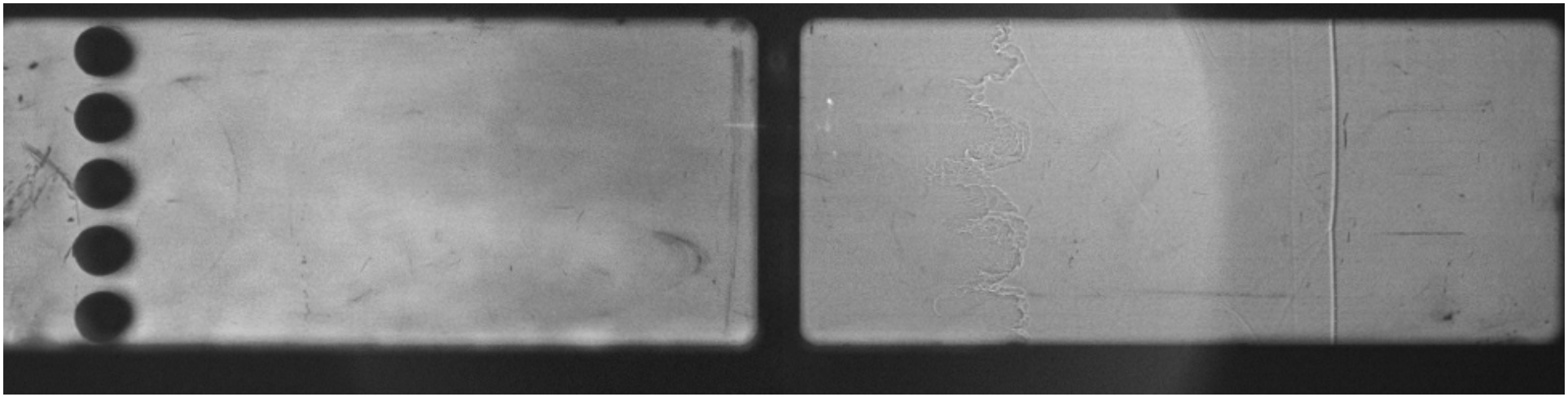

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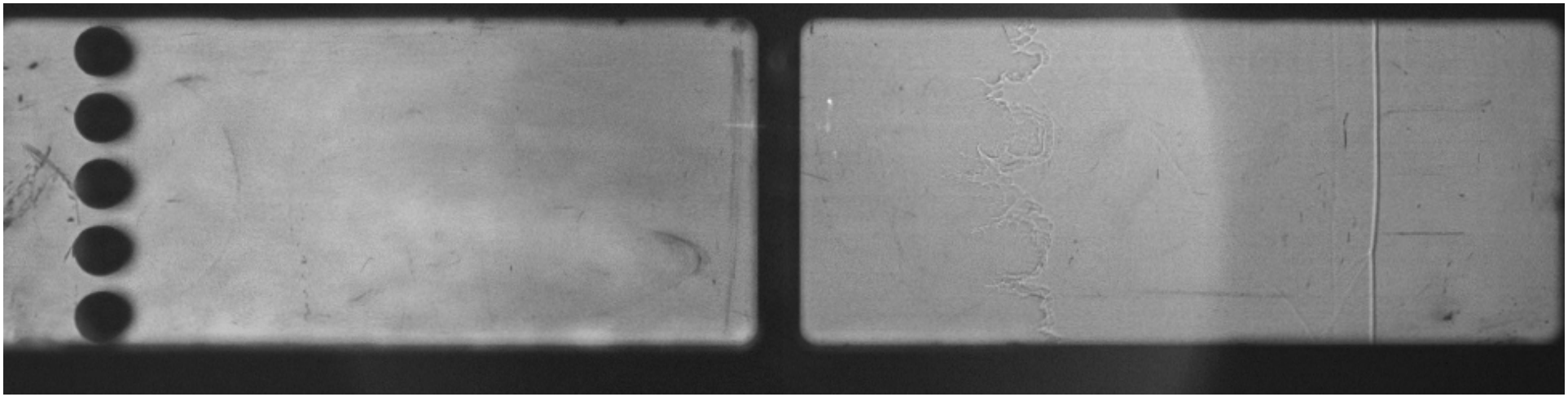

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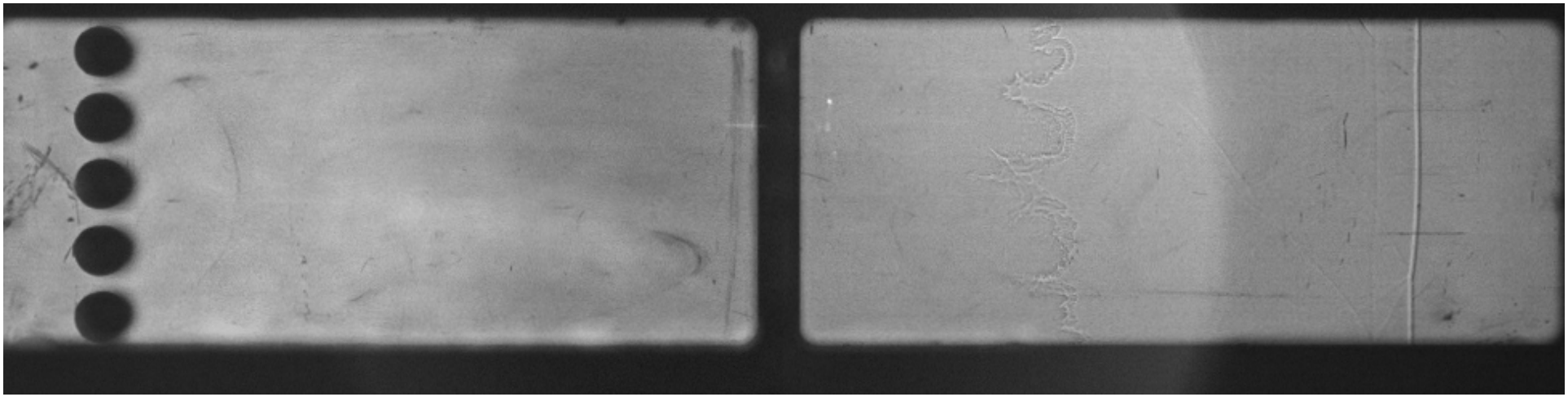

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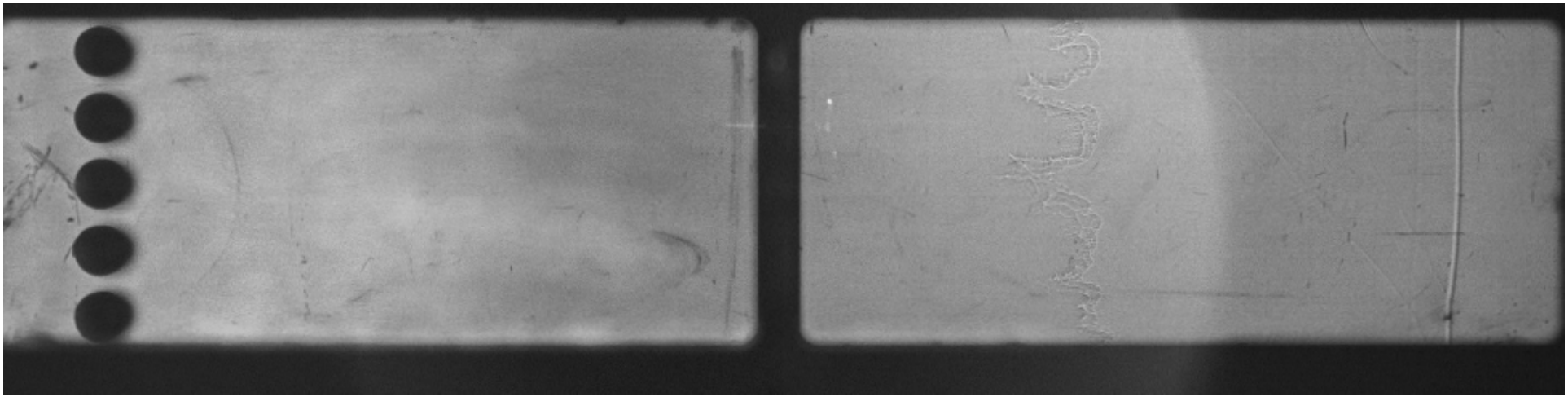

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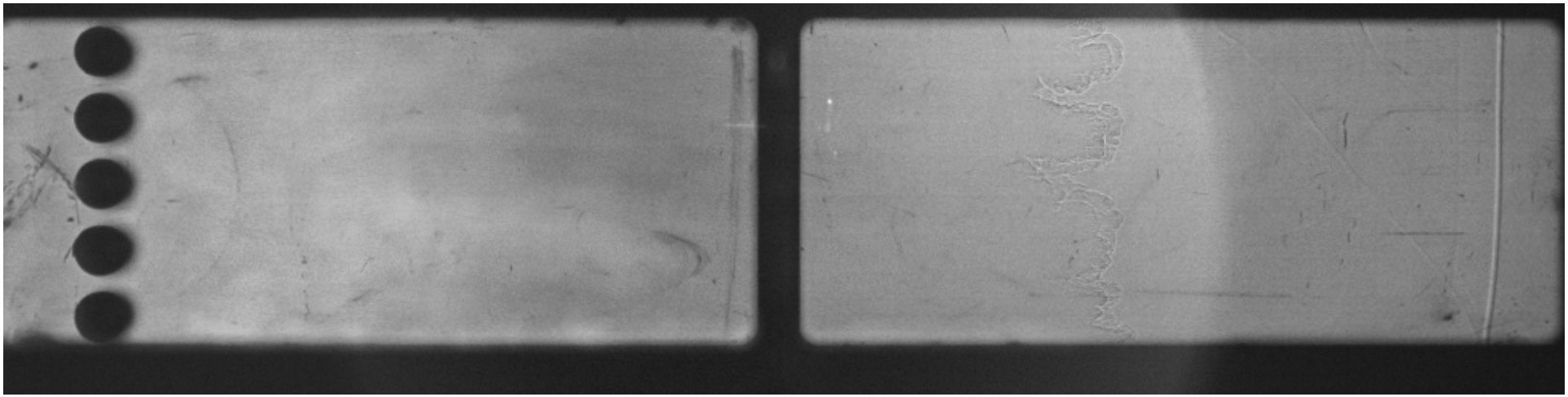

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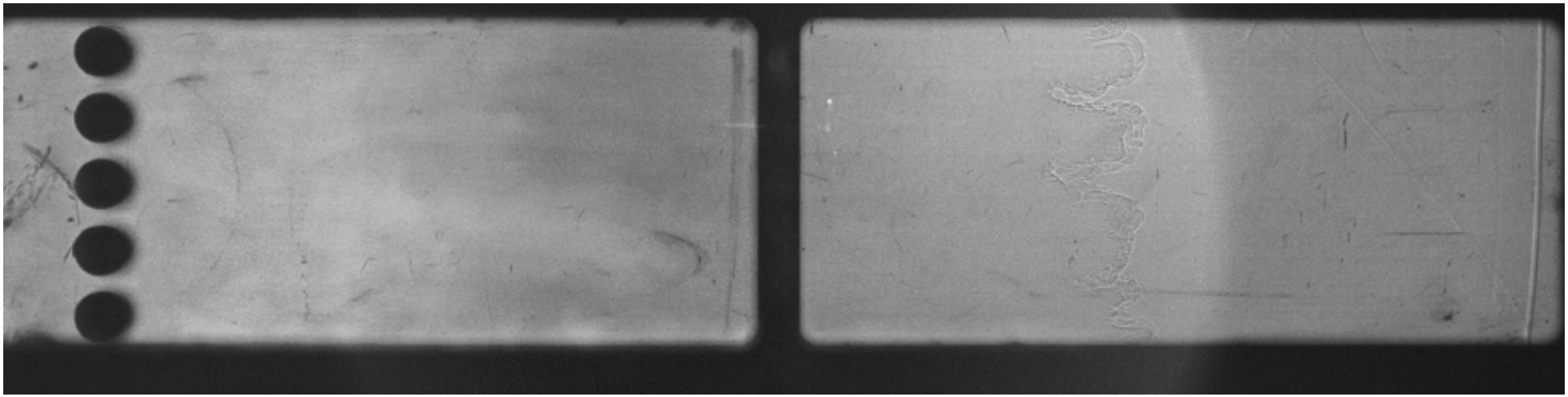

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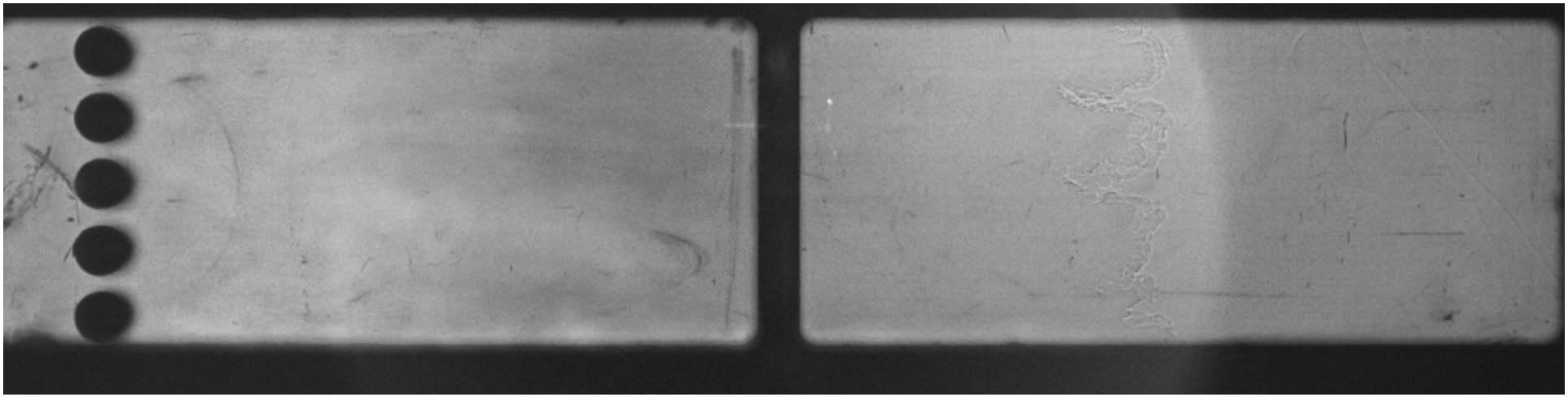

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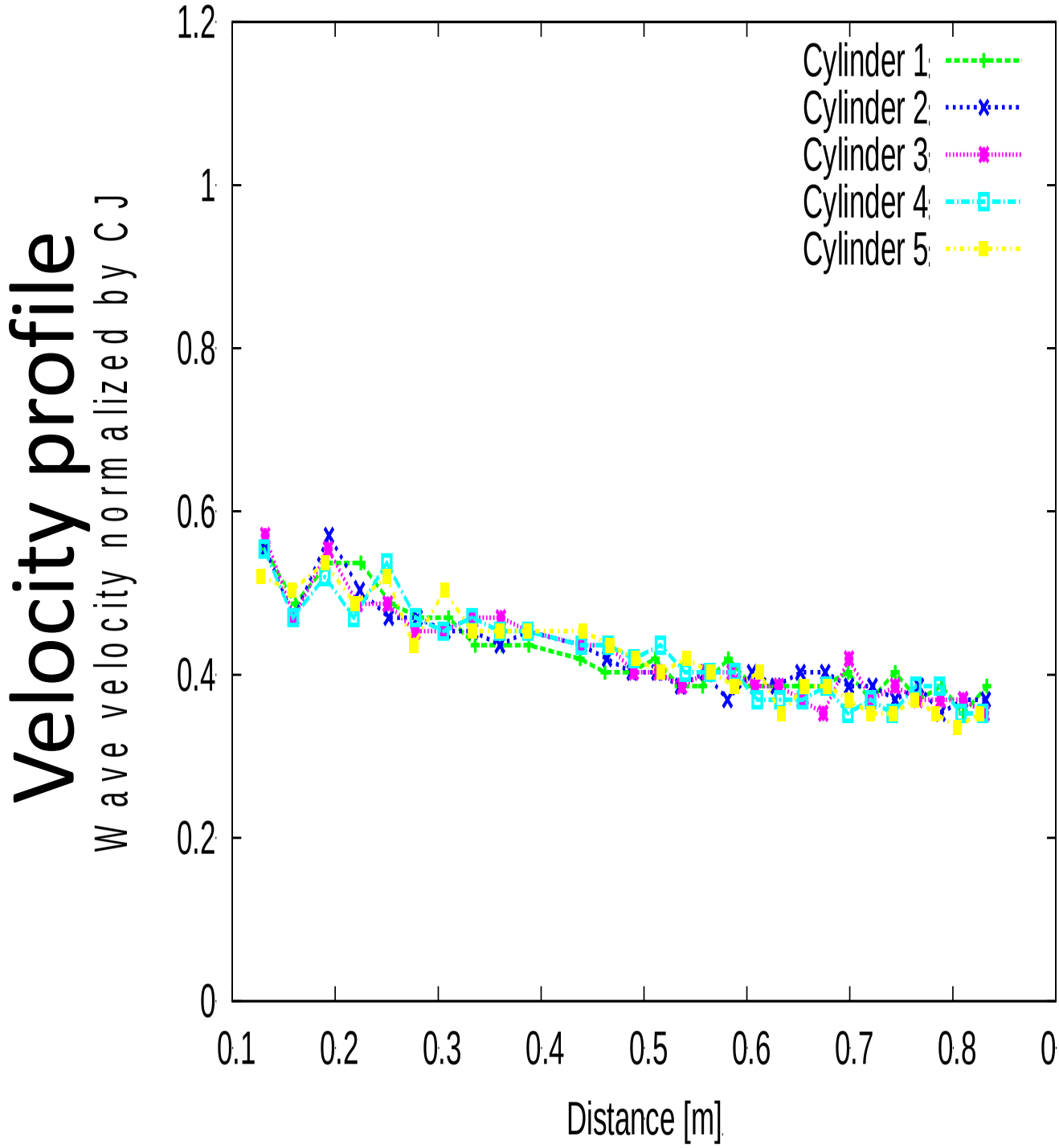
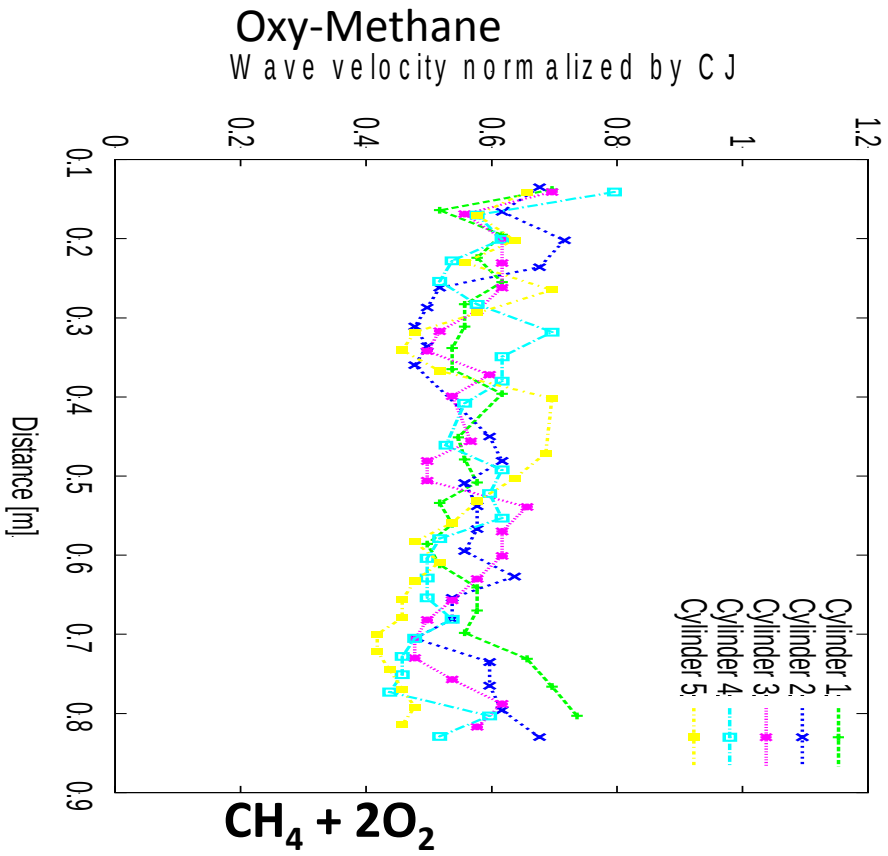
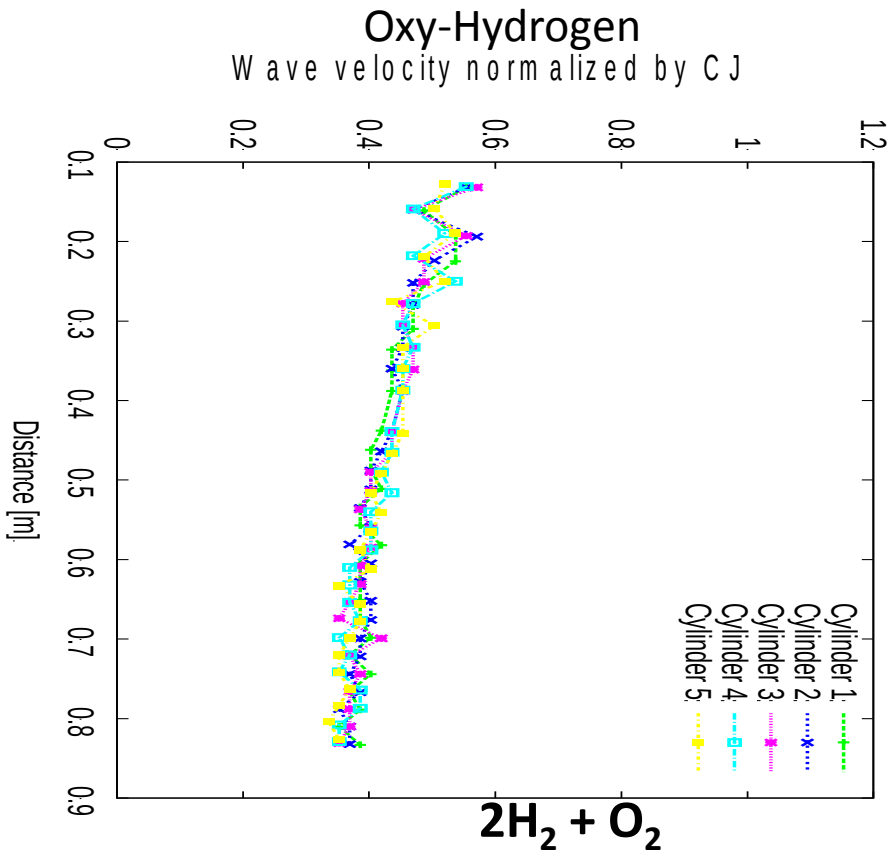

Velocity profile
Wave velocity normalized by CJ
Distance [m]
Cylinder 1
Cylinder 2
Cylinder 3
Cylinder 4
Cylinder 5
1.2
1
0.8
0.6
0.4
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

Why doesn’t hydrogen accelerate like methane?





Chemical Kinetics

	Oxy-Hydrogen	**Oxy-Methane**
Post Shock Temperature	982.47 K	1106.47 K
Ignition Delay	**4 497.1** us	**15 720.0** us
Activation Energy (Ea/RTvn)	37.36	17.15

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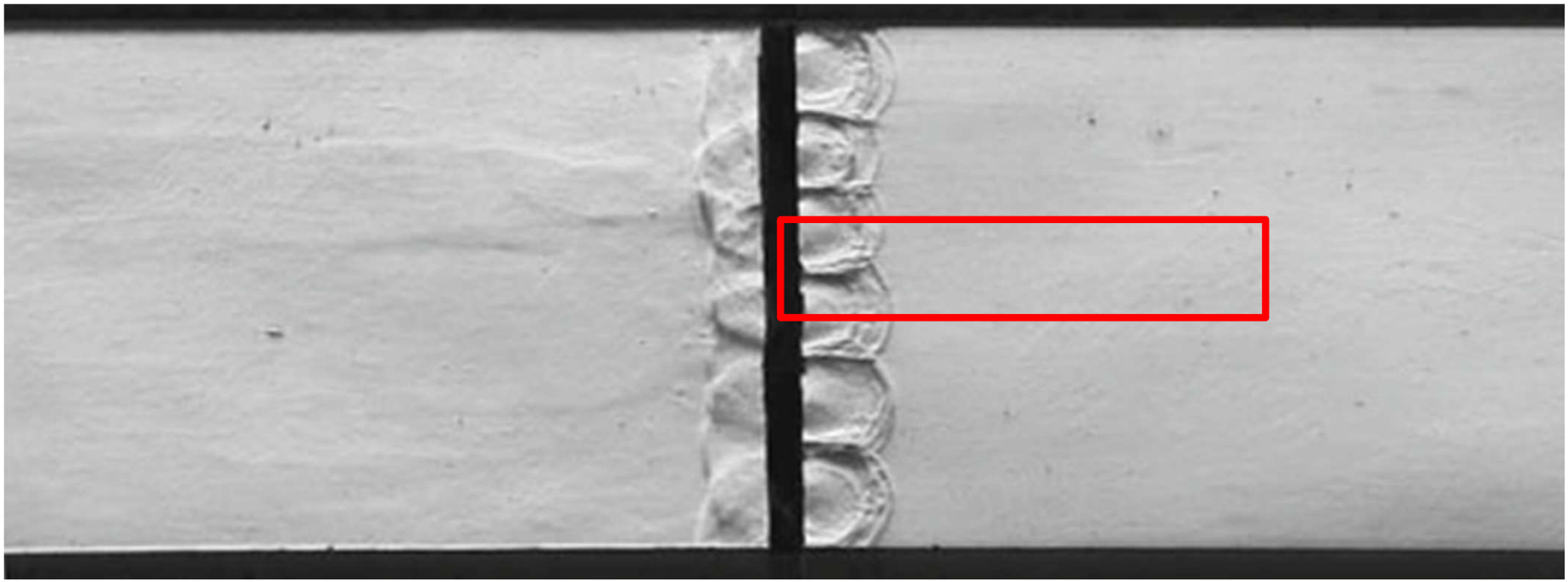
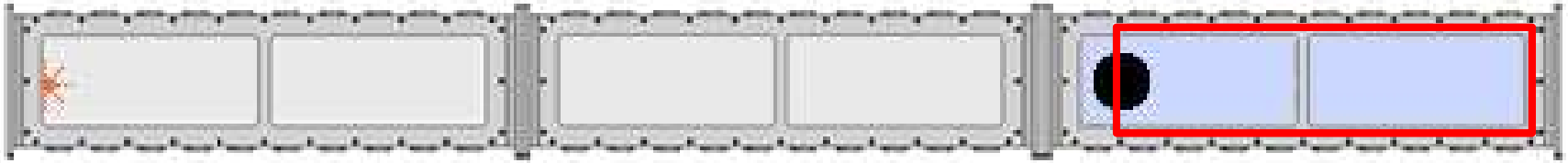
Chemical Kinetics can't seem to explain the discrepancies

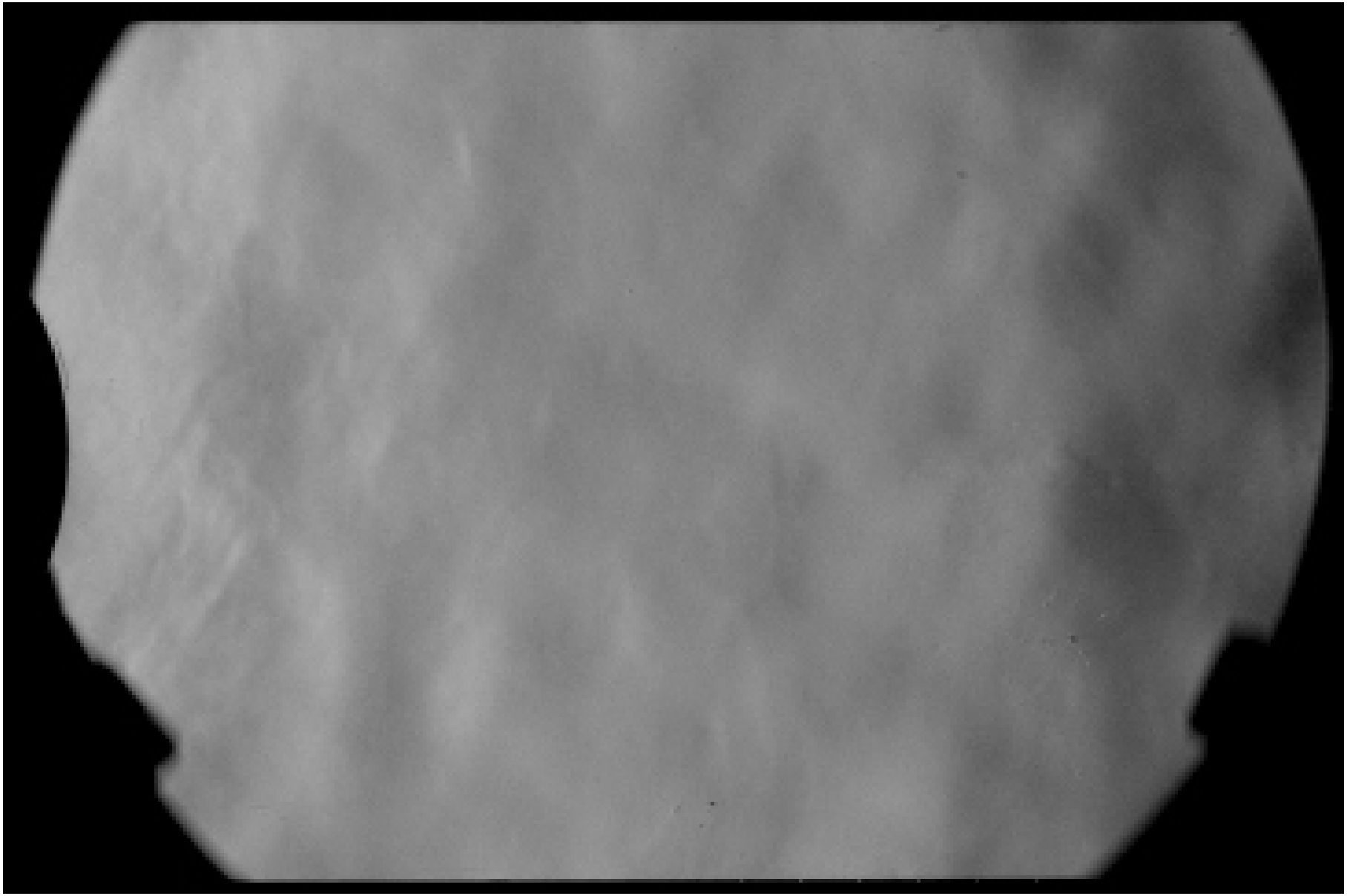
→ Lets look into the hydrodynamics

Isolating the First Reflection





Re-ignitions from wave reflections



$CH_4 + 2O_2$ P_o = 8.3 kPa

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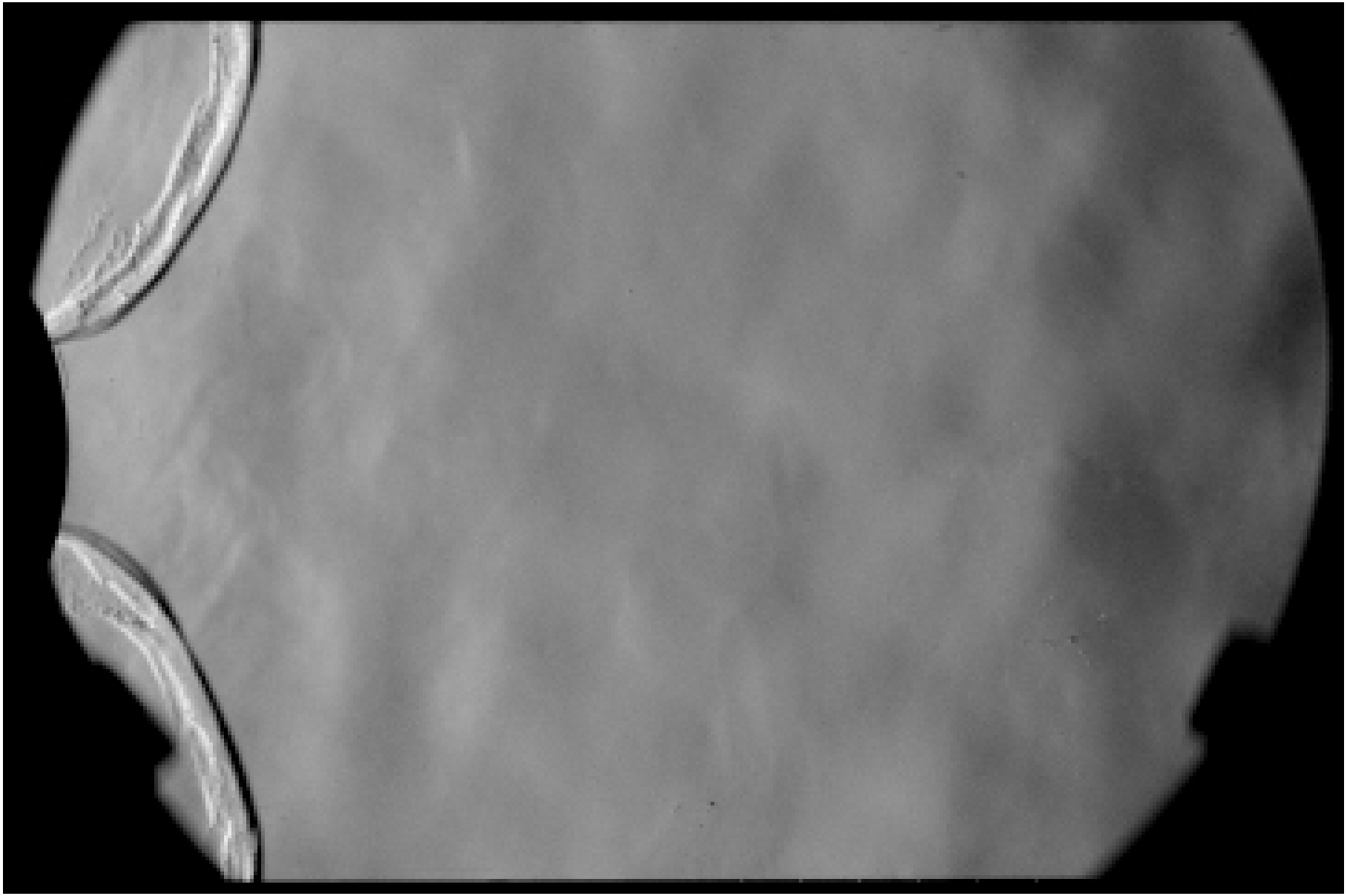

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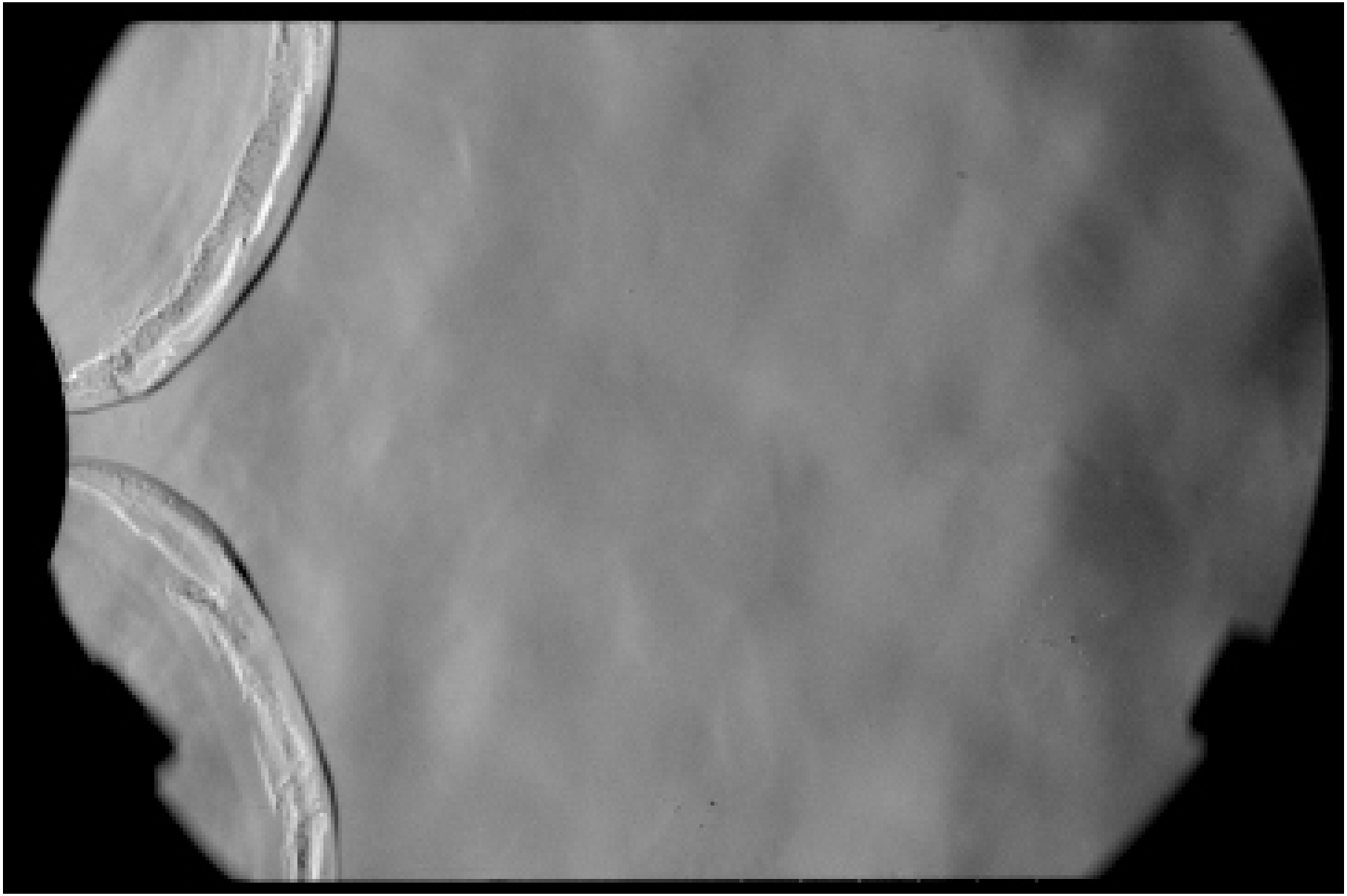

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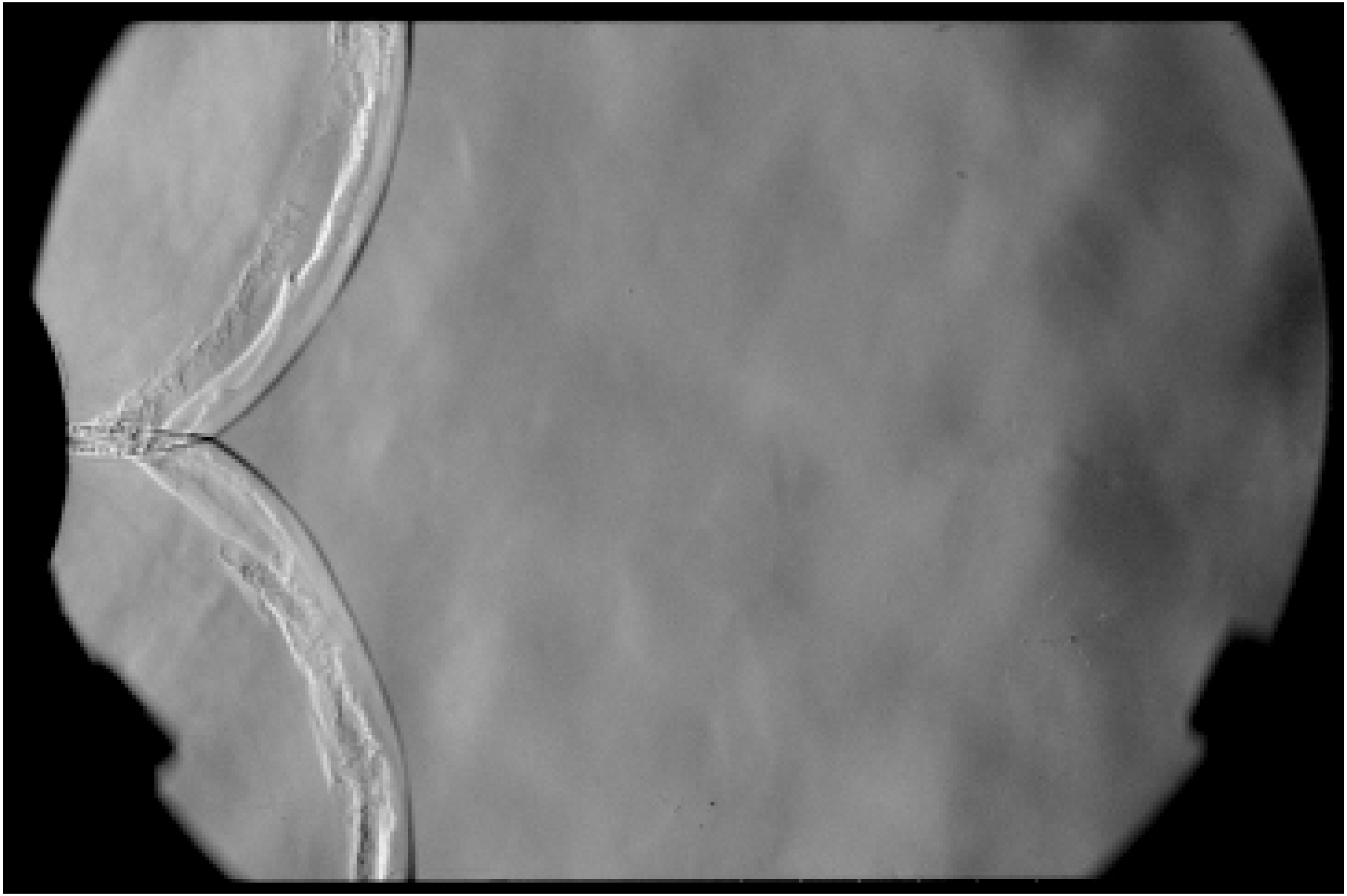

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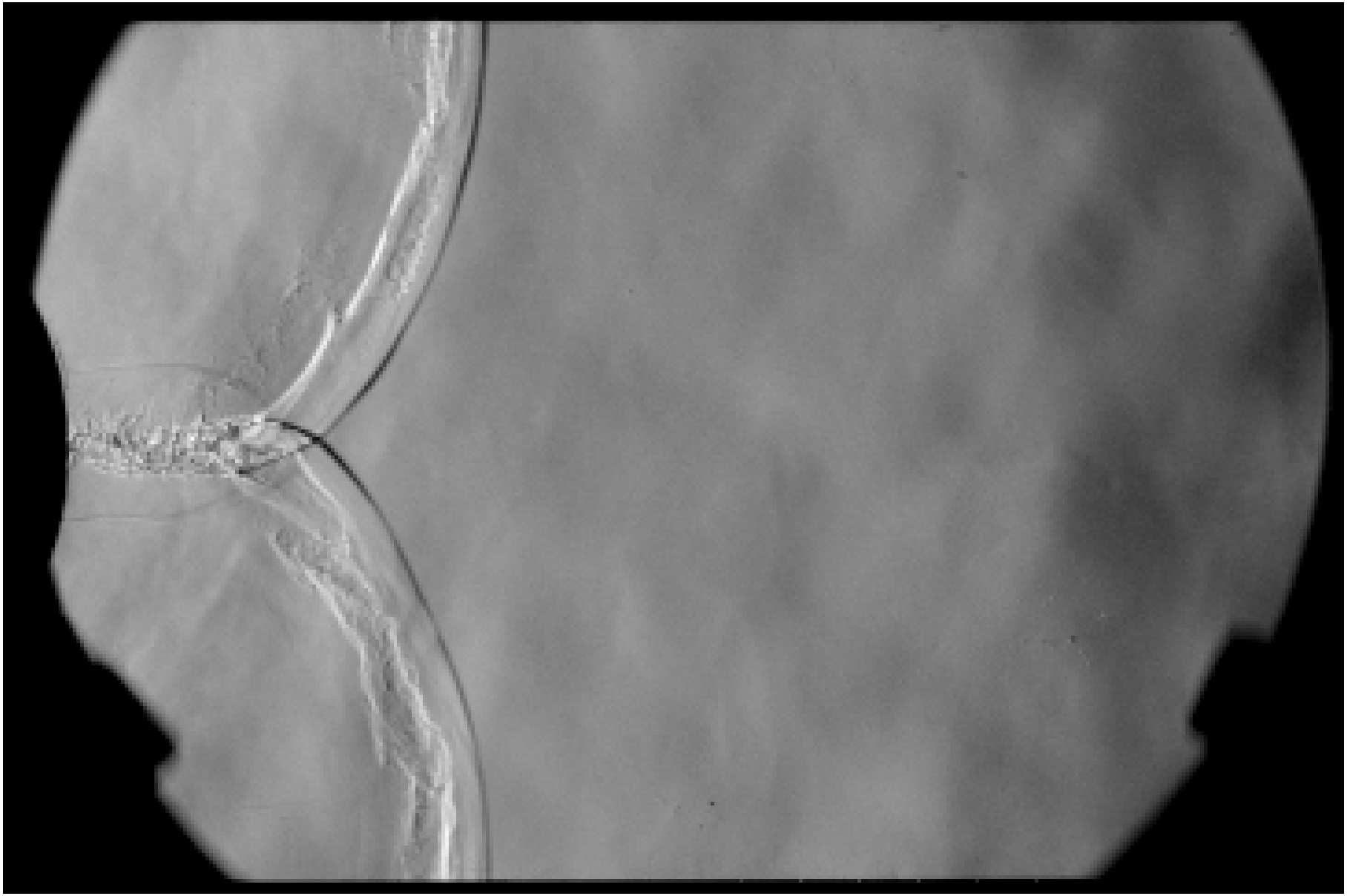

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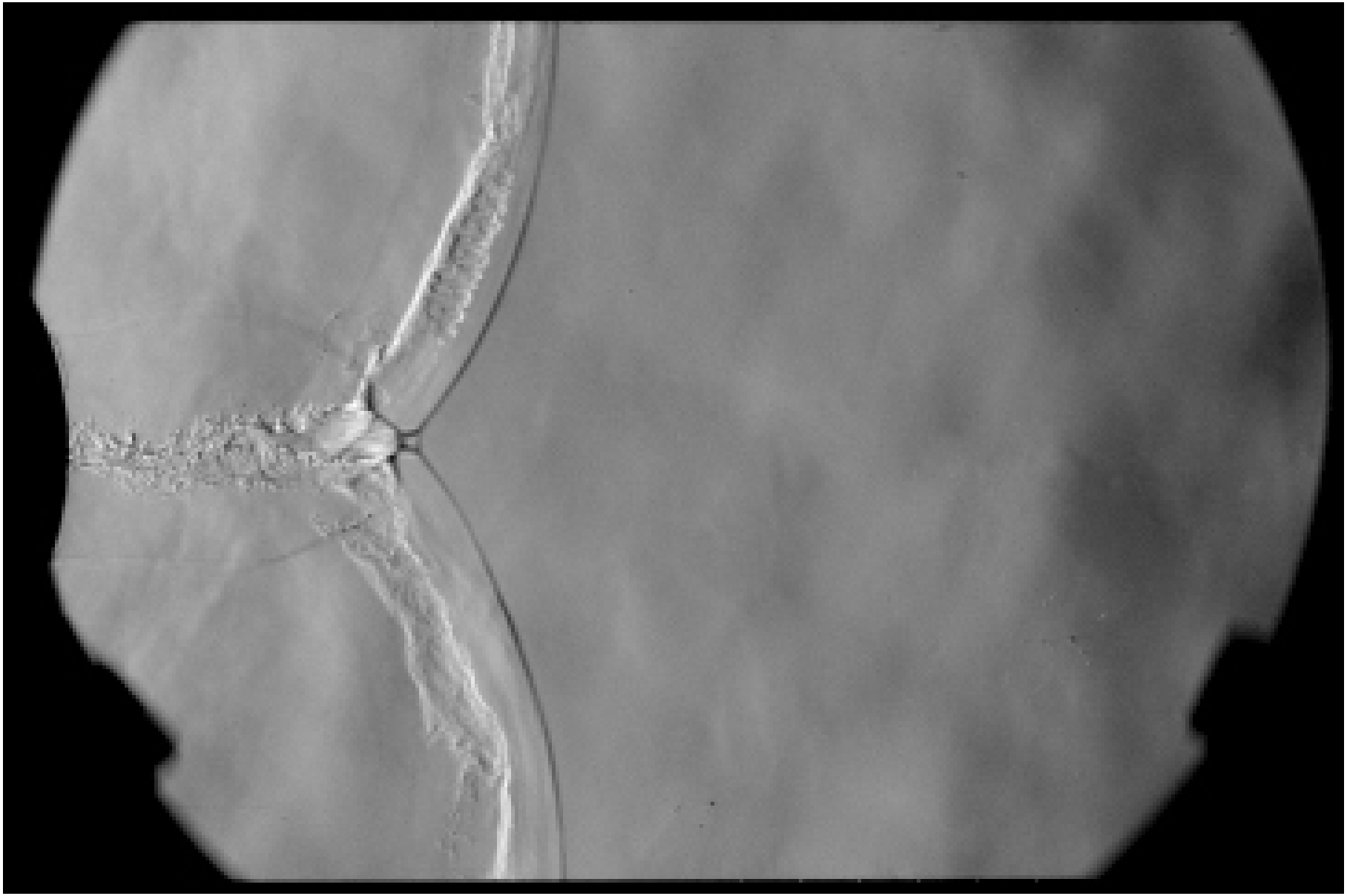

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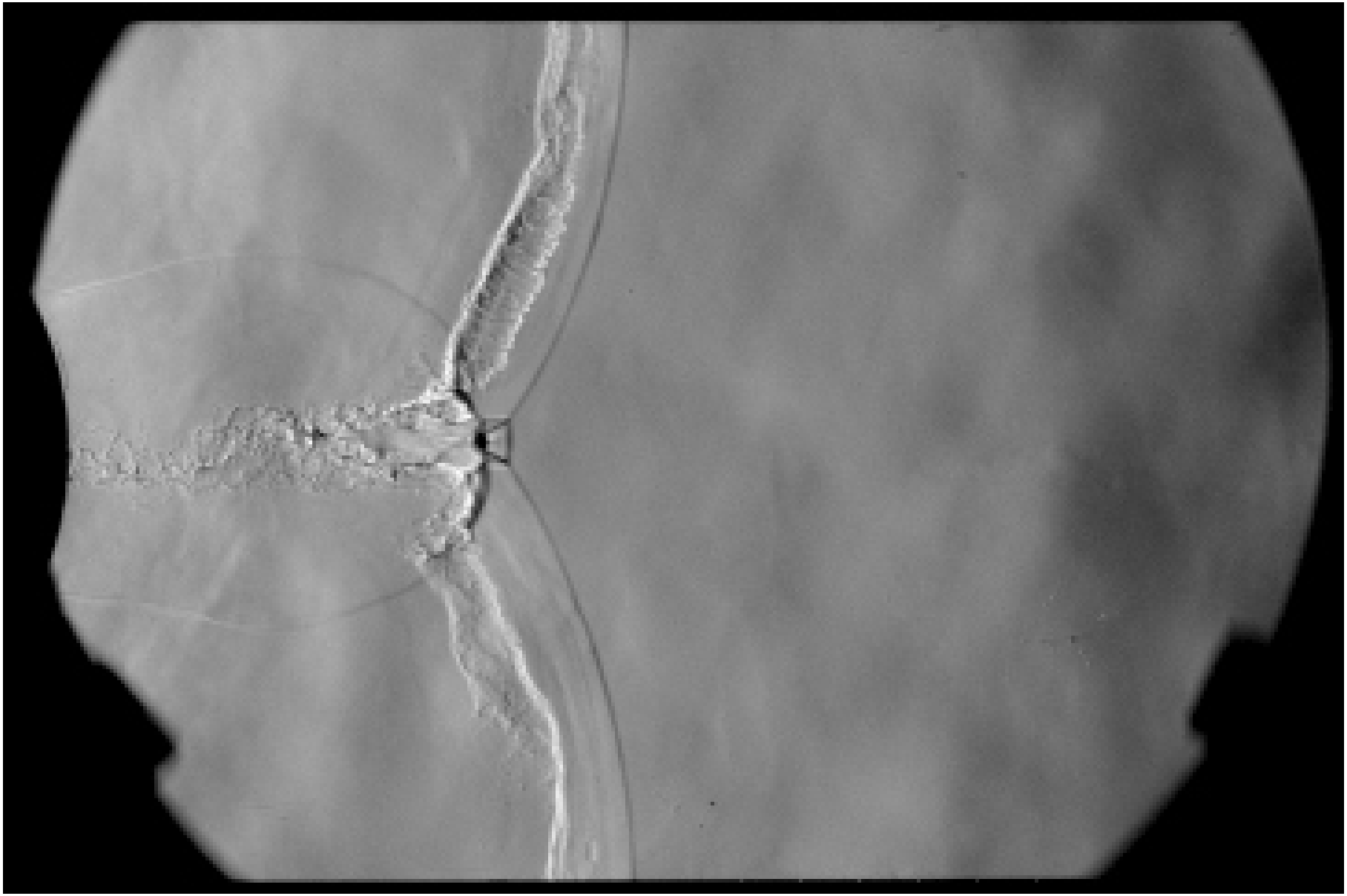

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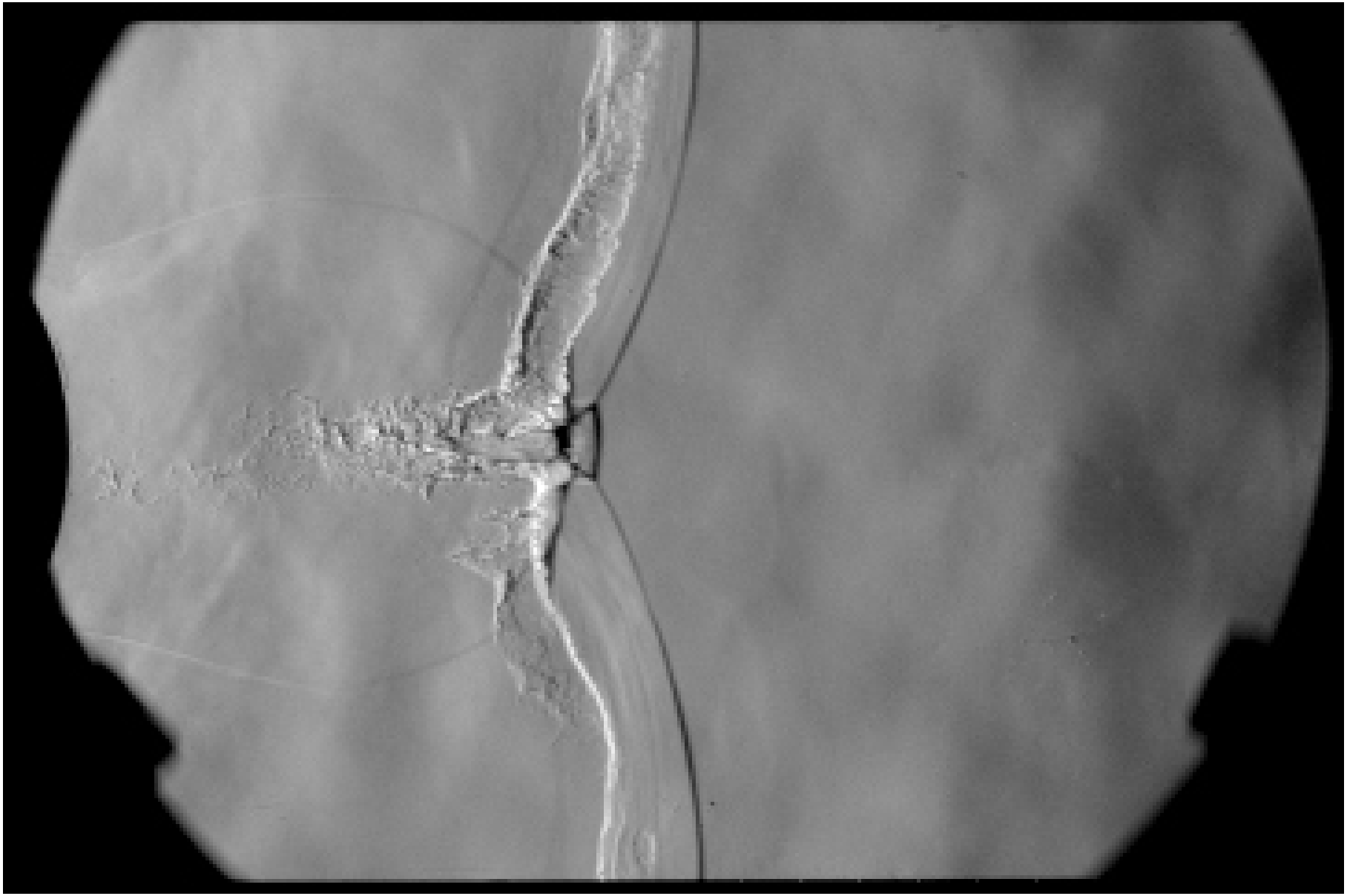
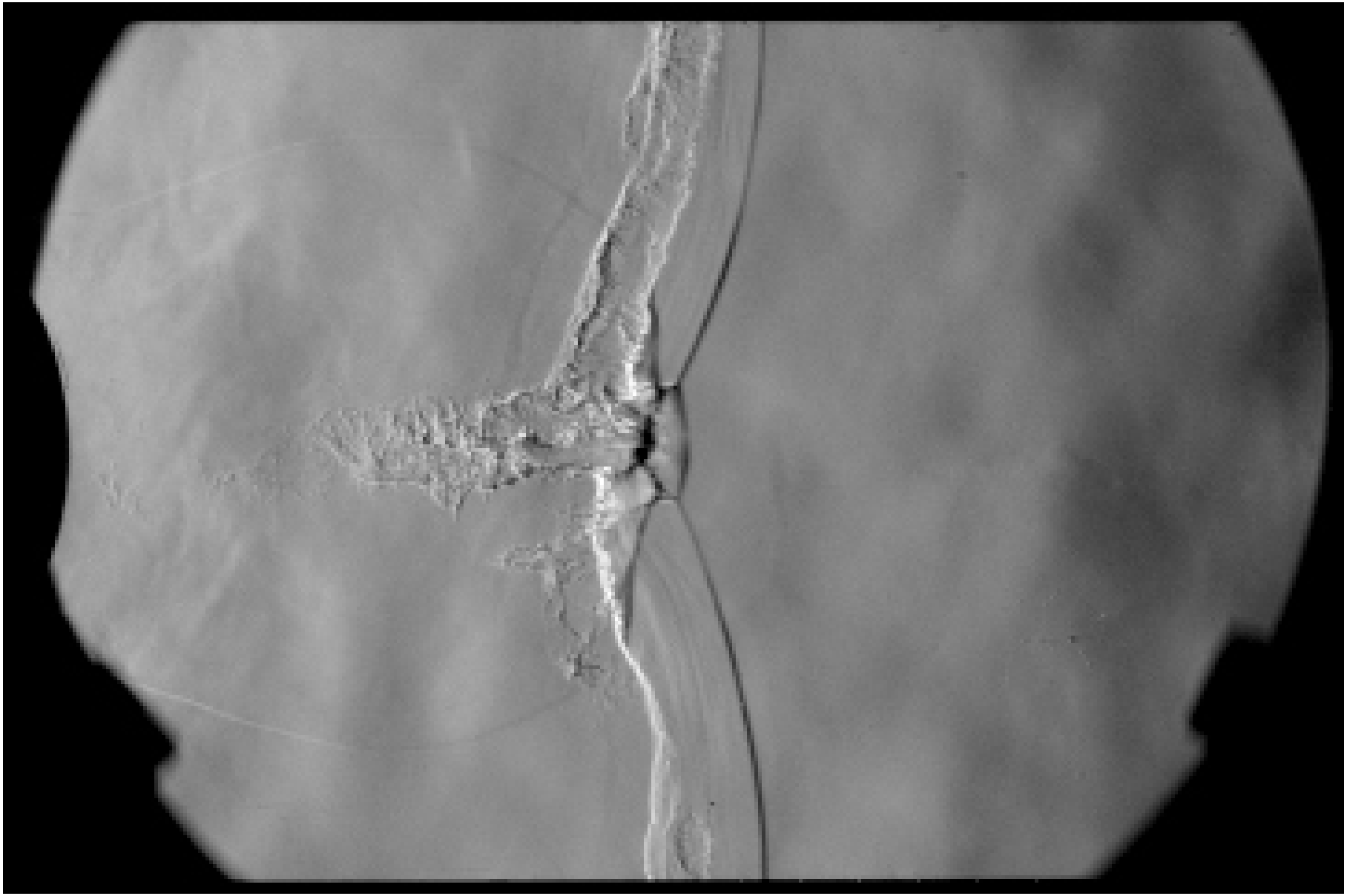


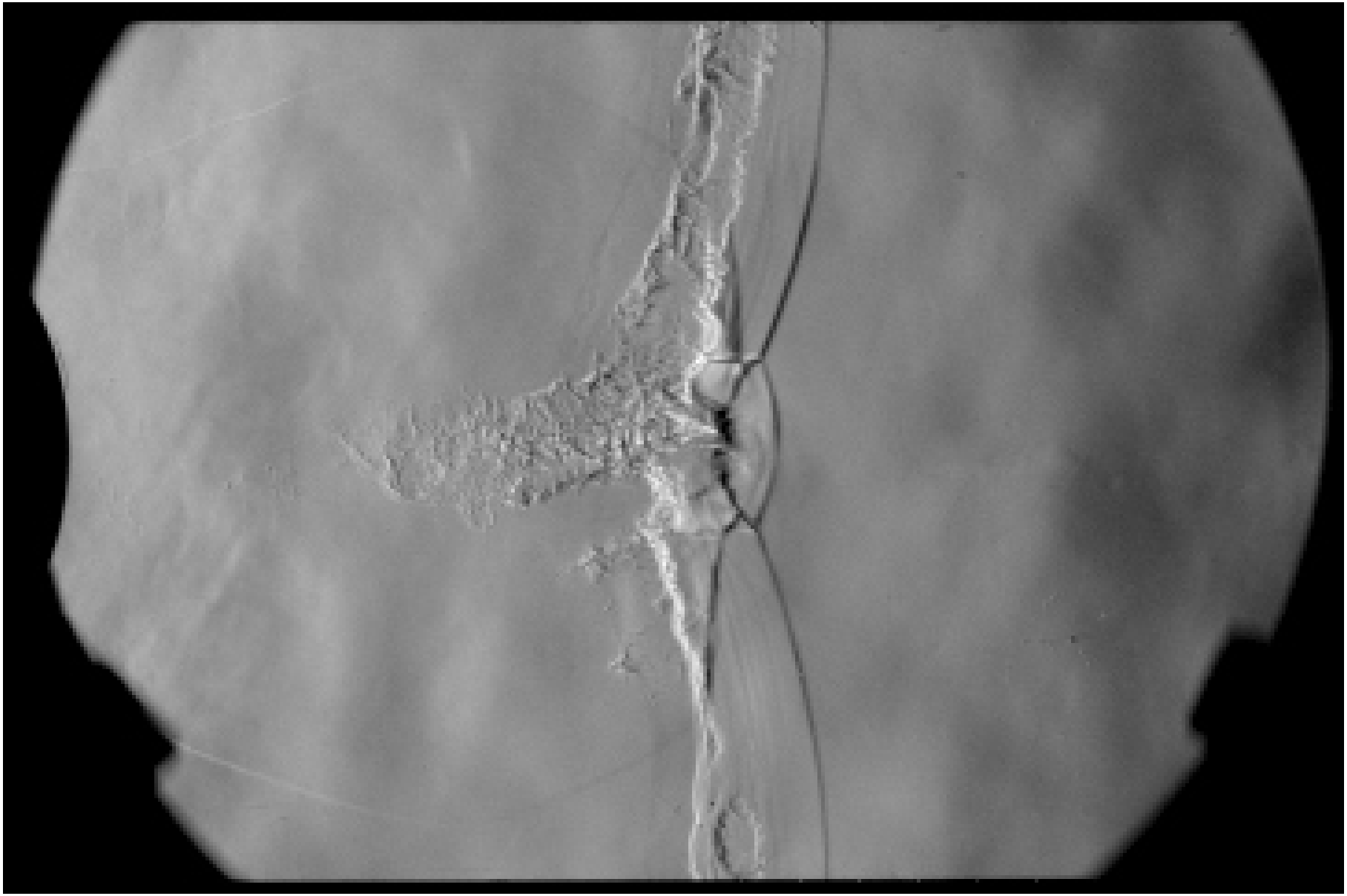
$CH_4 + 2O_2$ P_o = 8.3 kPa

Re-ignitions from wave reflections



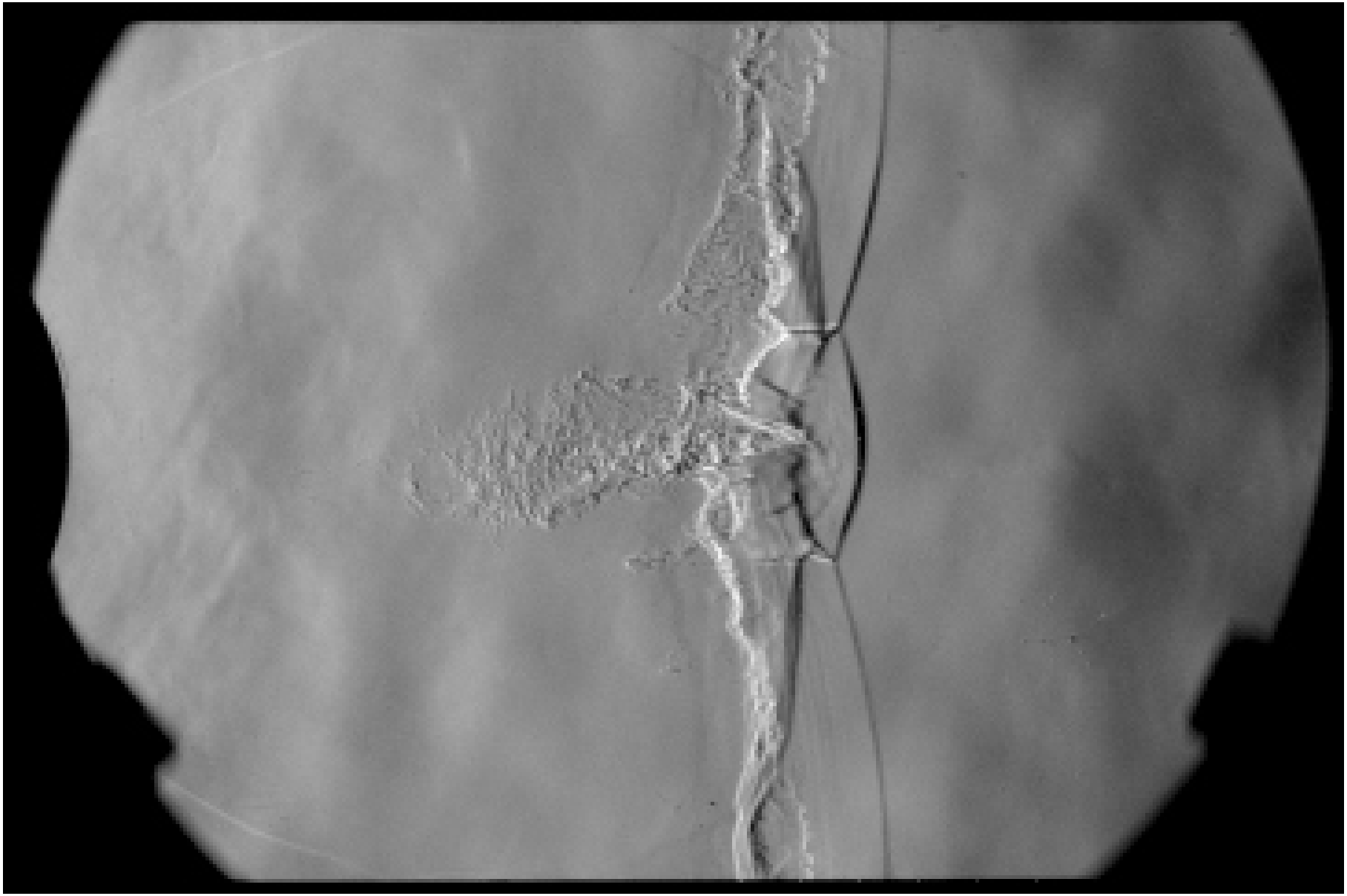
$CH_4 + 2O_2$ P_o = 8.3 kPa

Re-ignitions from wave reflections



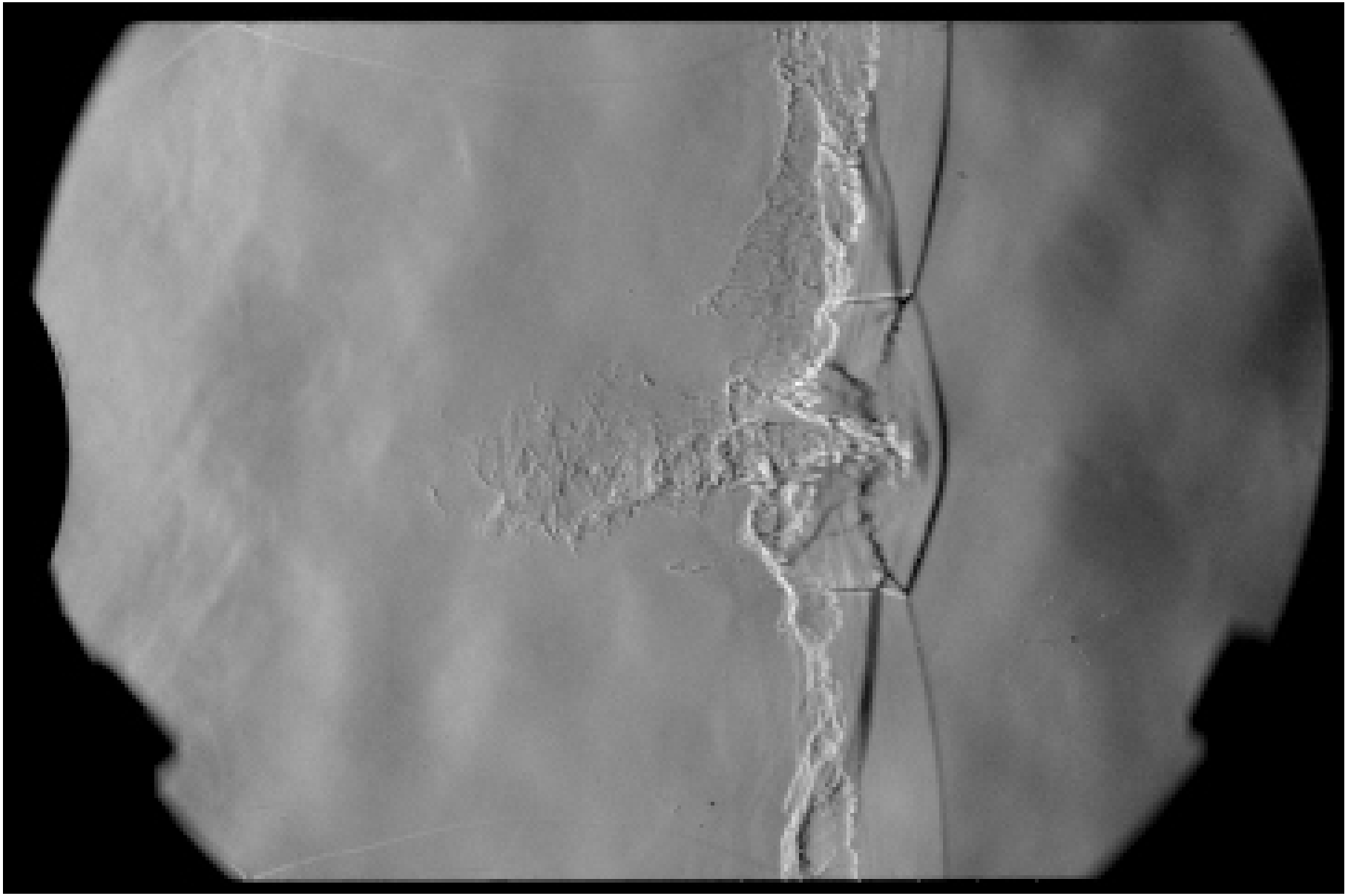
$CH_4 + 2O_2$ P_o = 8.3 kPa

Re-ignitions from wave reflections



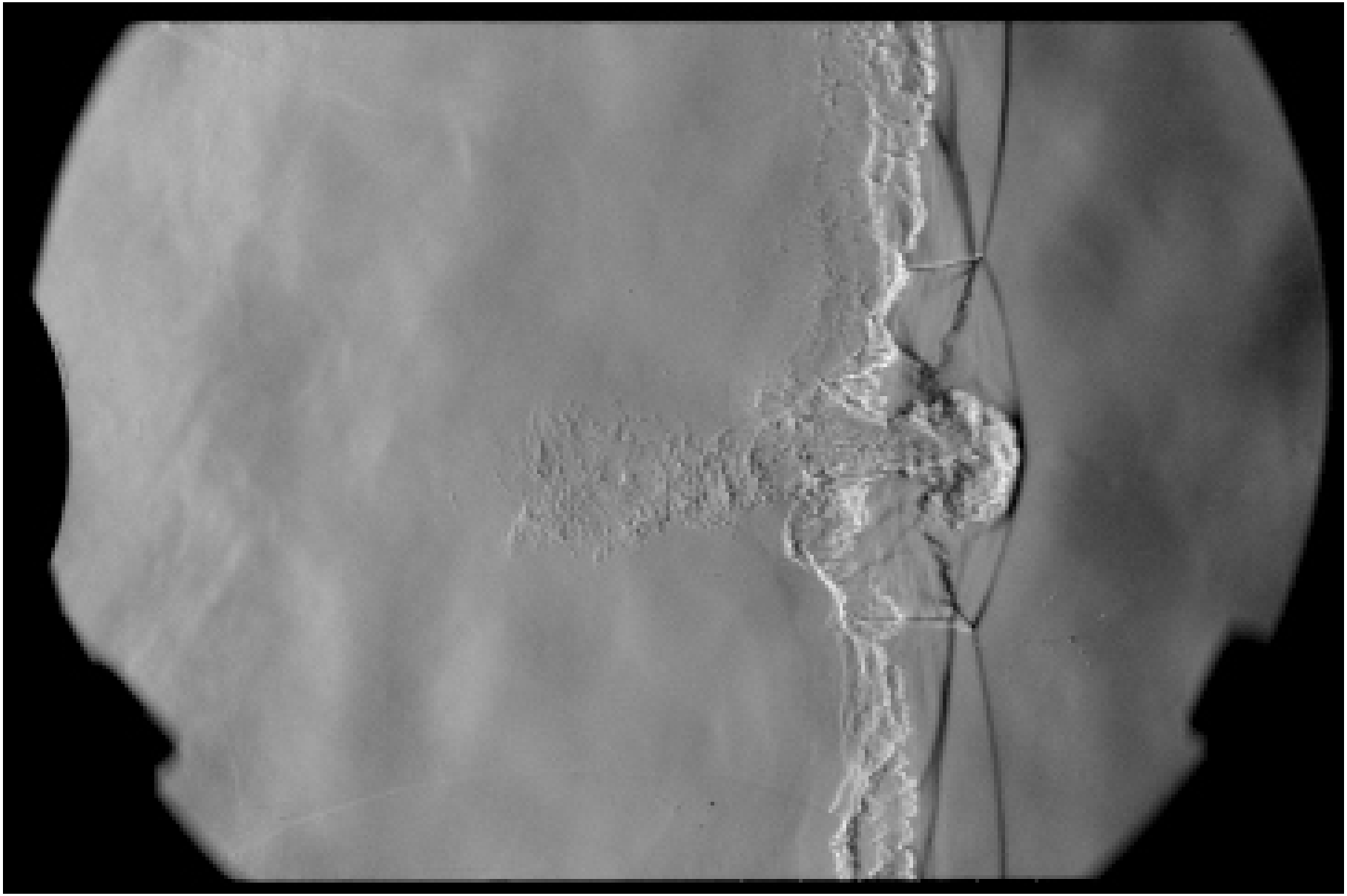
$CH_4 + 2O_2$ P_o = 8.3 kPa

Re-ignitions from wave reflections



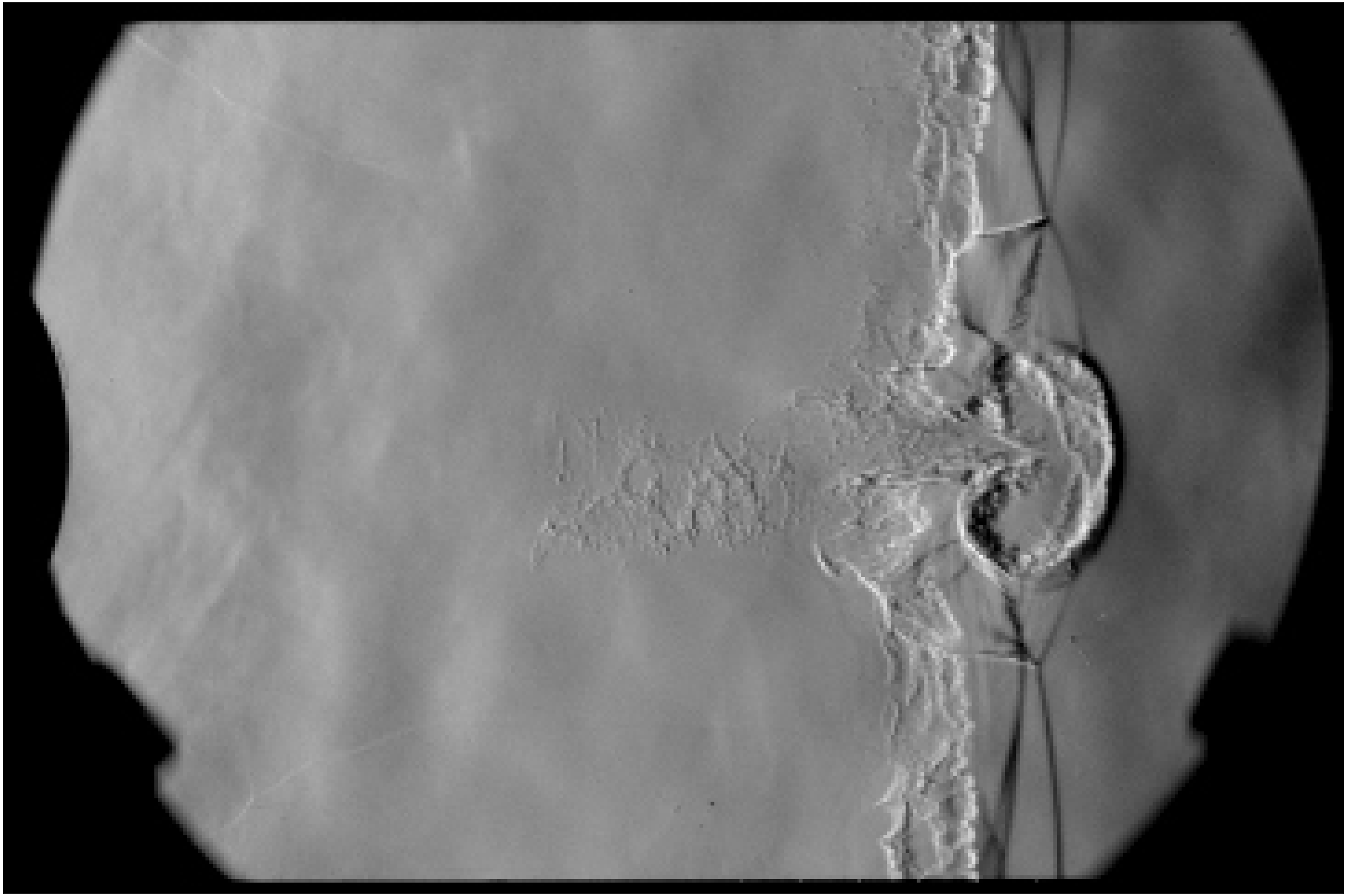
$CH_4 + 2O_2$ P_o = 8.3 kPa

Re-ignitions from wave reflections



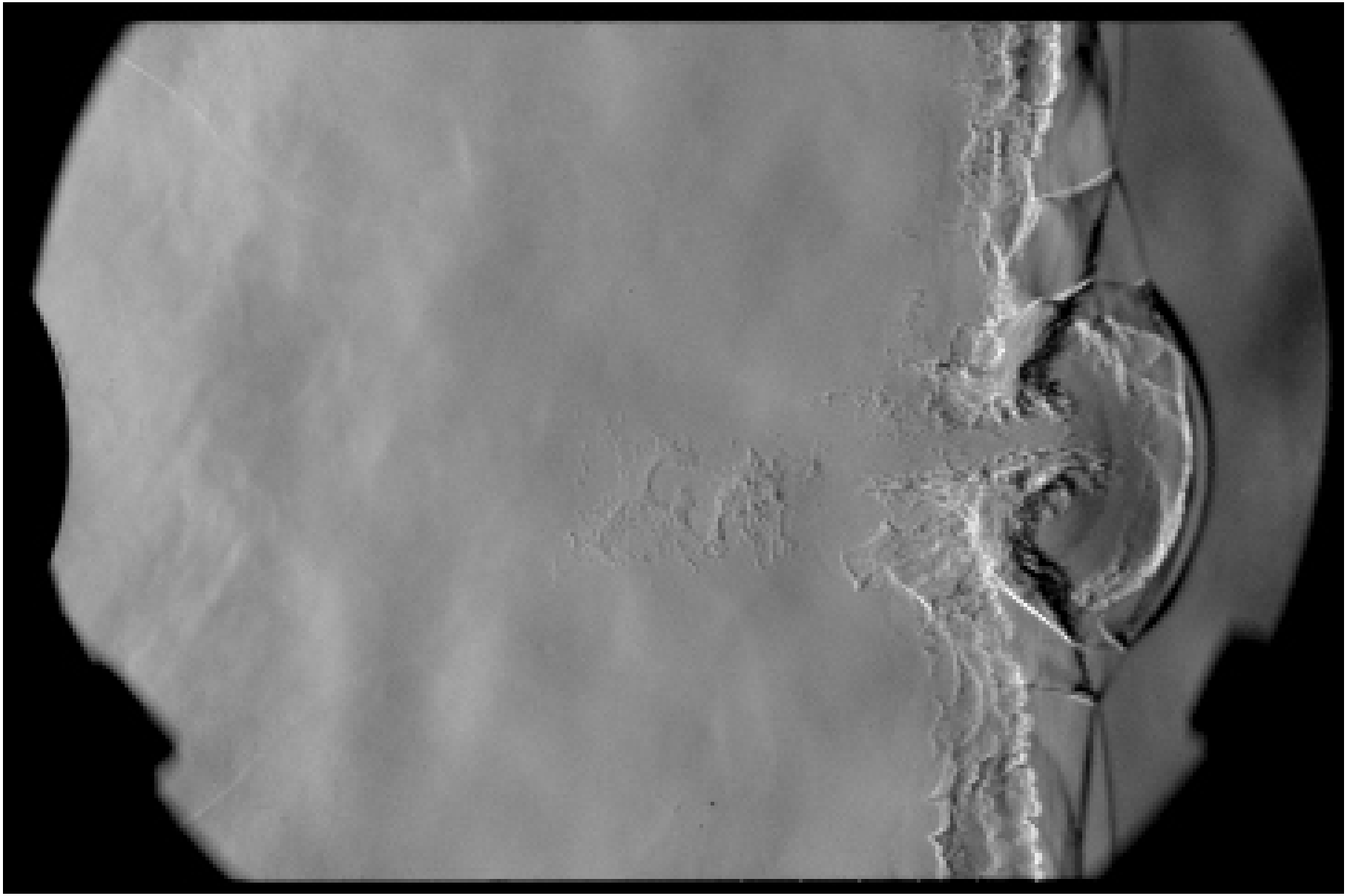
$CH_4 + 2O_2$ P_o = 8.3 kPa

Re-ignitions from wave reflections



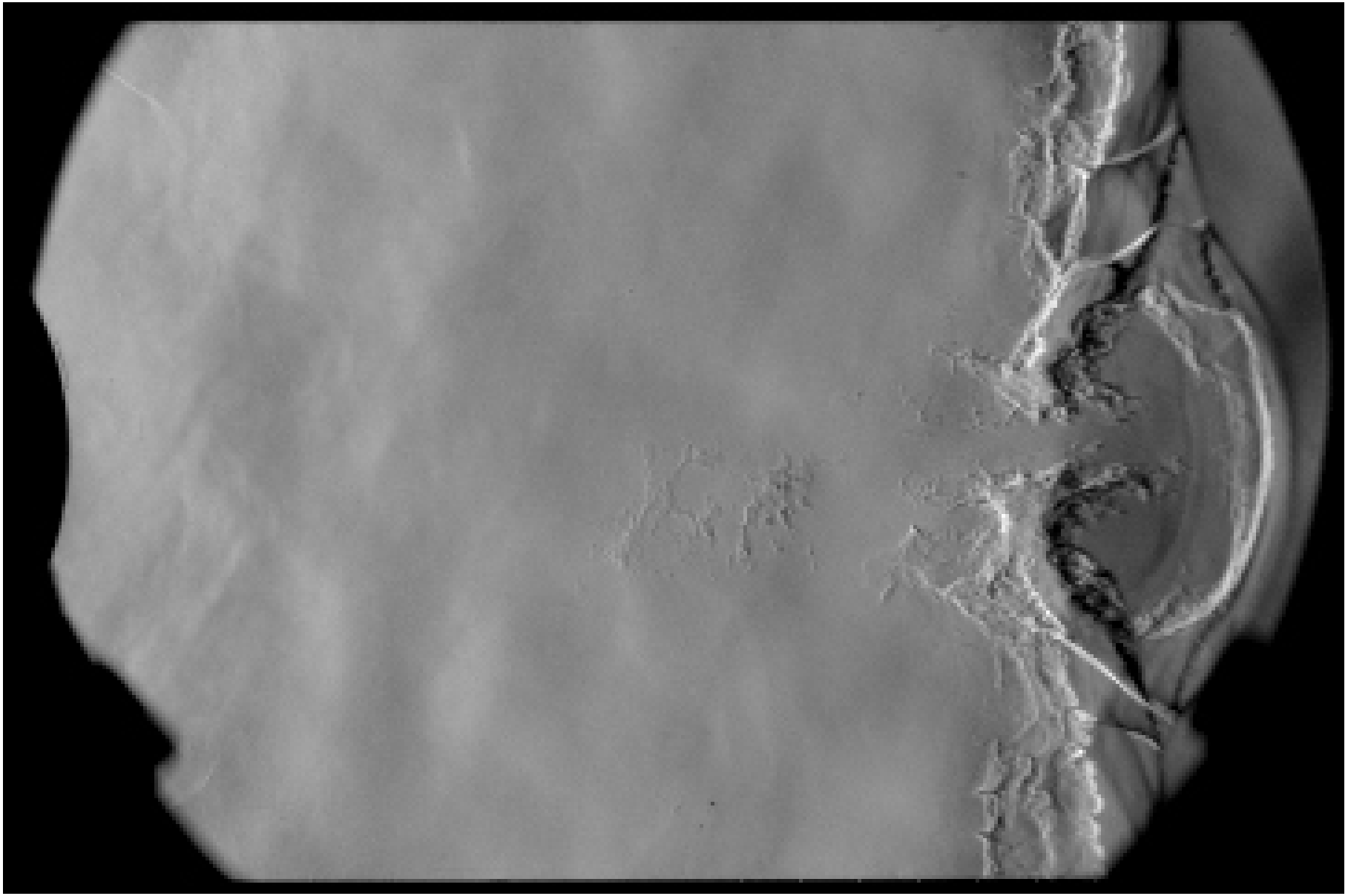
$CH_4 + 2O_2$ P_o = 8.3 kPa

Re-ignitions from wave reflections



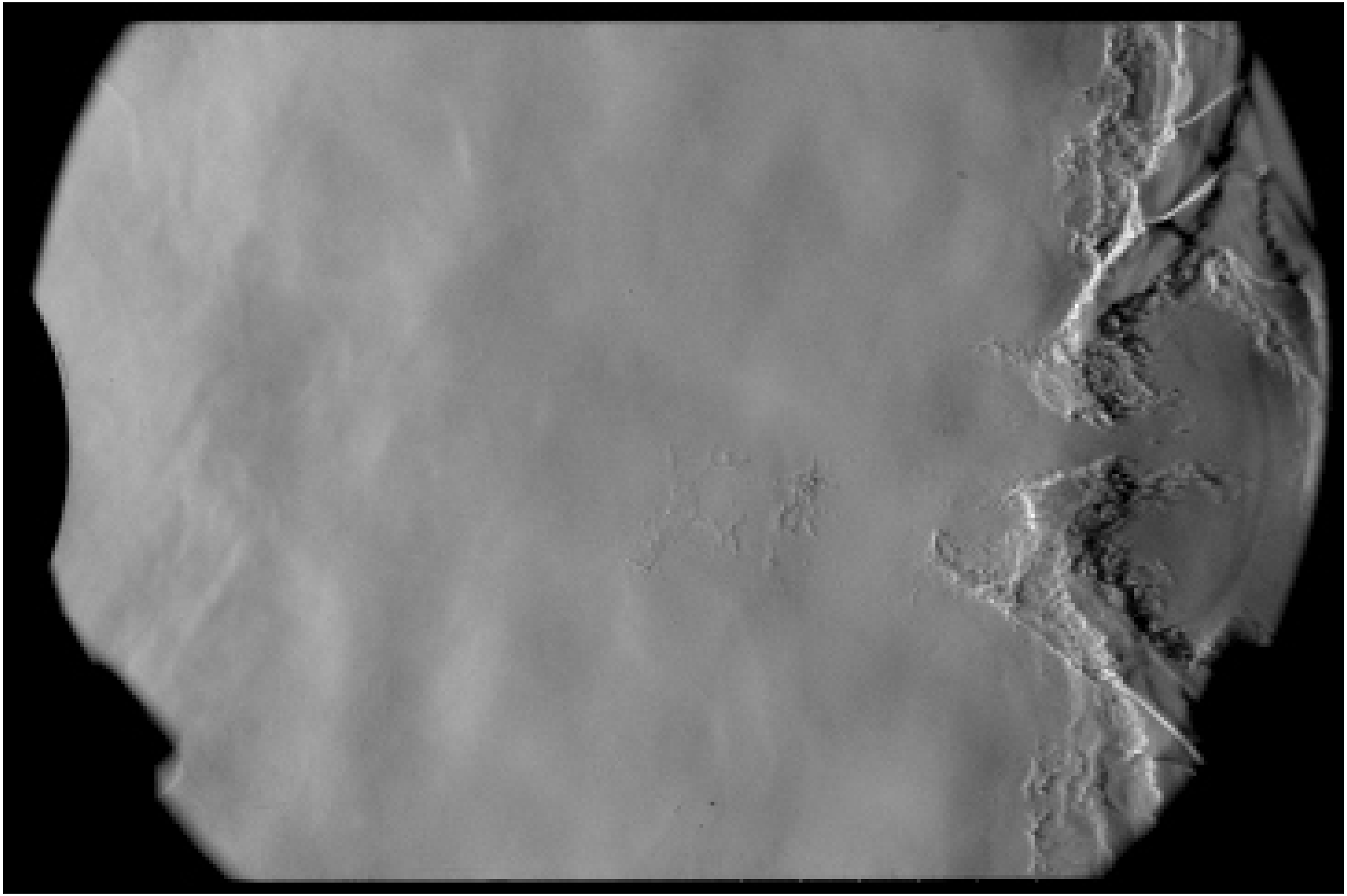
$CH_4 + 2O_2$ P_o = 8.3 kPa

Re-ignitions from wave reflections



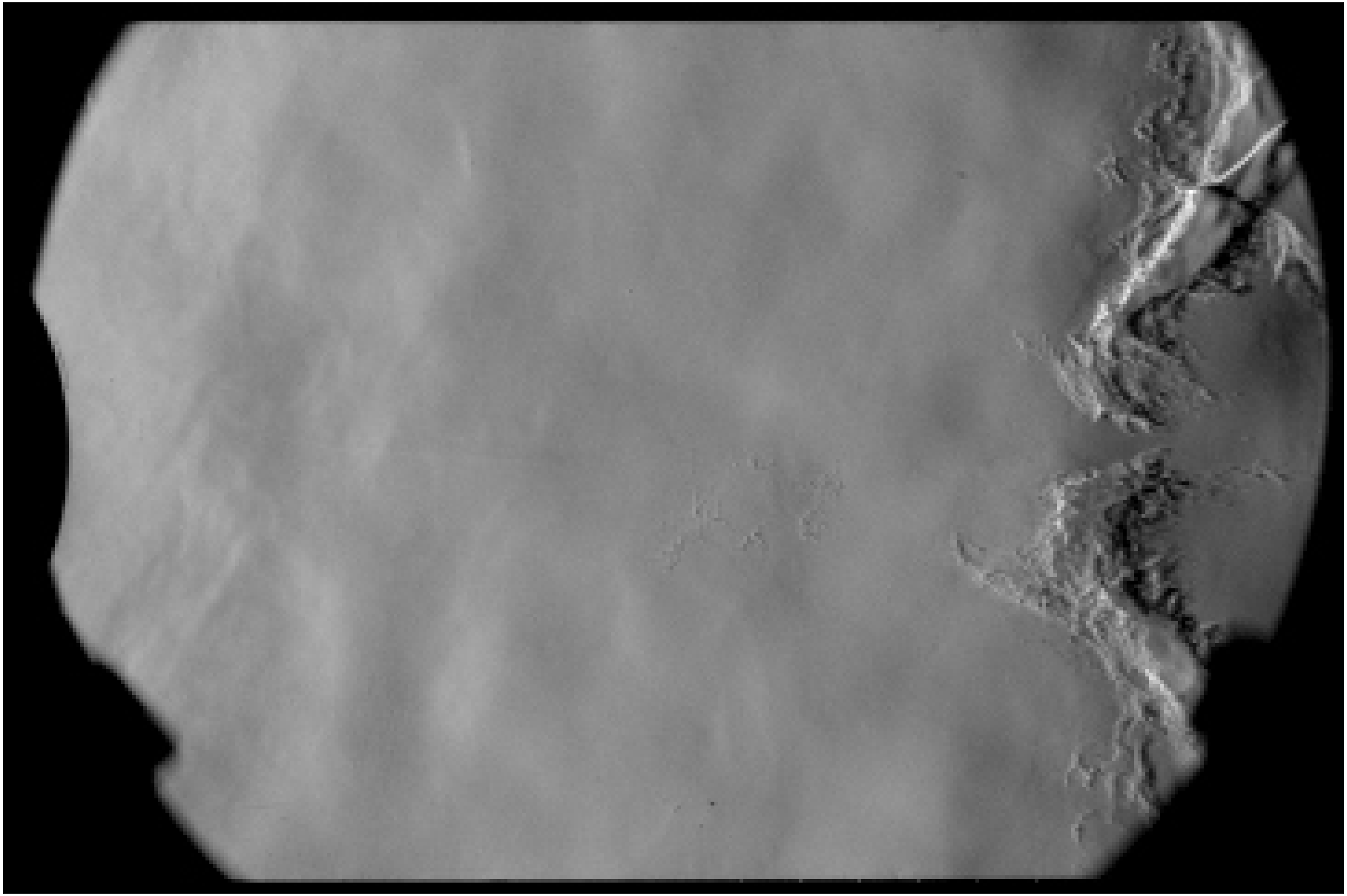
$CH_4 + 2O_2$ P_o = 8.3 kPa

Re-ignitions from wave reflections



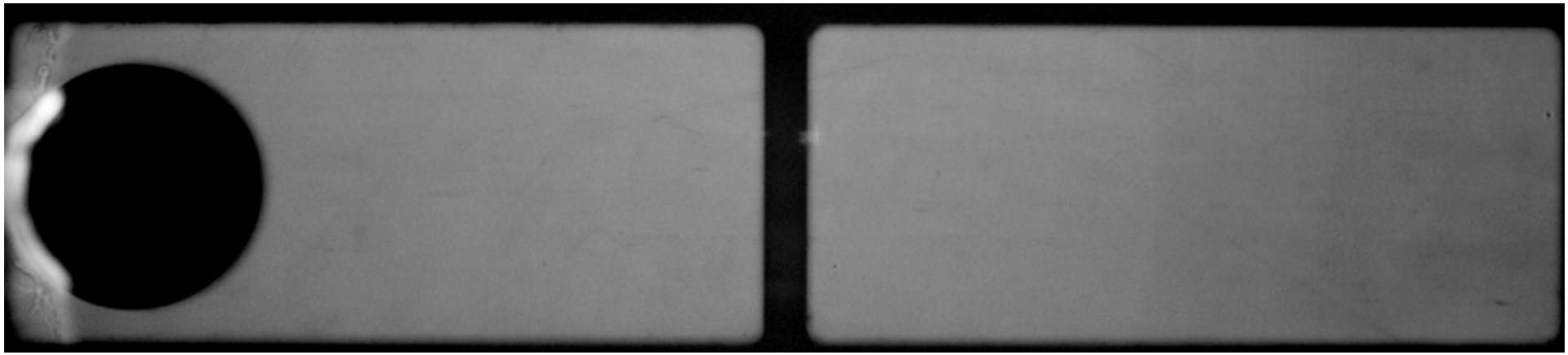
$CH_4 + 2O_2$ P_o = 8.3 kPa

Re-ignitions from wave reflections



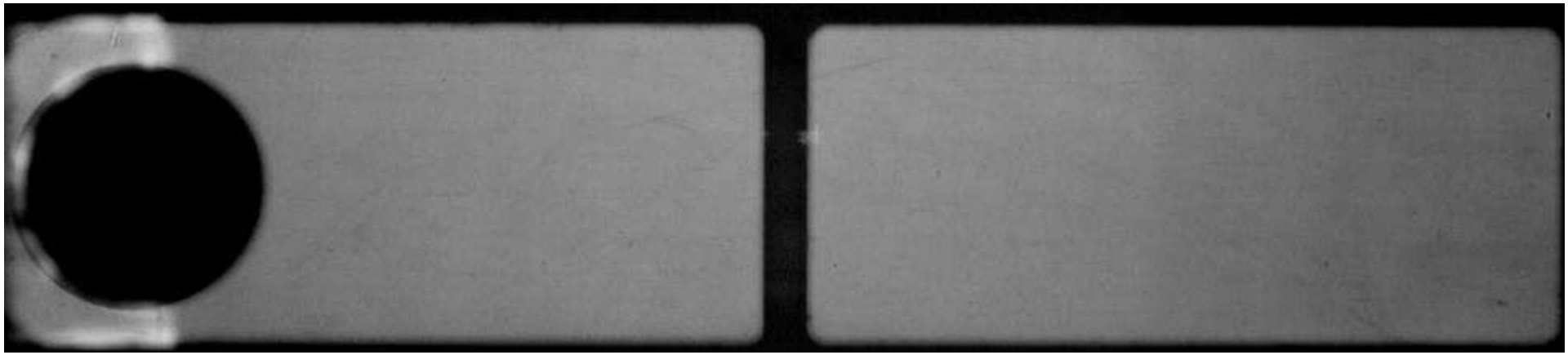
$CH_4 + 2O_2$ P_o = 8.3 kPa

Fast Flame Amplification



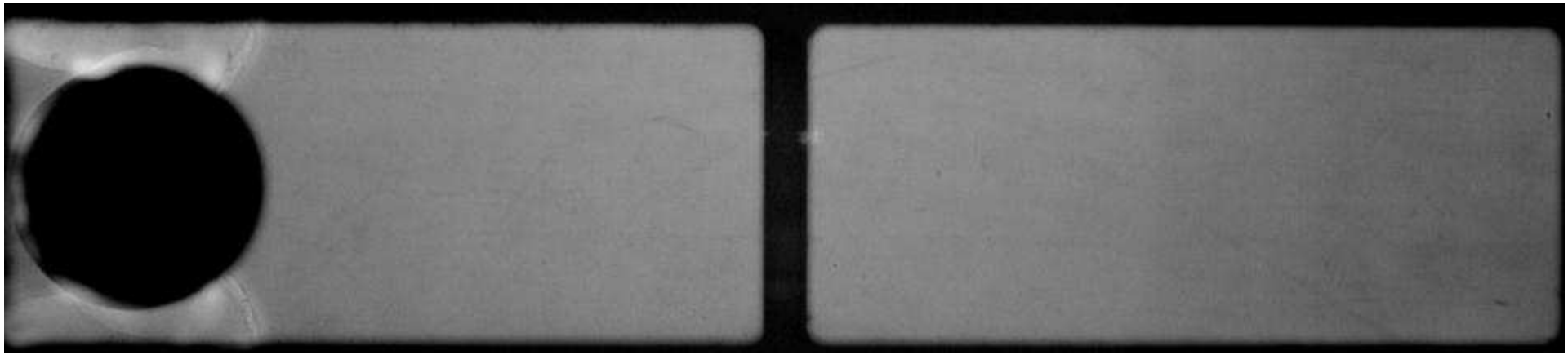
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



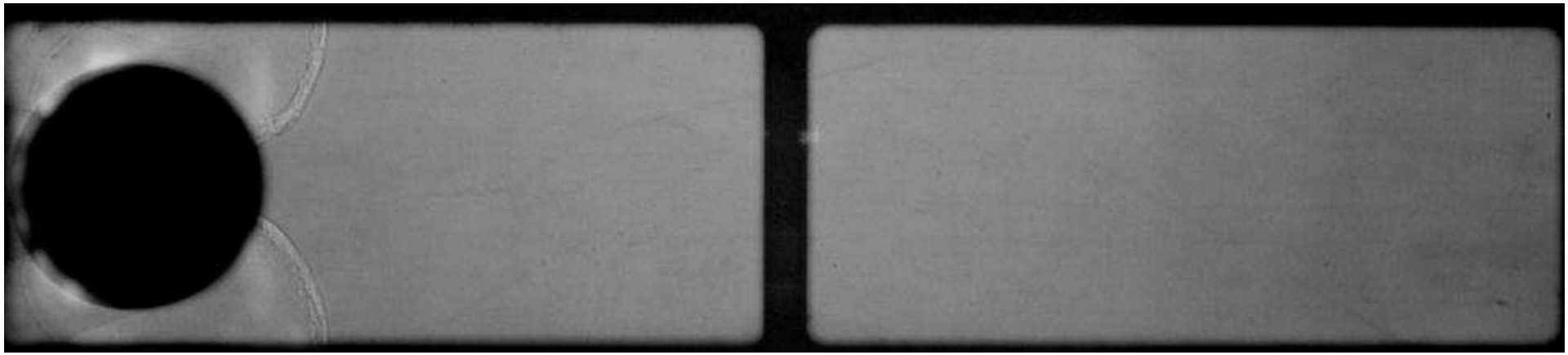
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



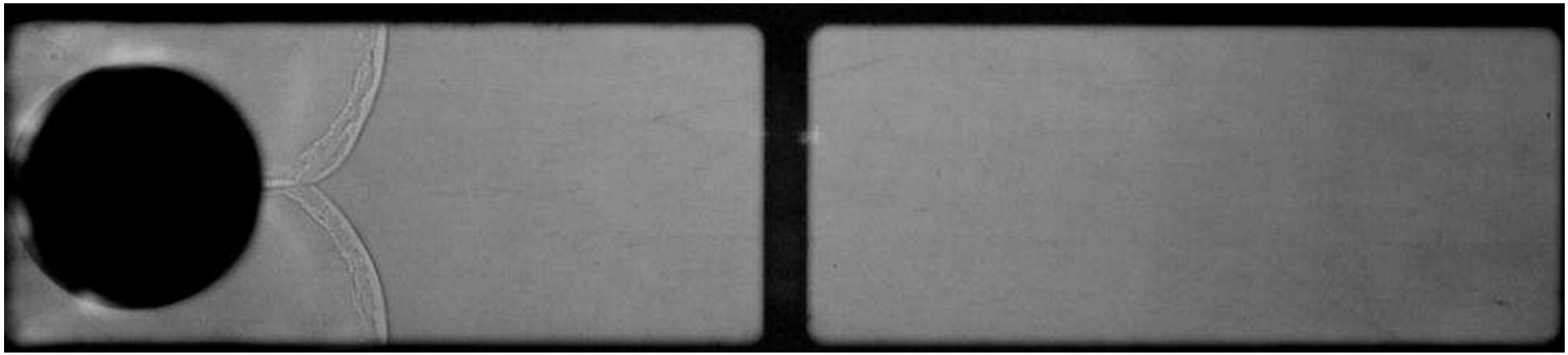
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



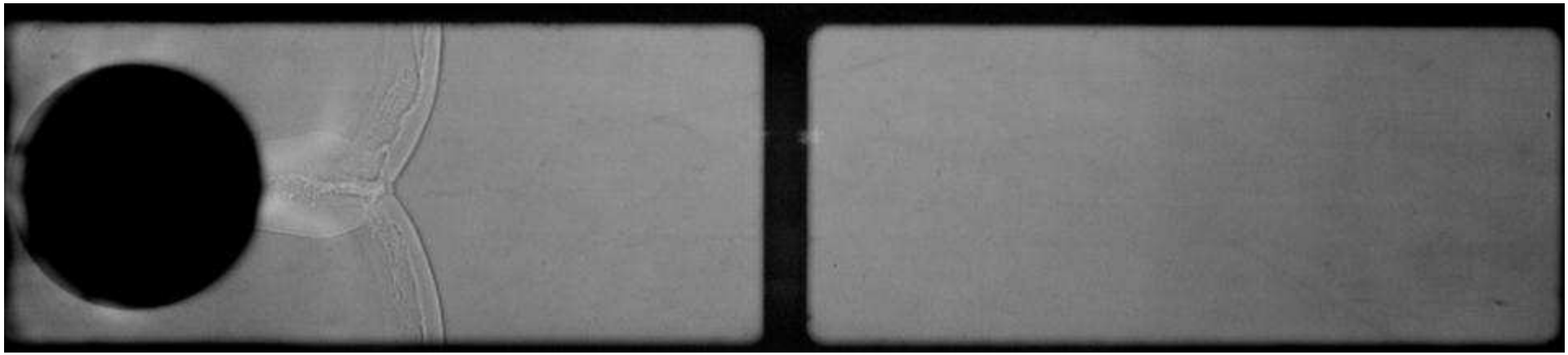
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



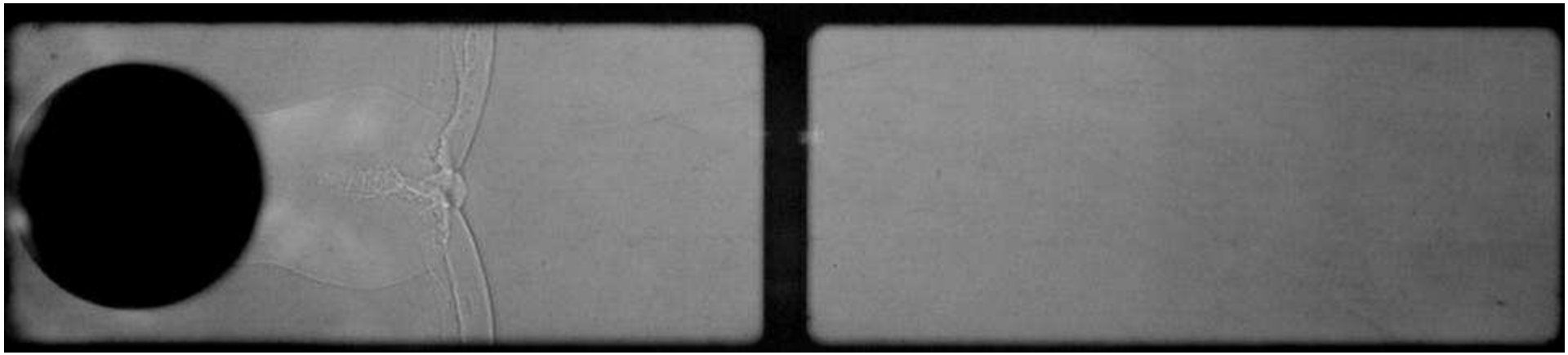
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



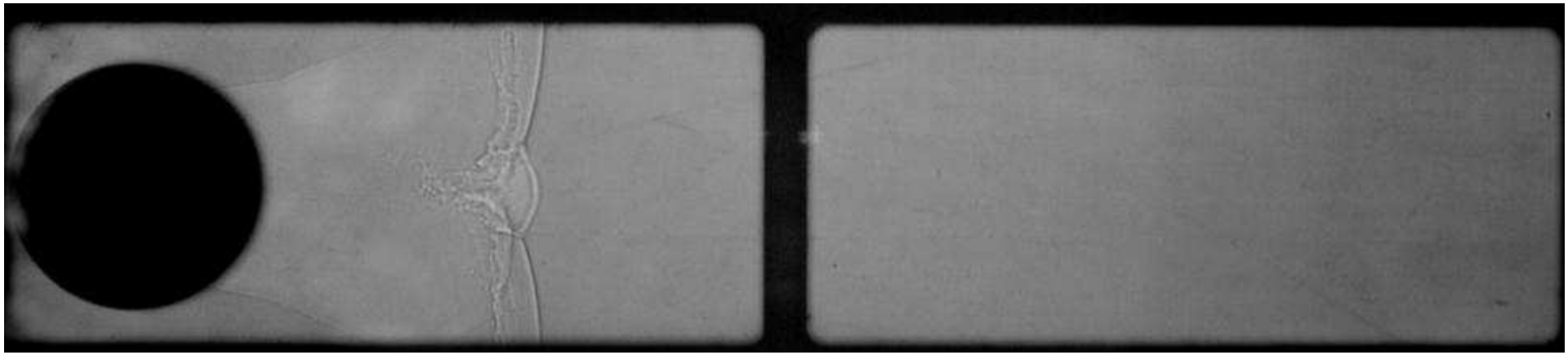
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



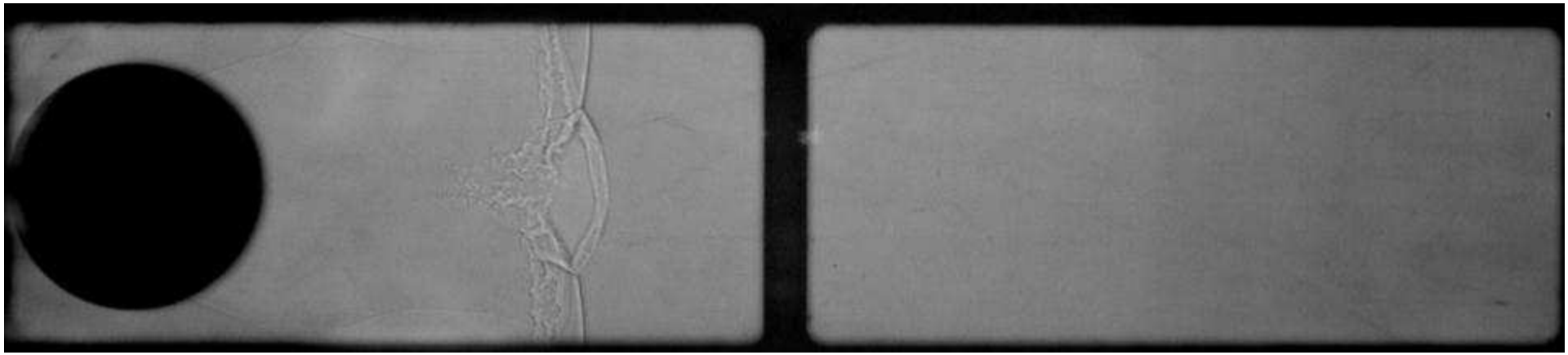
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



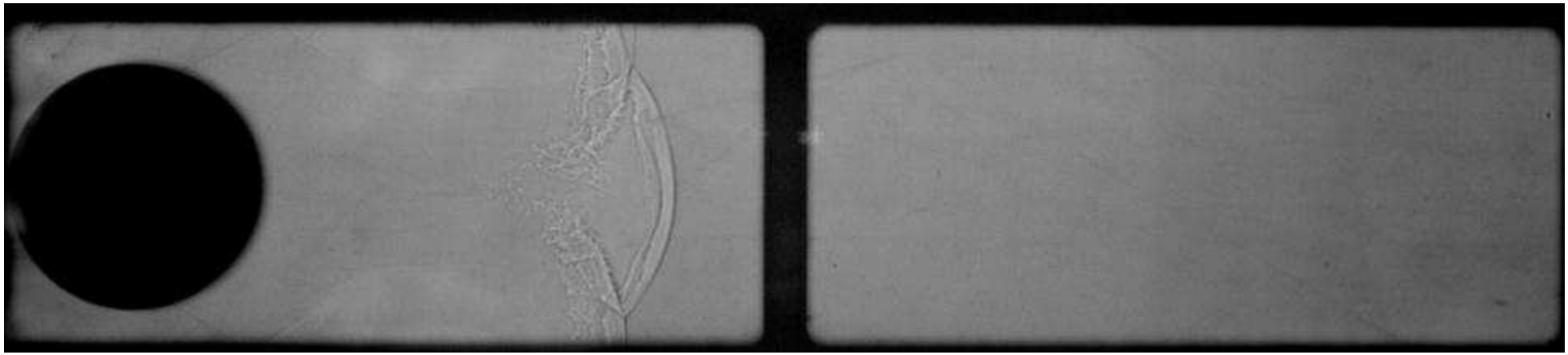
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



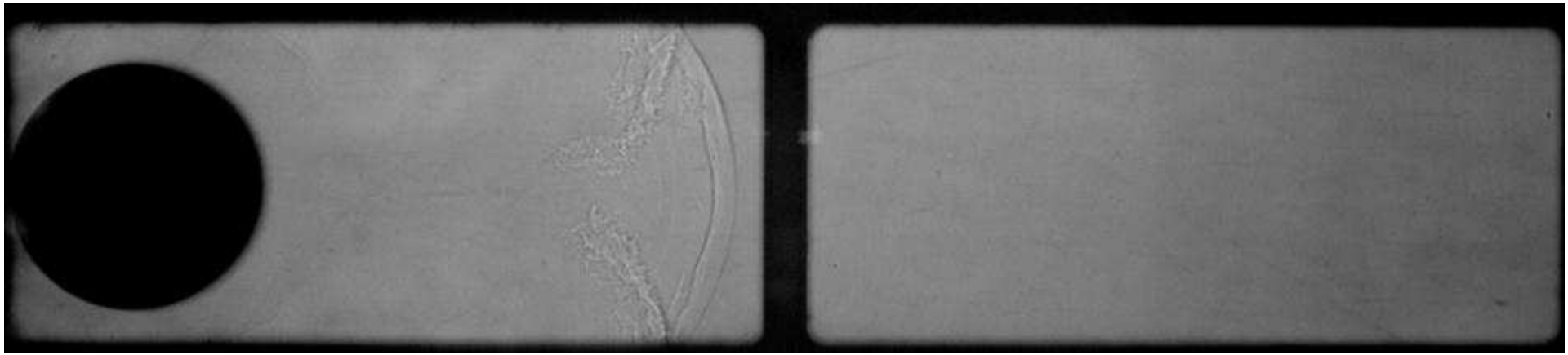
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



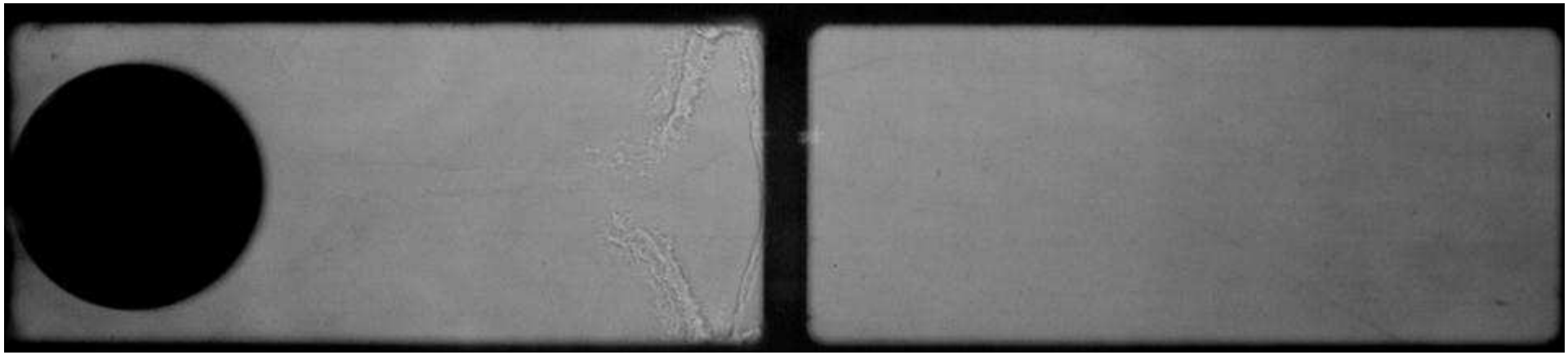
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



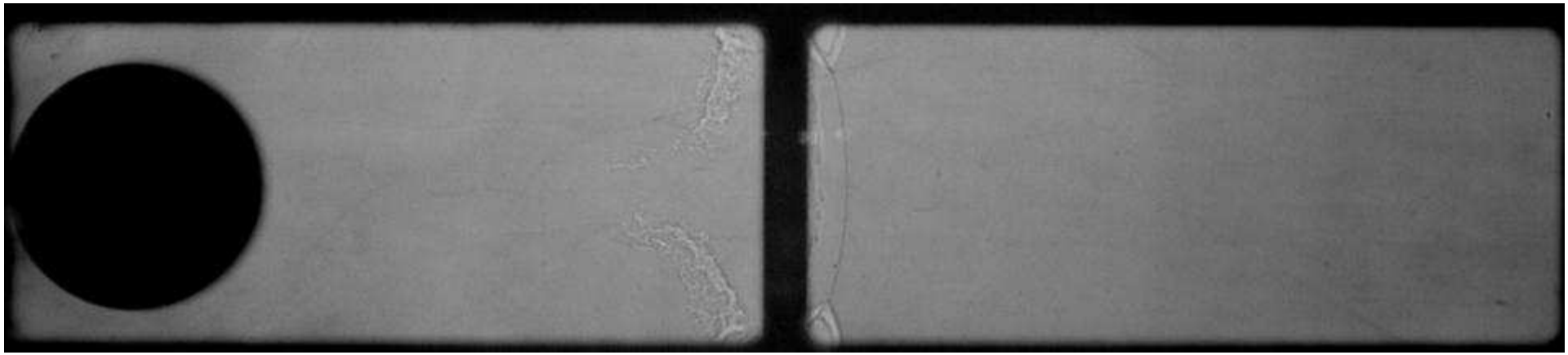
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



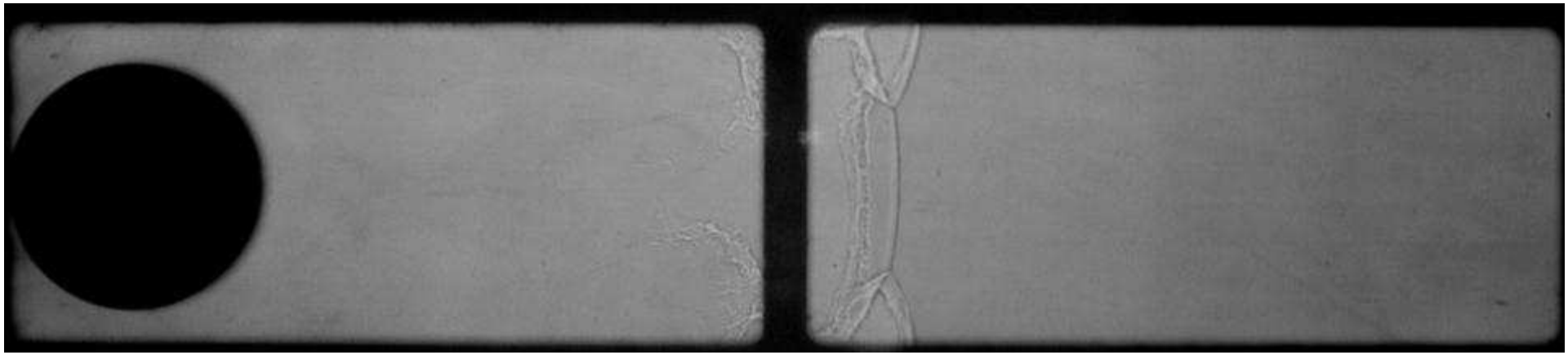
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



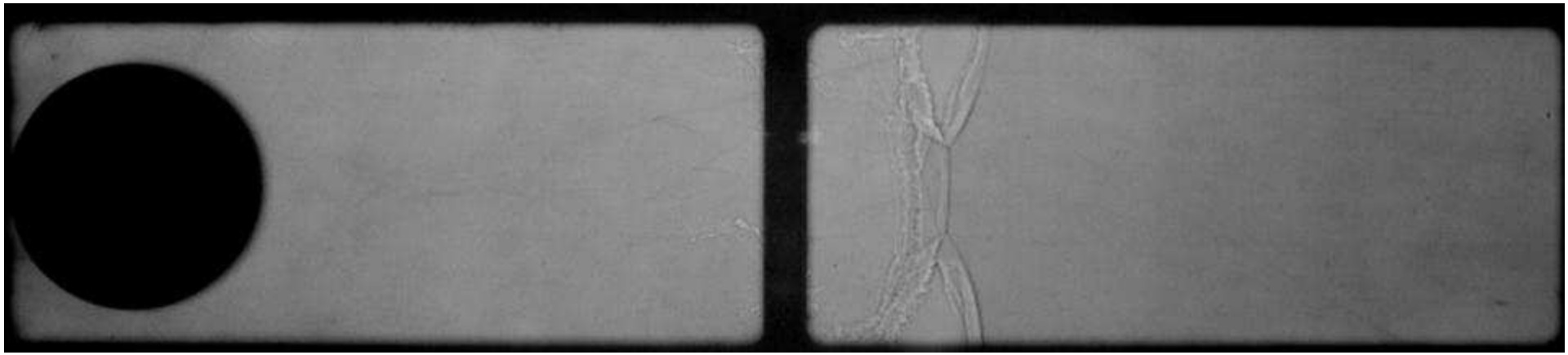
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



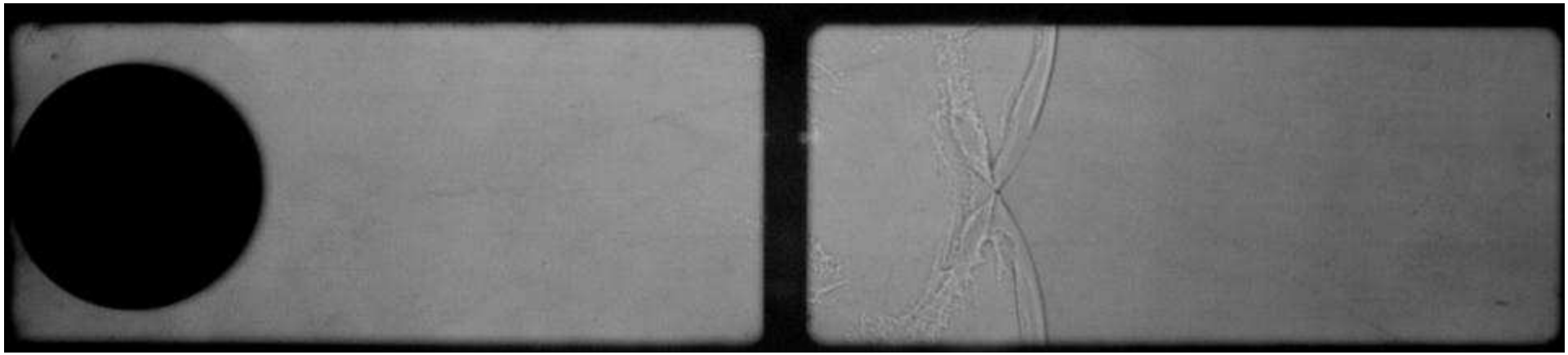
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



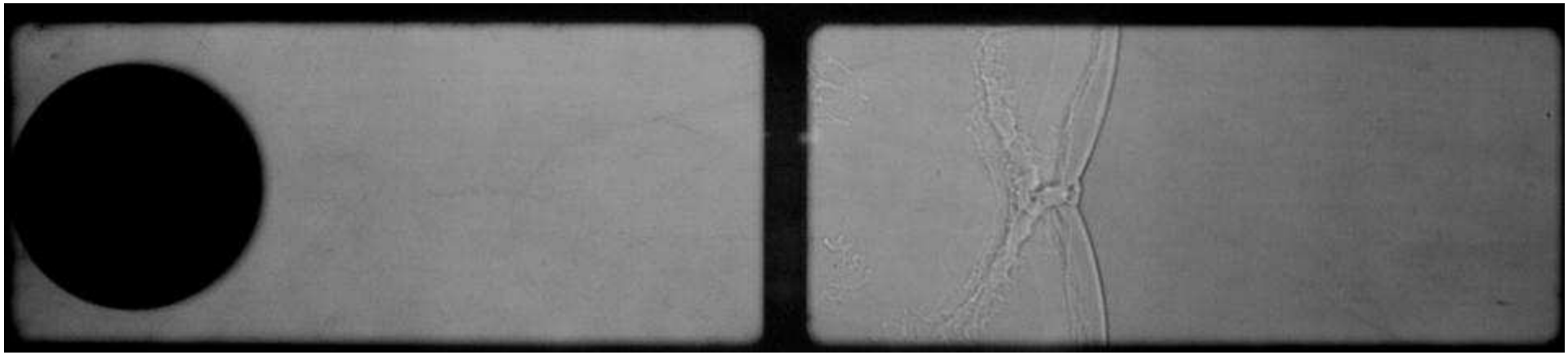
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



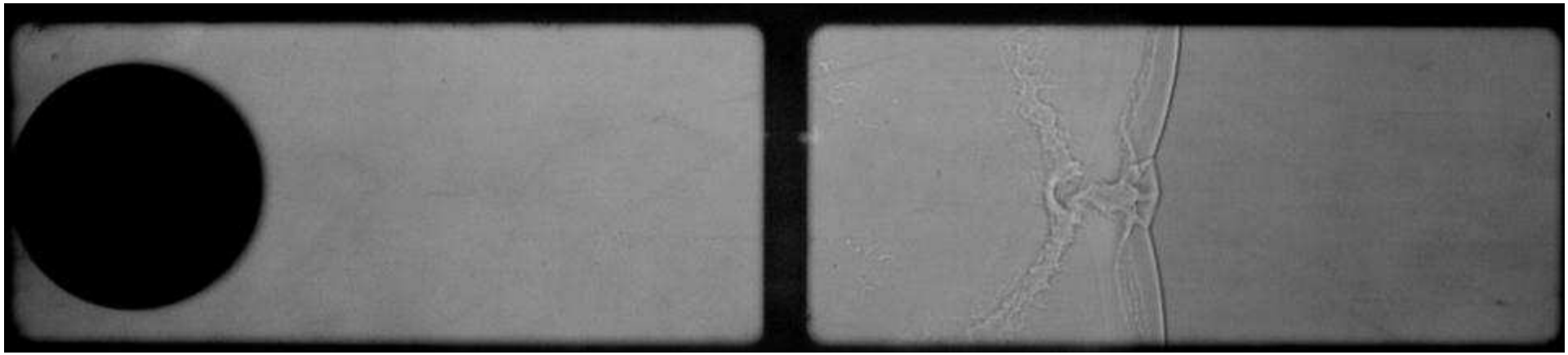
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



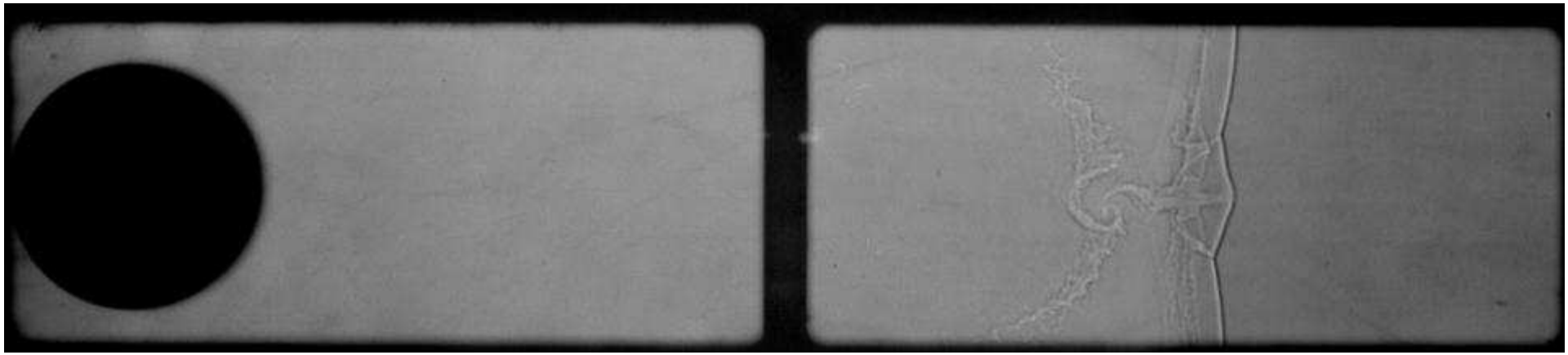
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



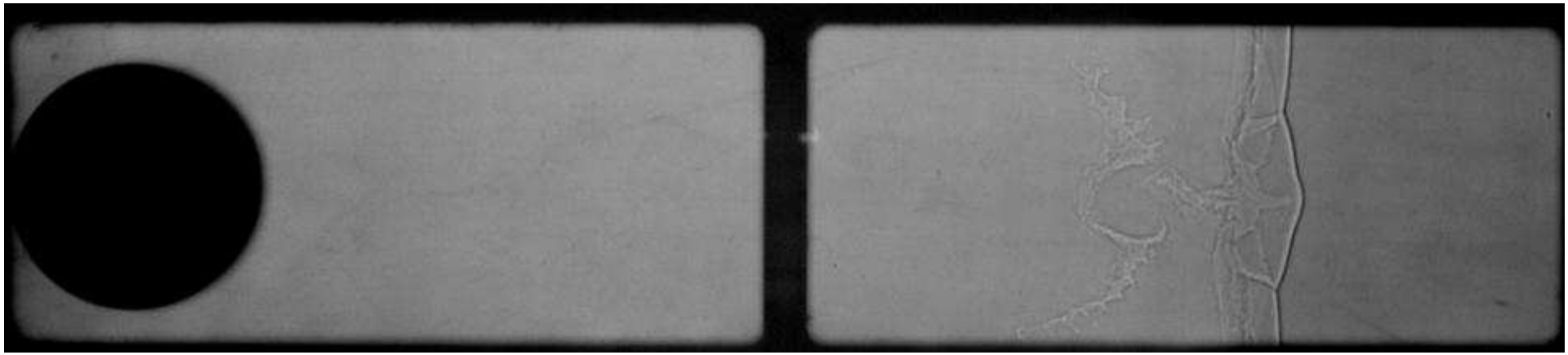
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



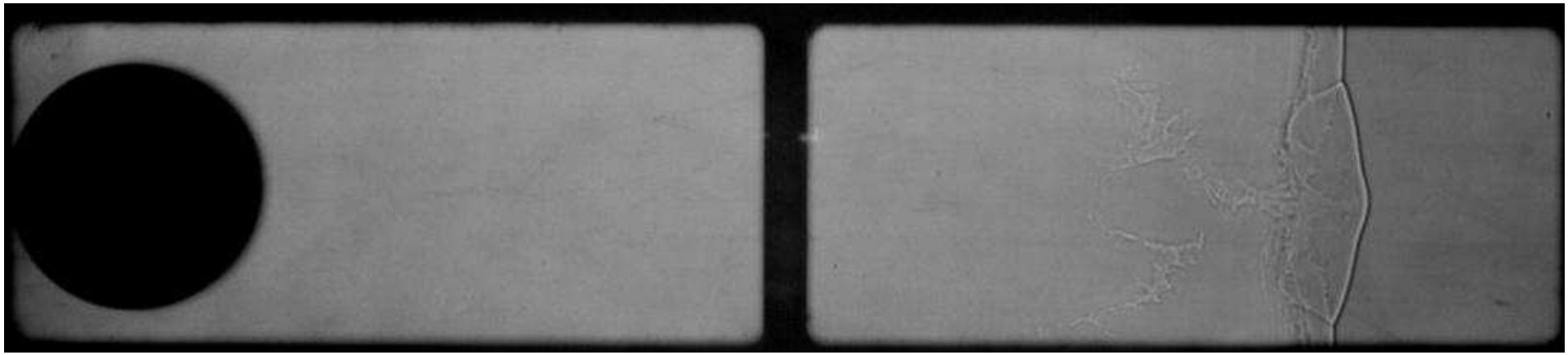
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



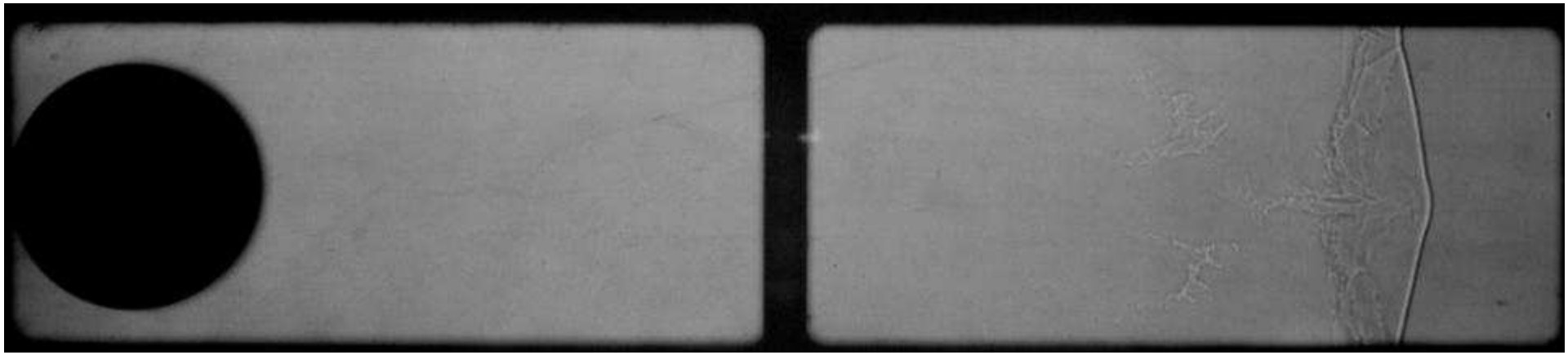
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



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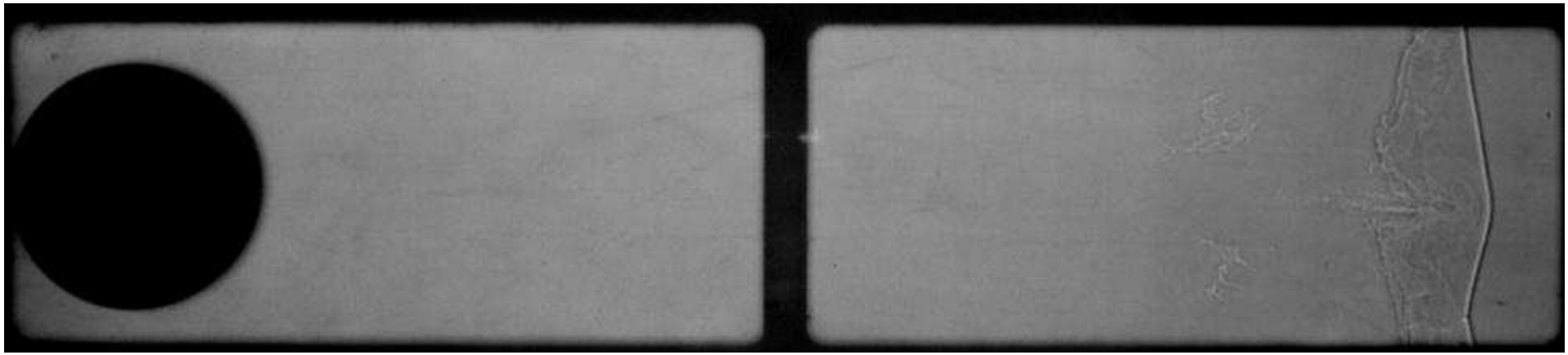
Fast Flame Amplification



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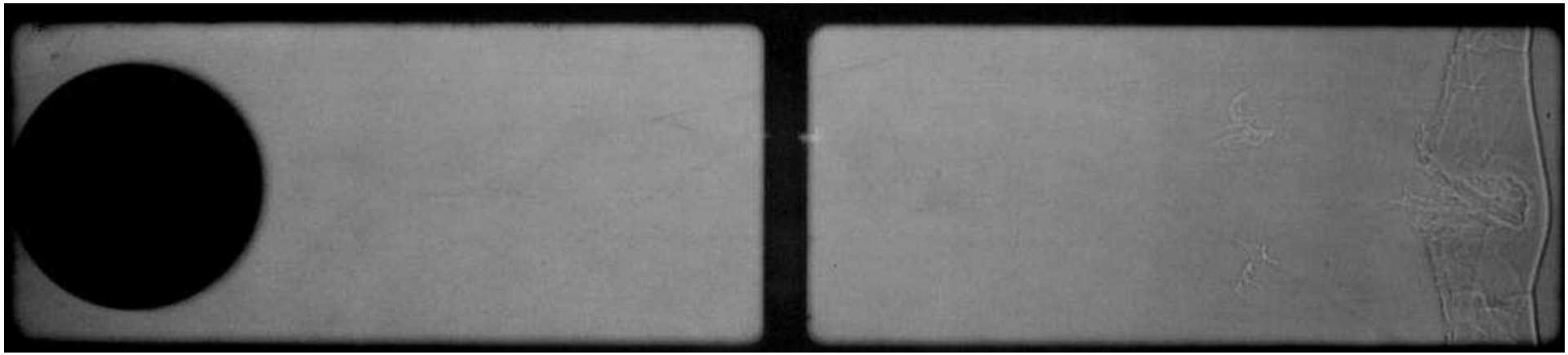
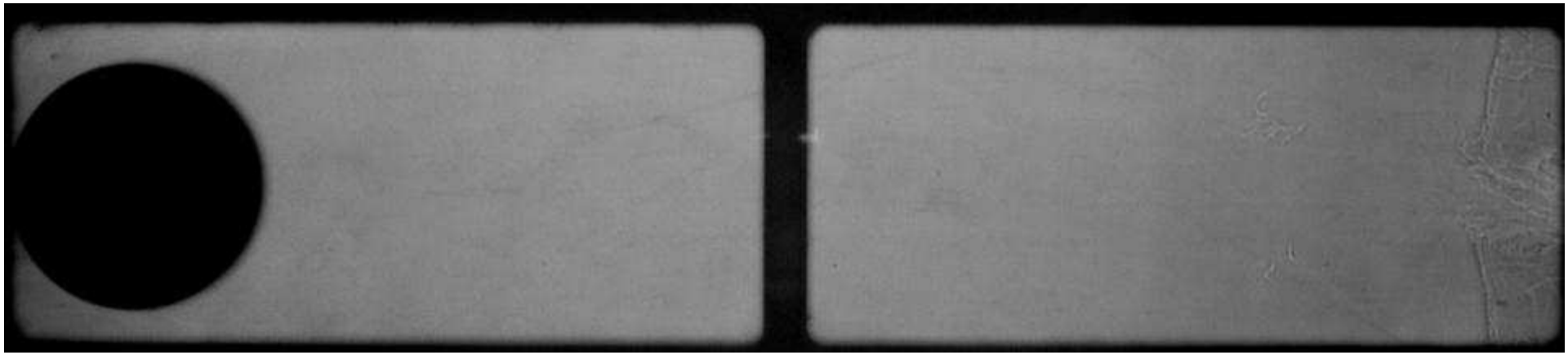
Fast Flame Amplification



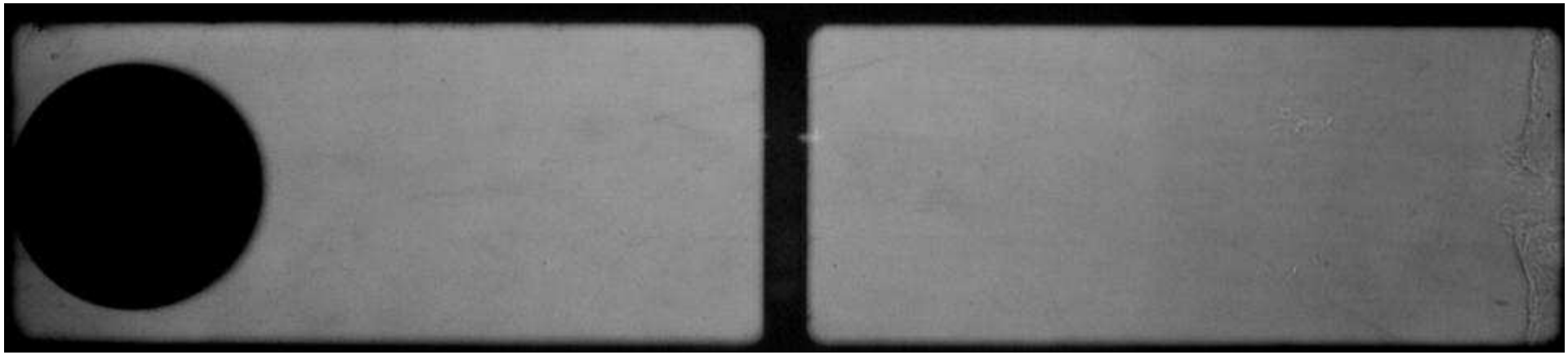
$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



$CH_4 + 2O_2$ P_o = 8.5kPa

Fast Flame Amplification



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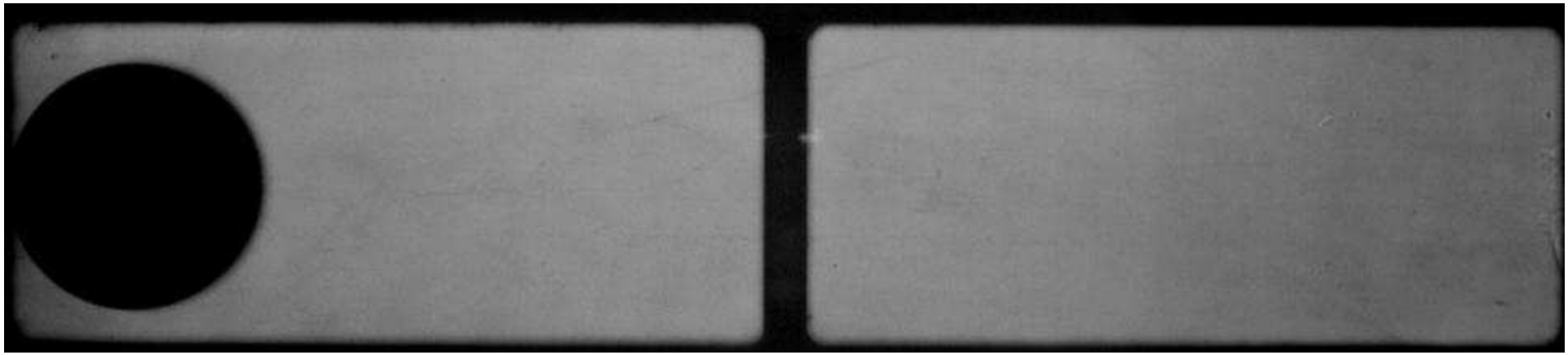
Fast Flame Amplification



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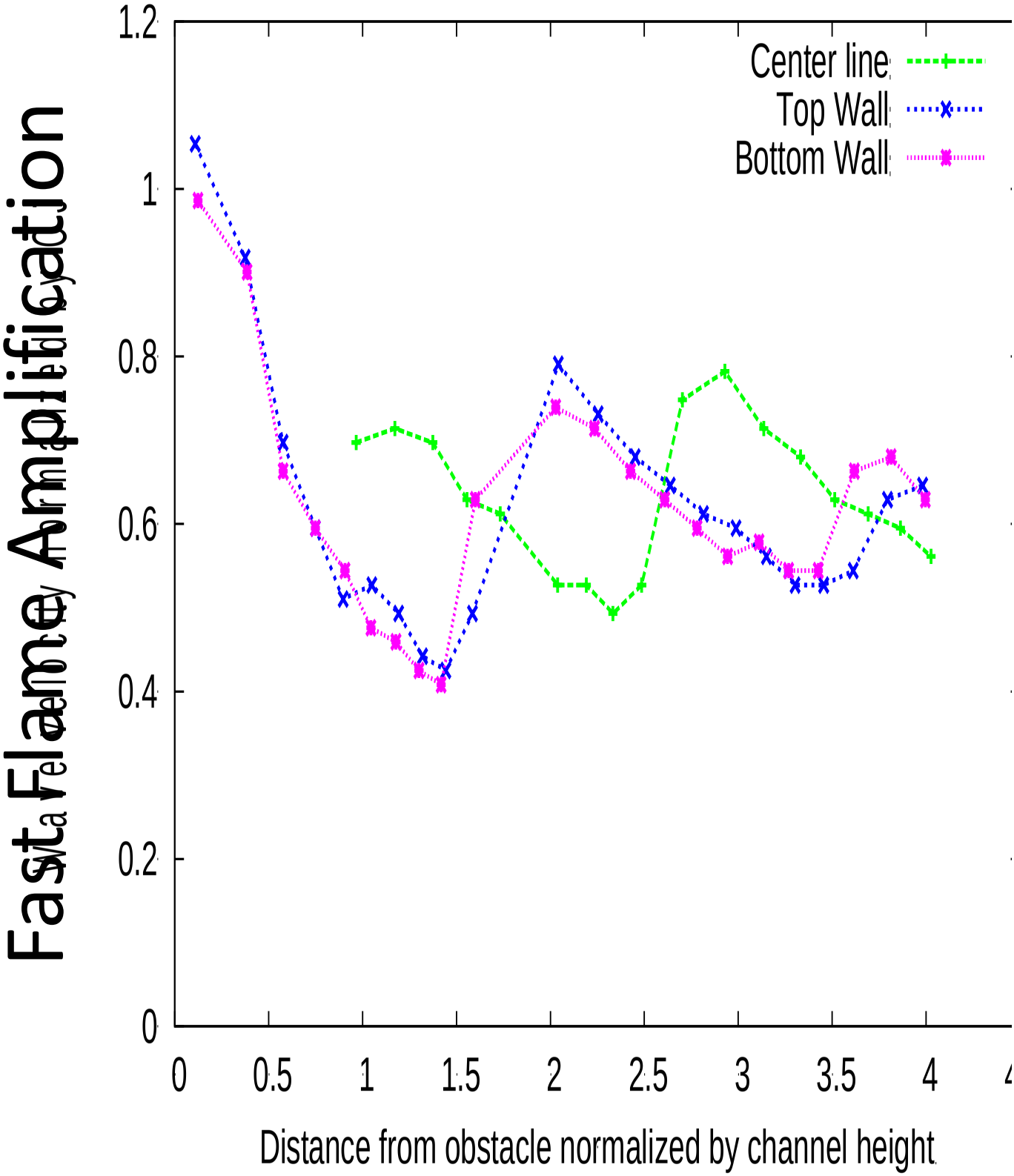
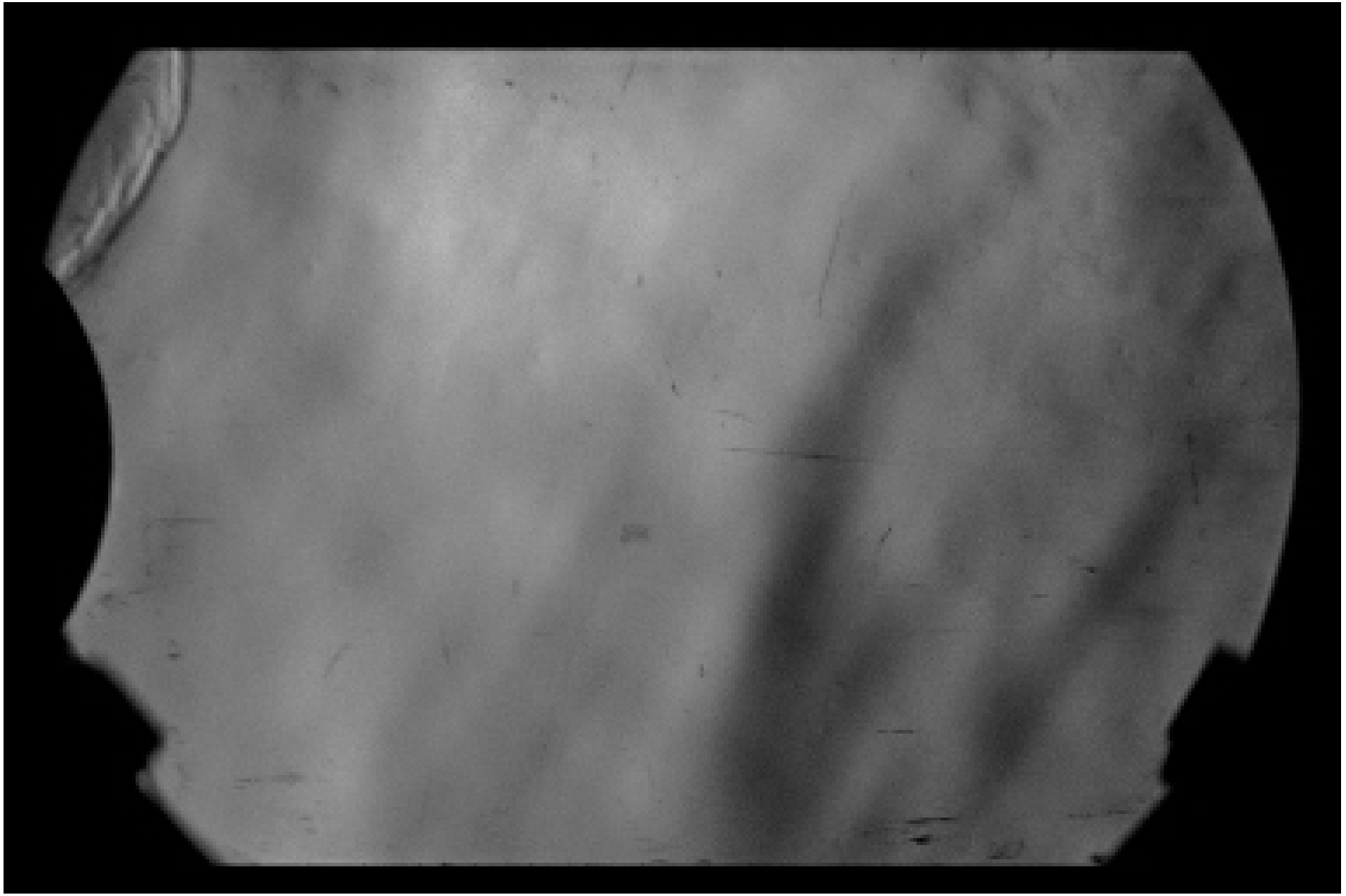
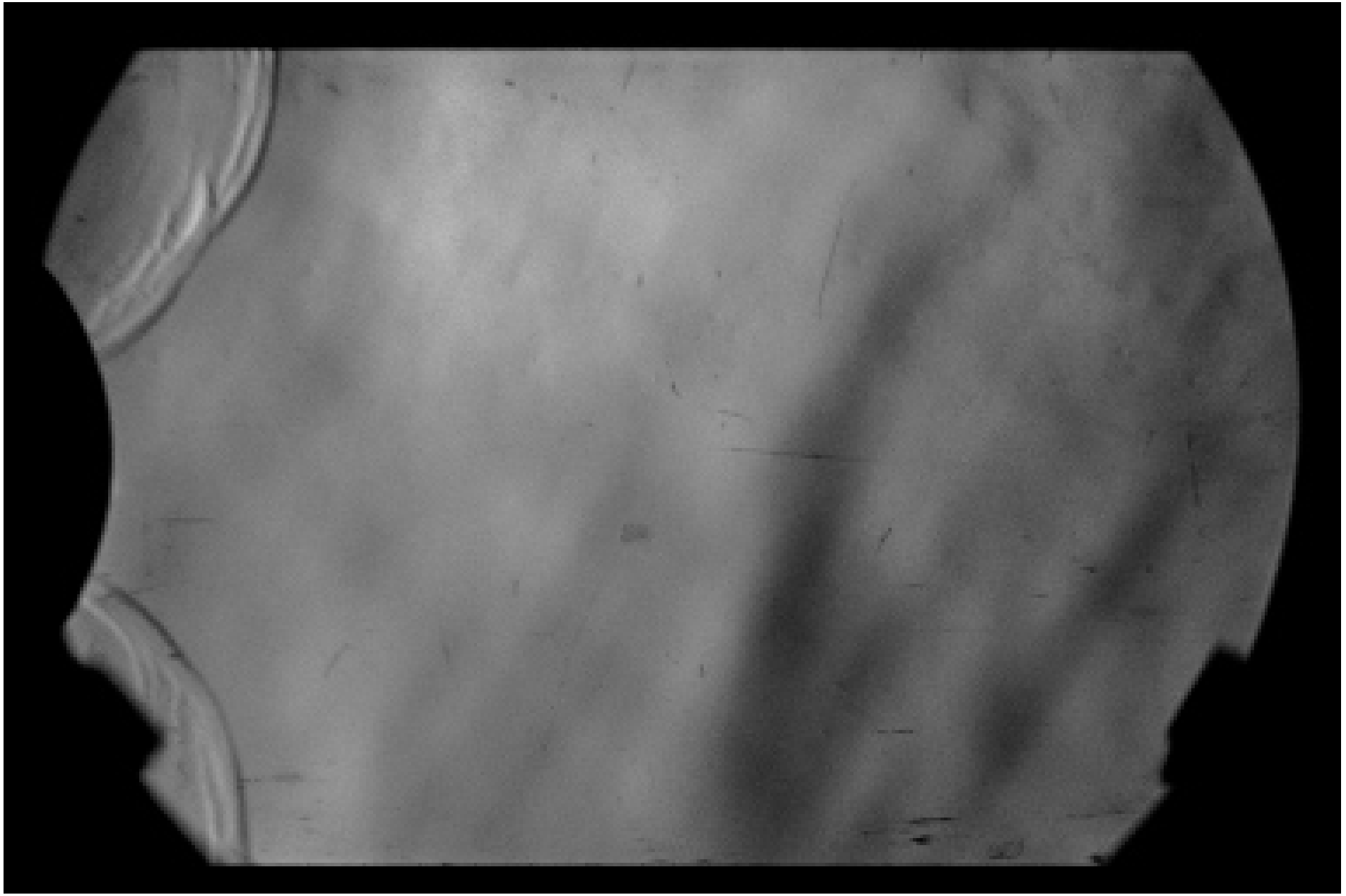

Fast Flame Amplification
Flame velocity / Laminar velocity
Distance from obstacle normalized by channel height
Center line
Top Wall
Bottom Wall
0
0.2
0.4
0.6
0.8
1
1.2
0
0.5
1
1.5
2
2.5
3
3.5
4

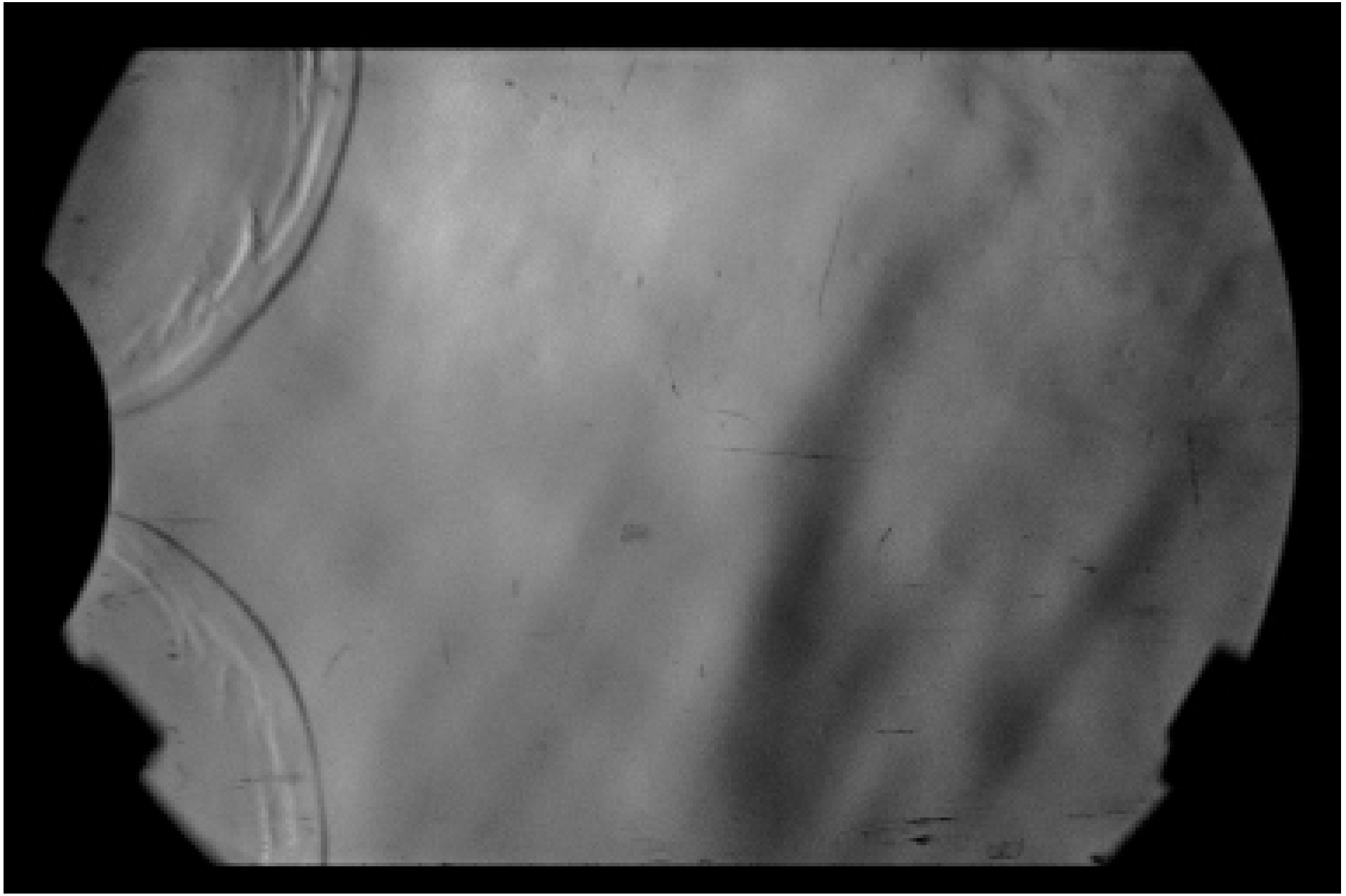
Oxy-Hydrogen



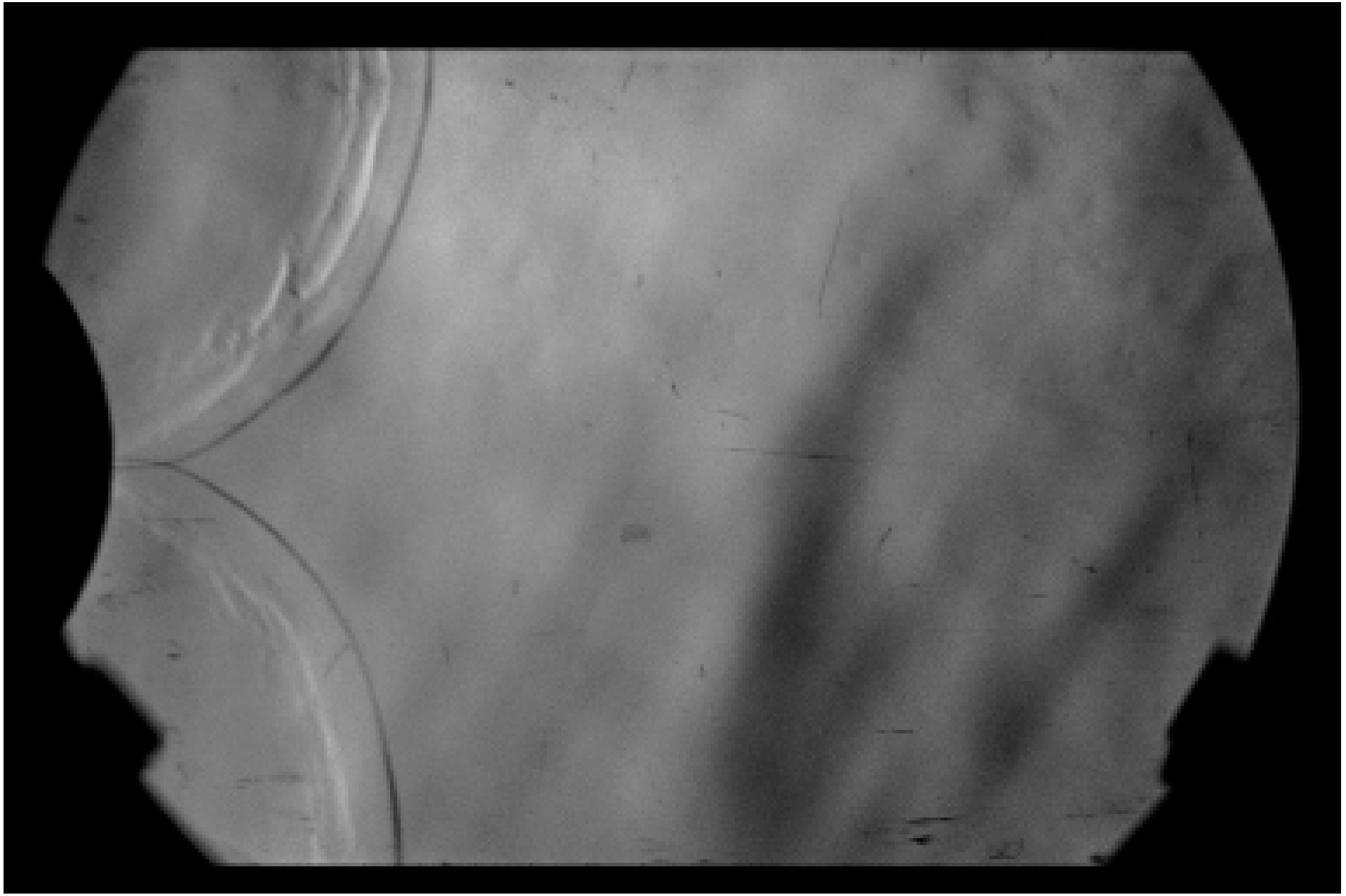
Oxy-Hydrogen



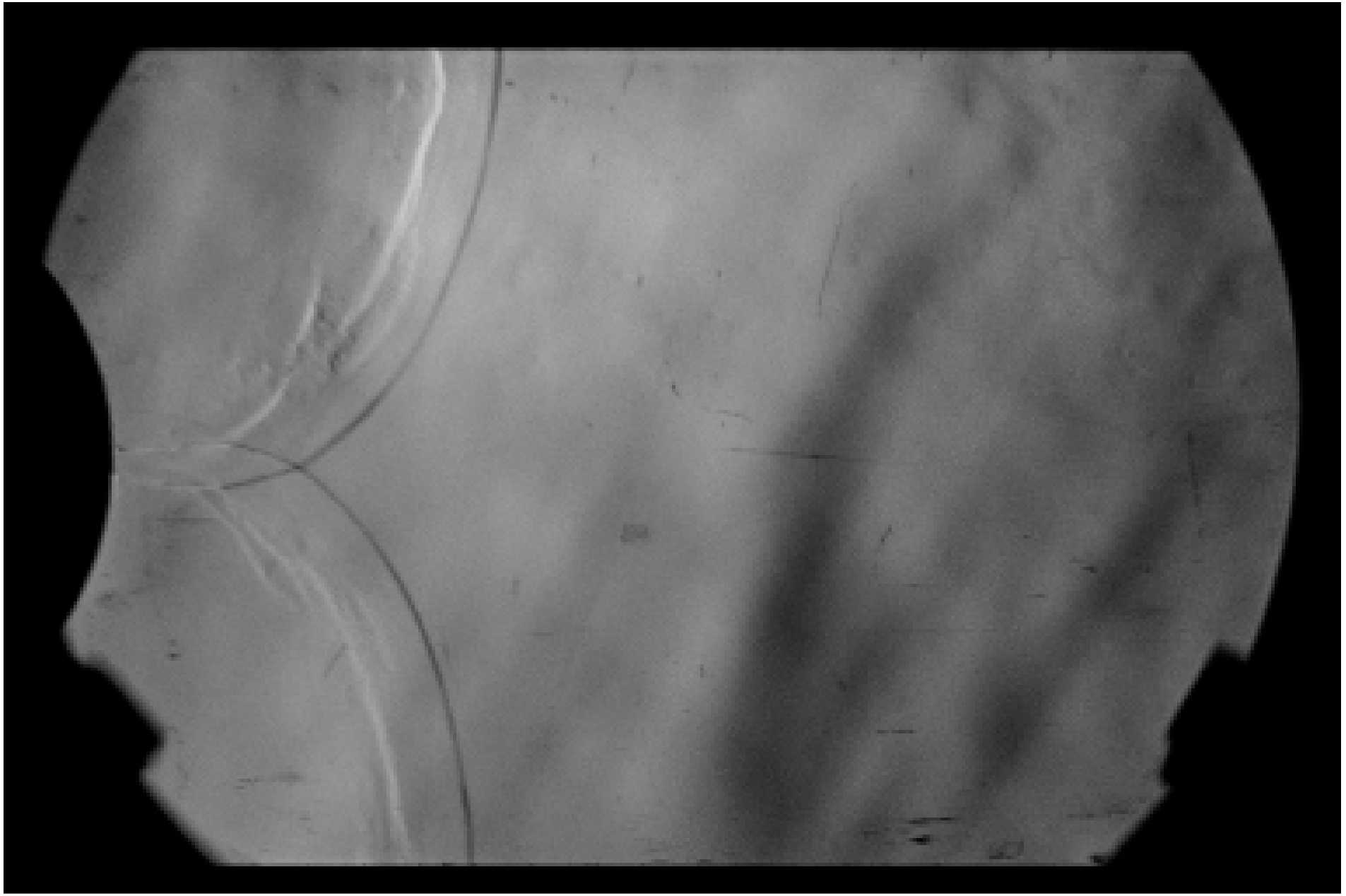
Oxy-Hydrogen



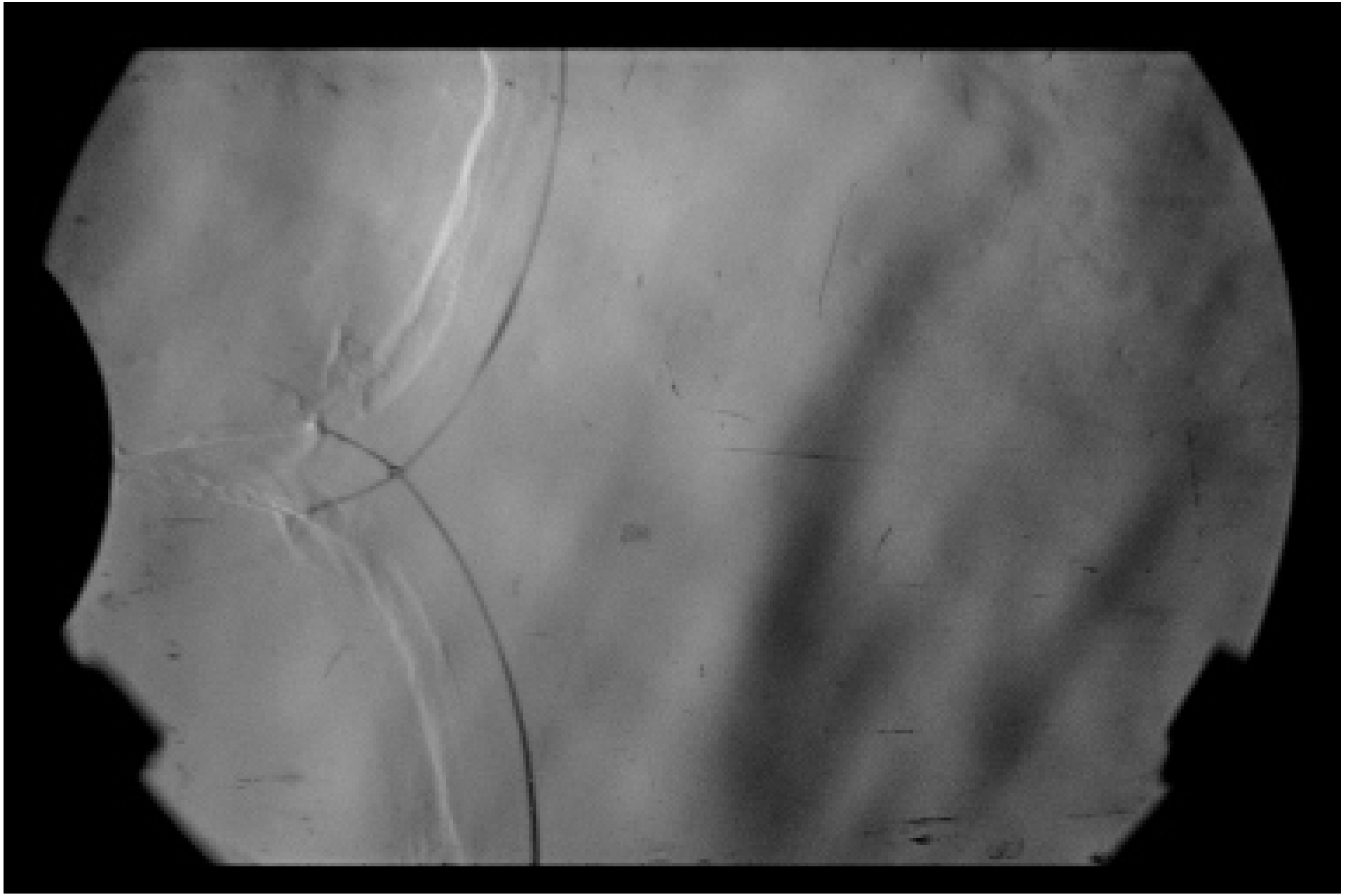
Oxy-Hydrogen



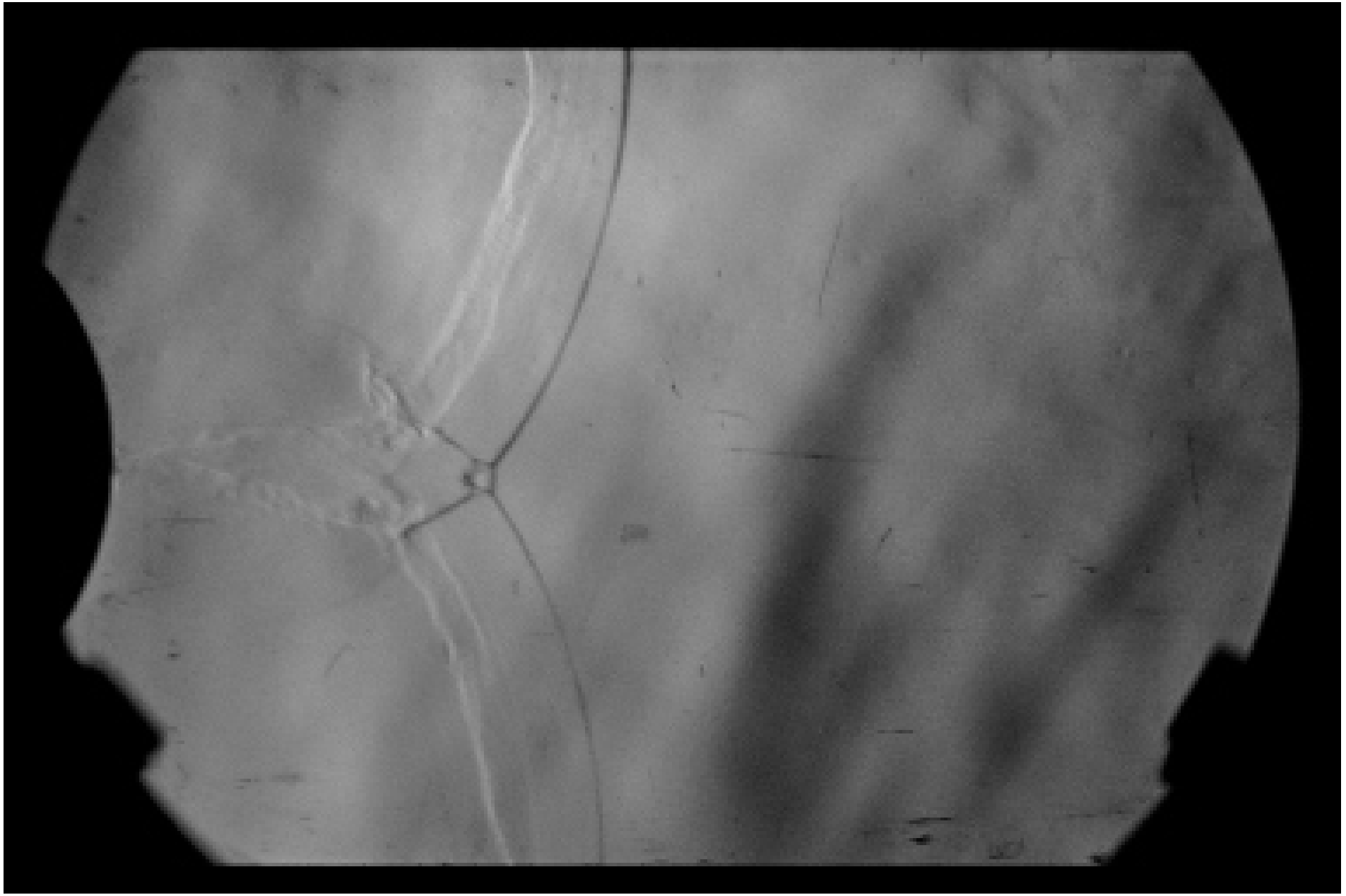
Oxy-Hydrogen



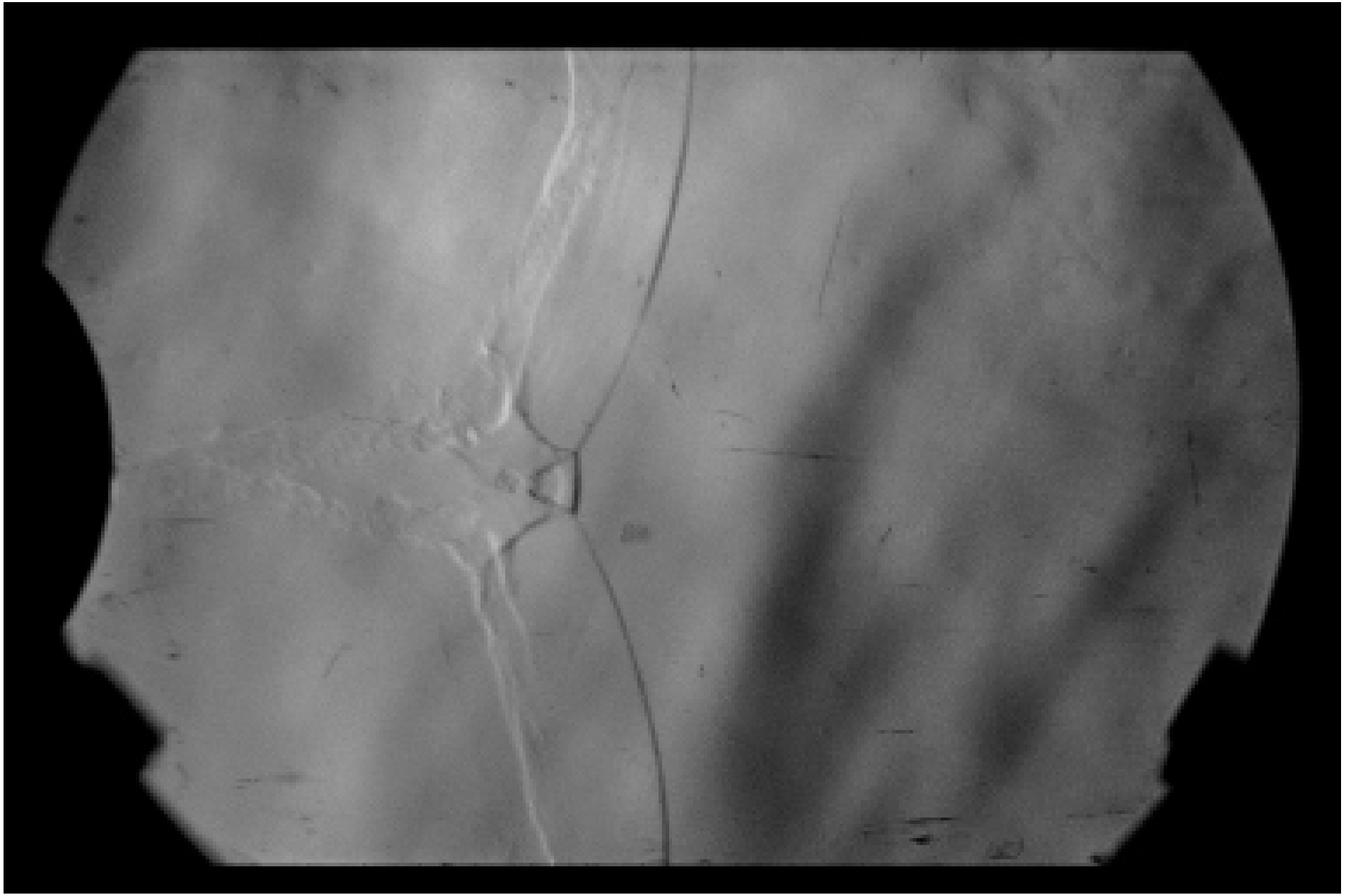
Oxy-Hydrogen



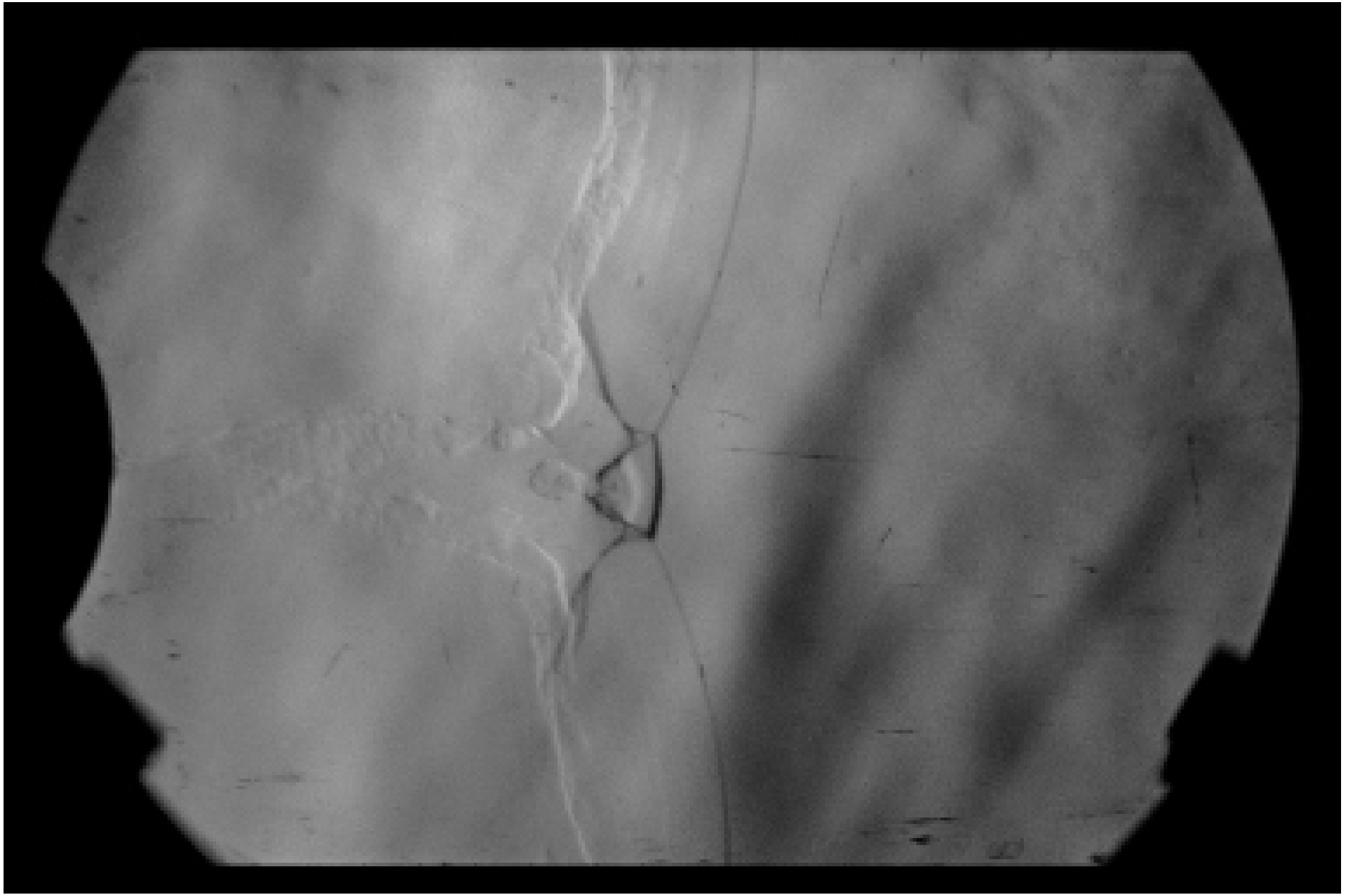
Oxy-Hydrogen



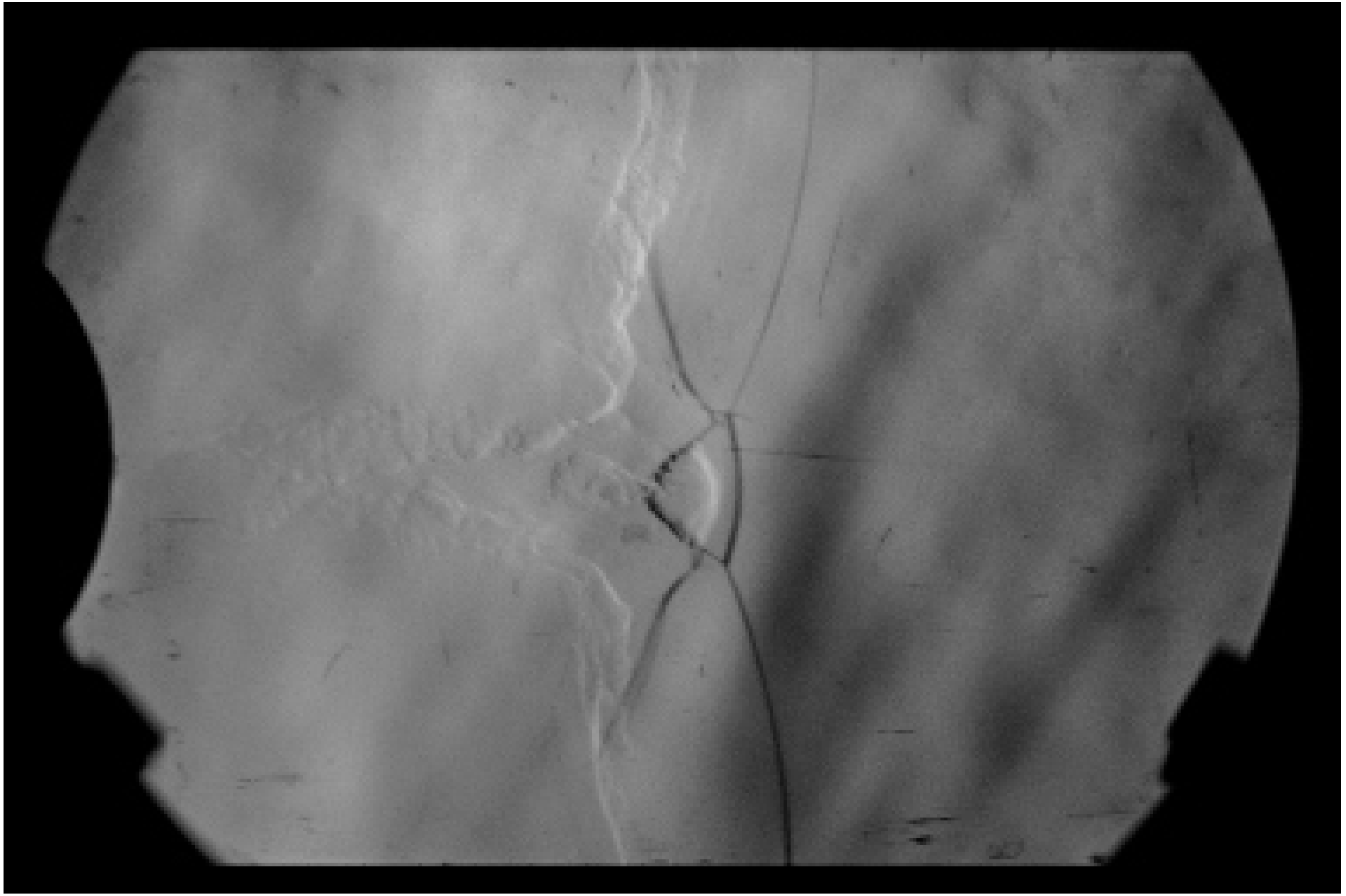
Oxy-Hydrogen



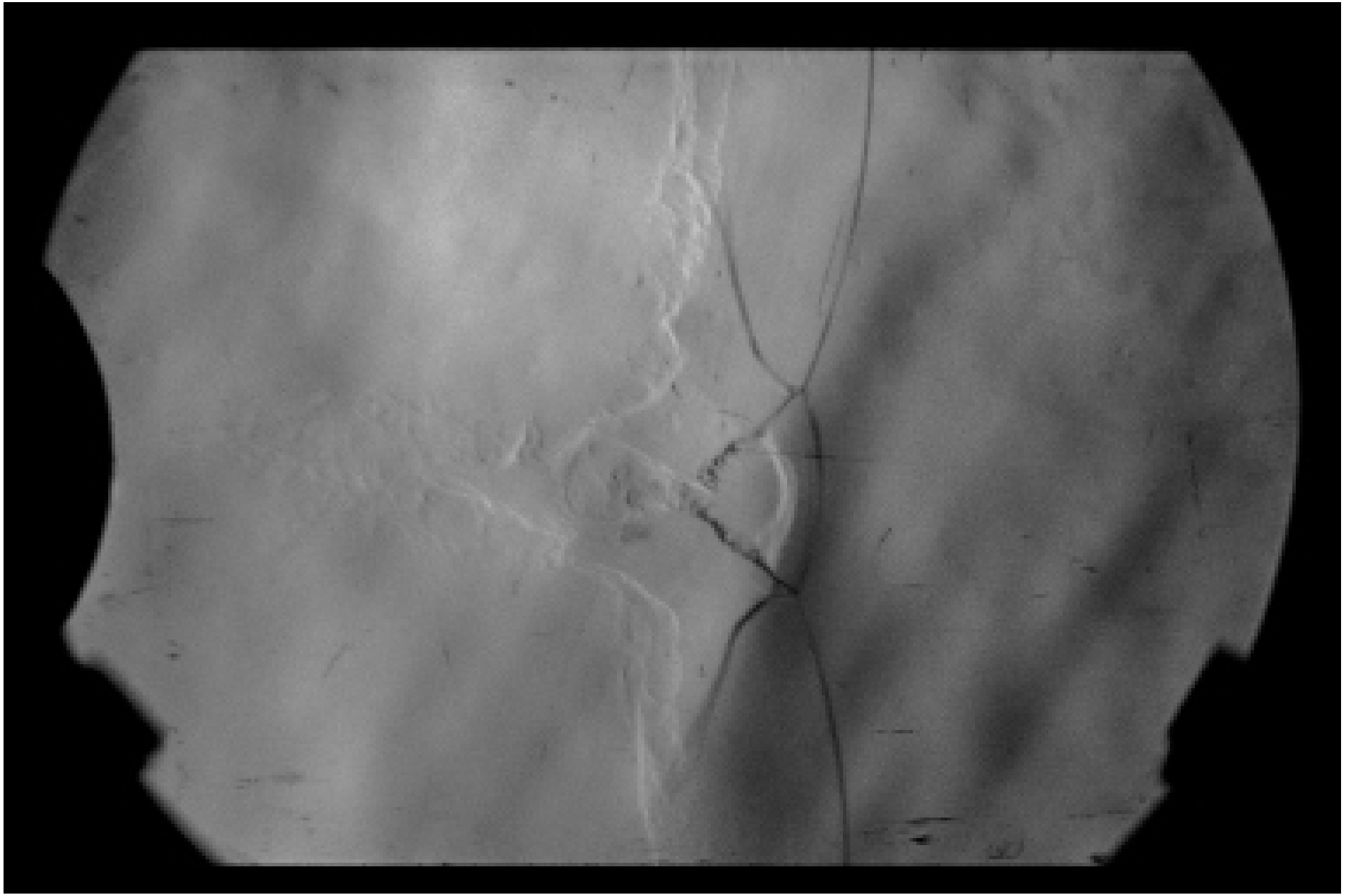
Oxy-Hydrogen



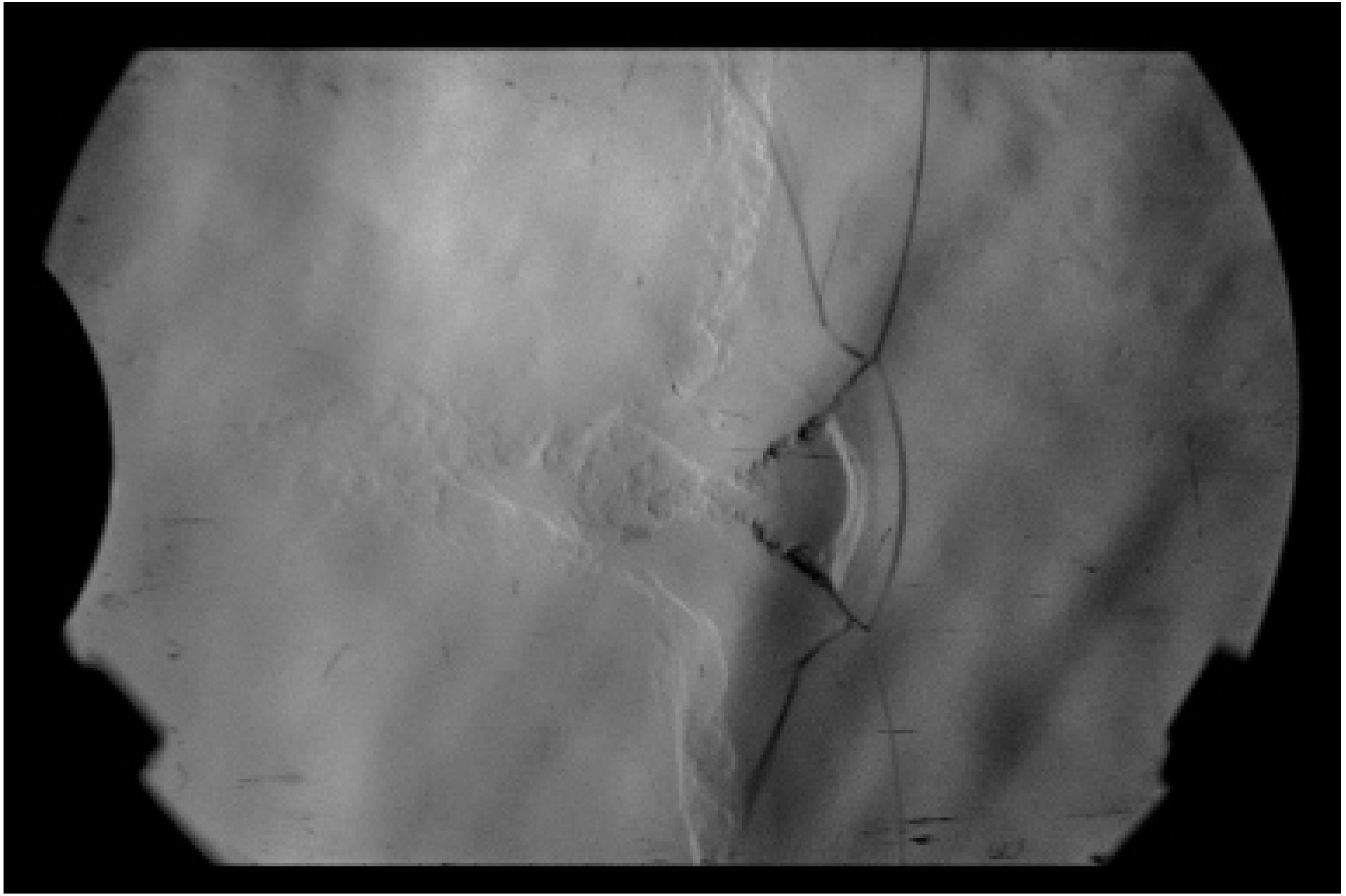
Oxy-Hydrogen



Oxy-Hydrogen



Oxy-Hydrogen



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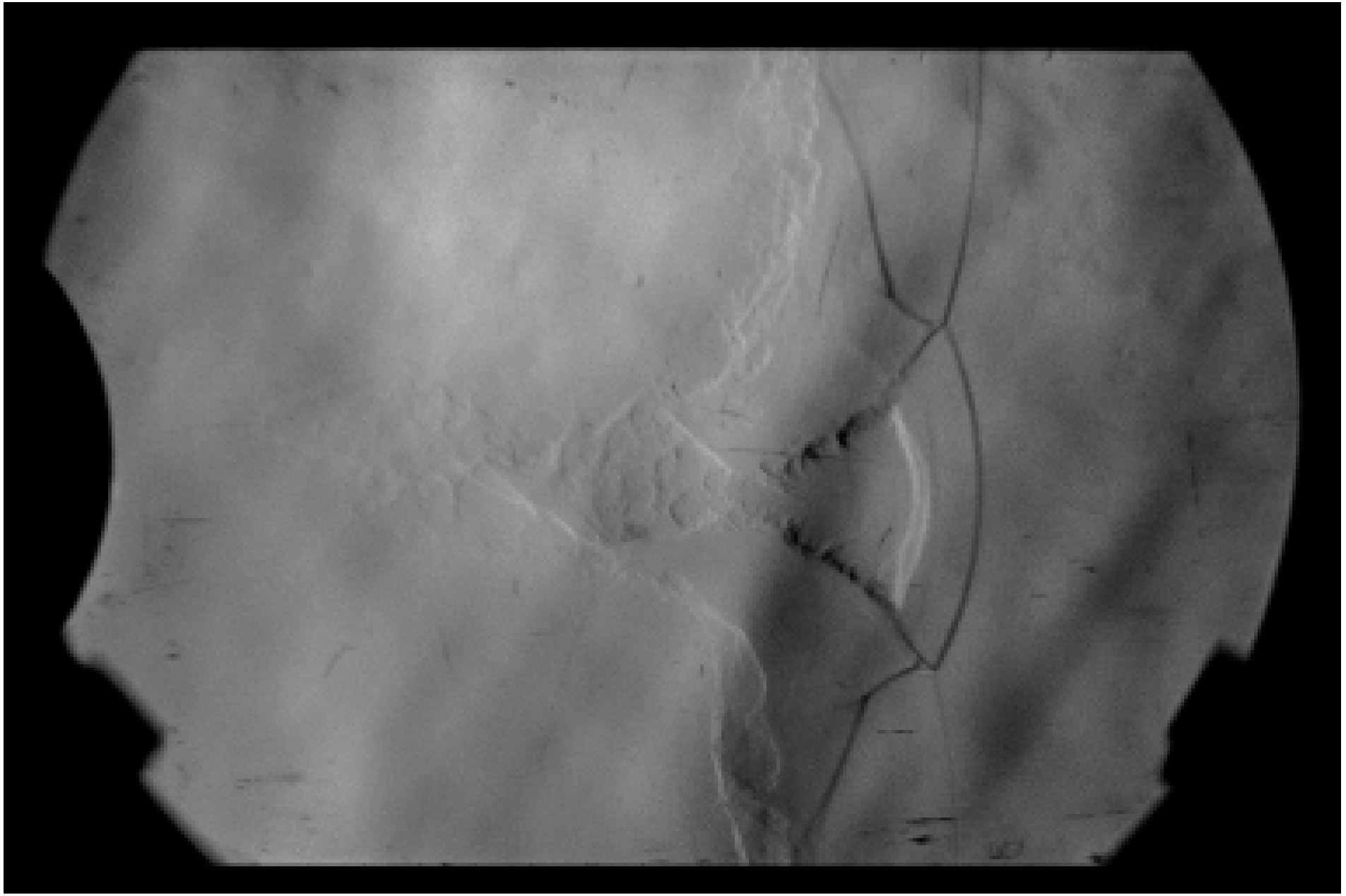

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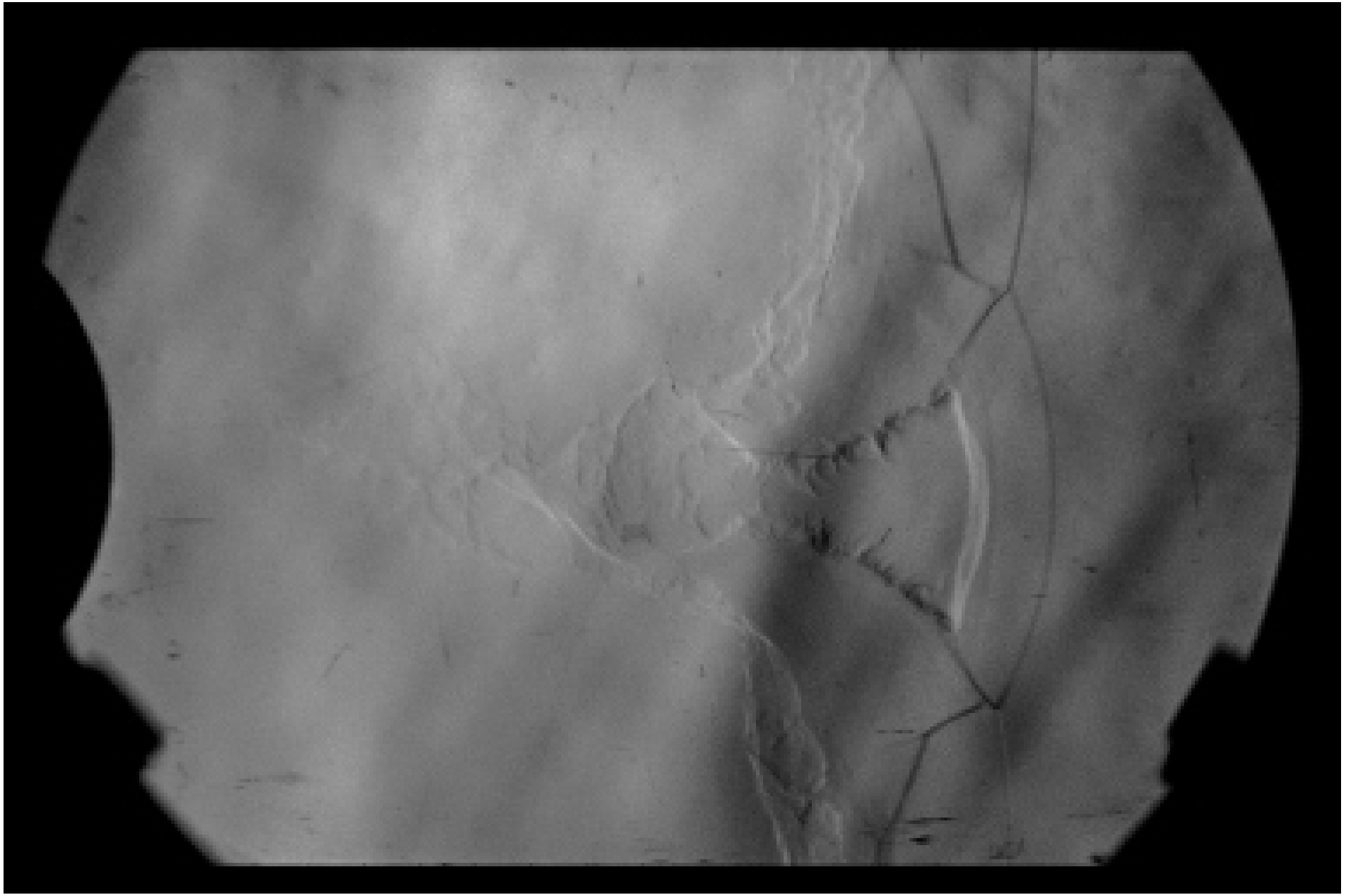

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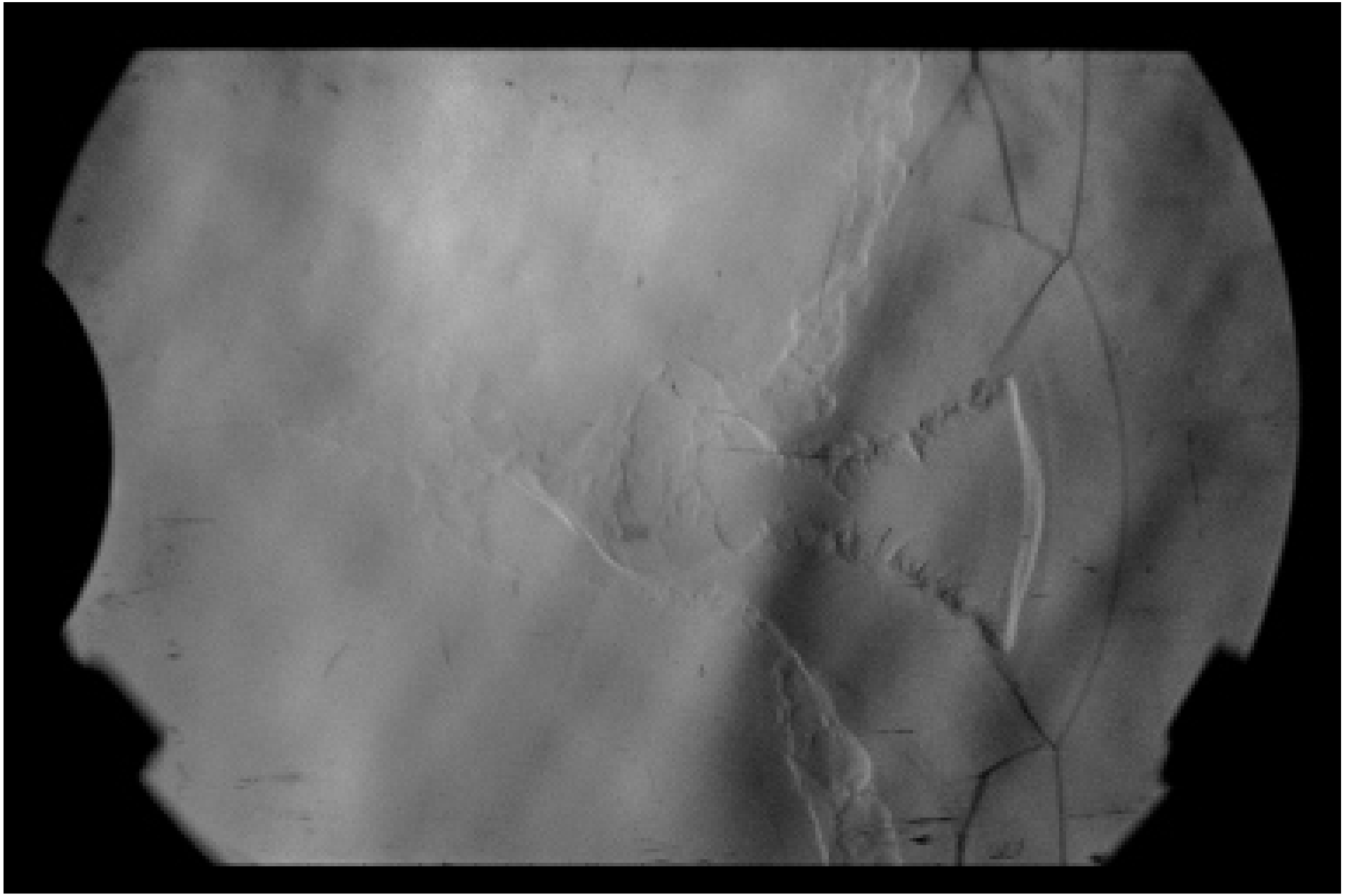

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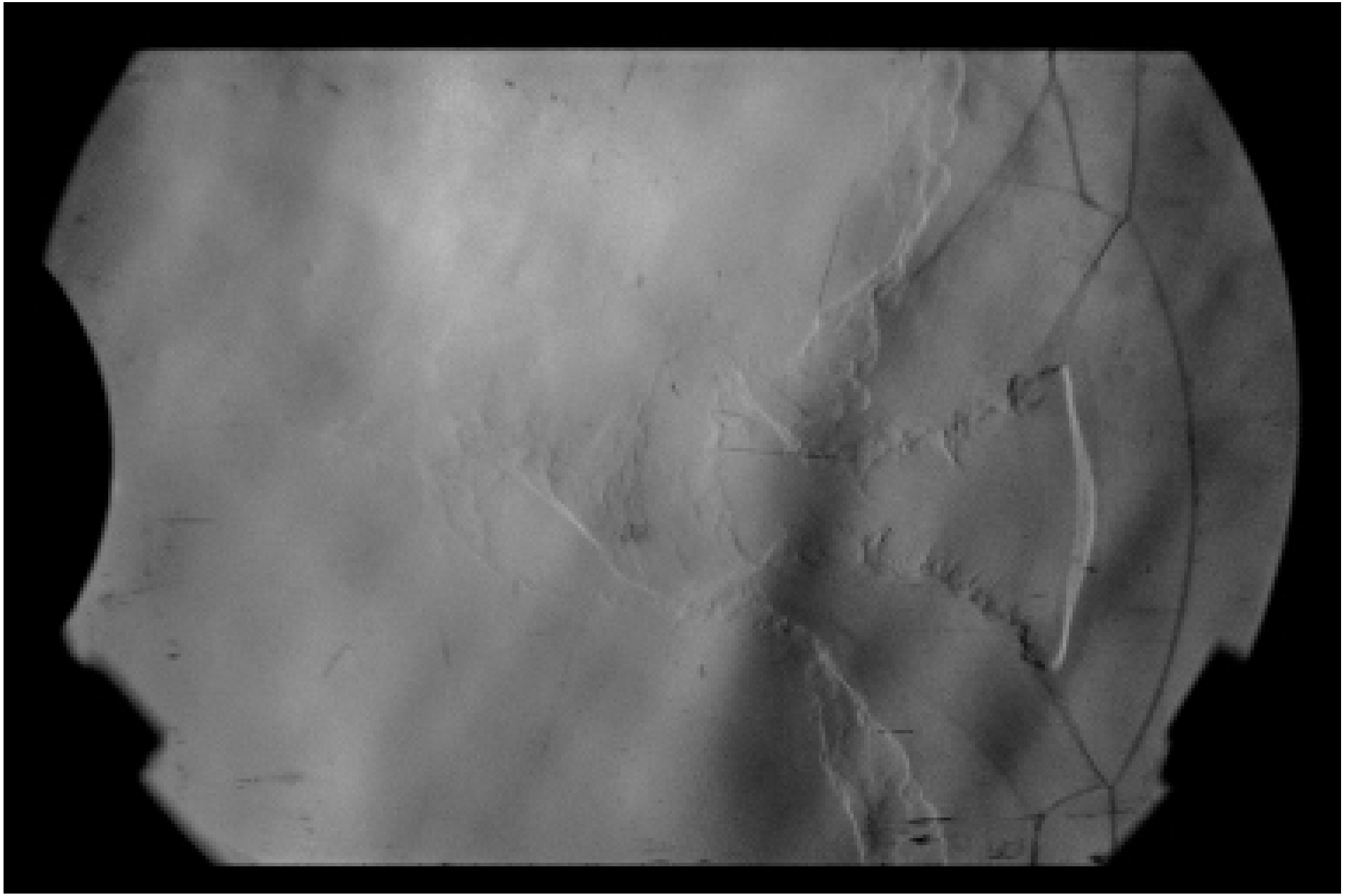

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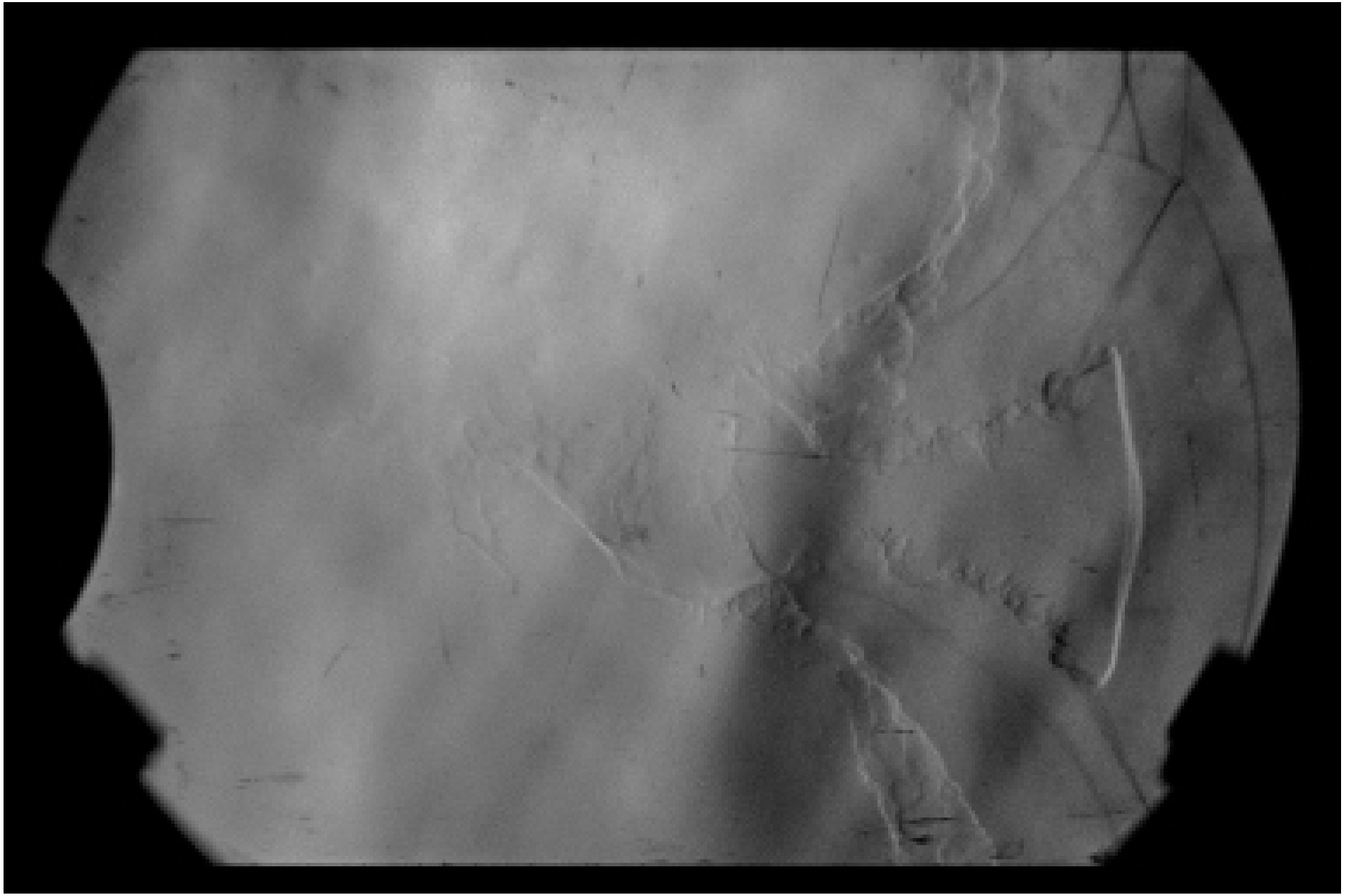

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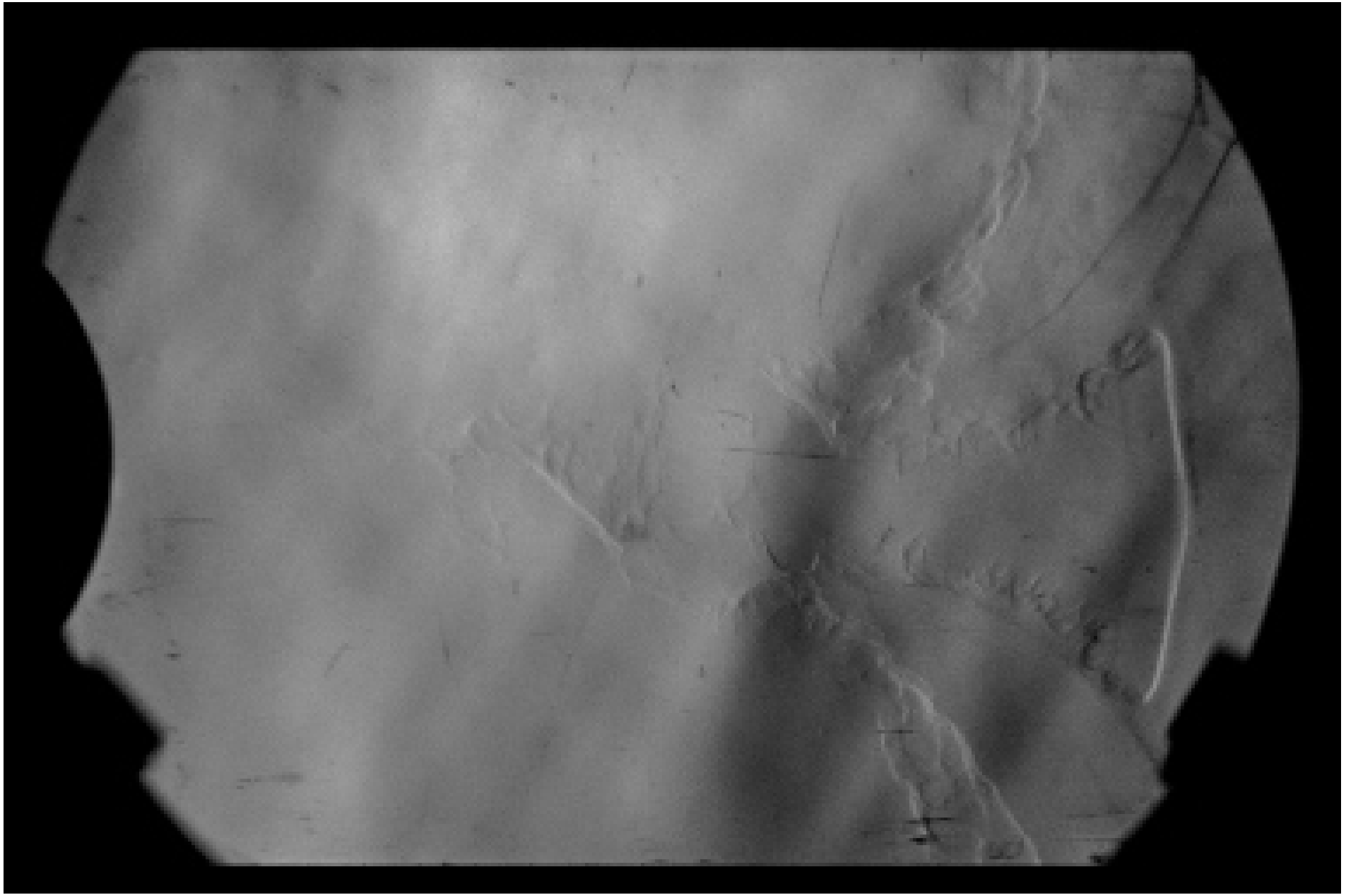

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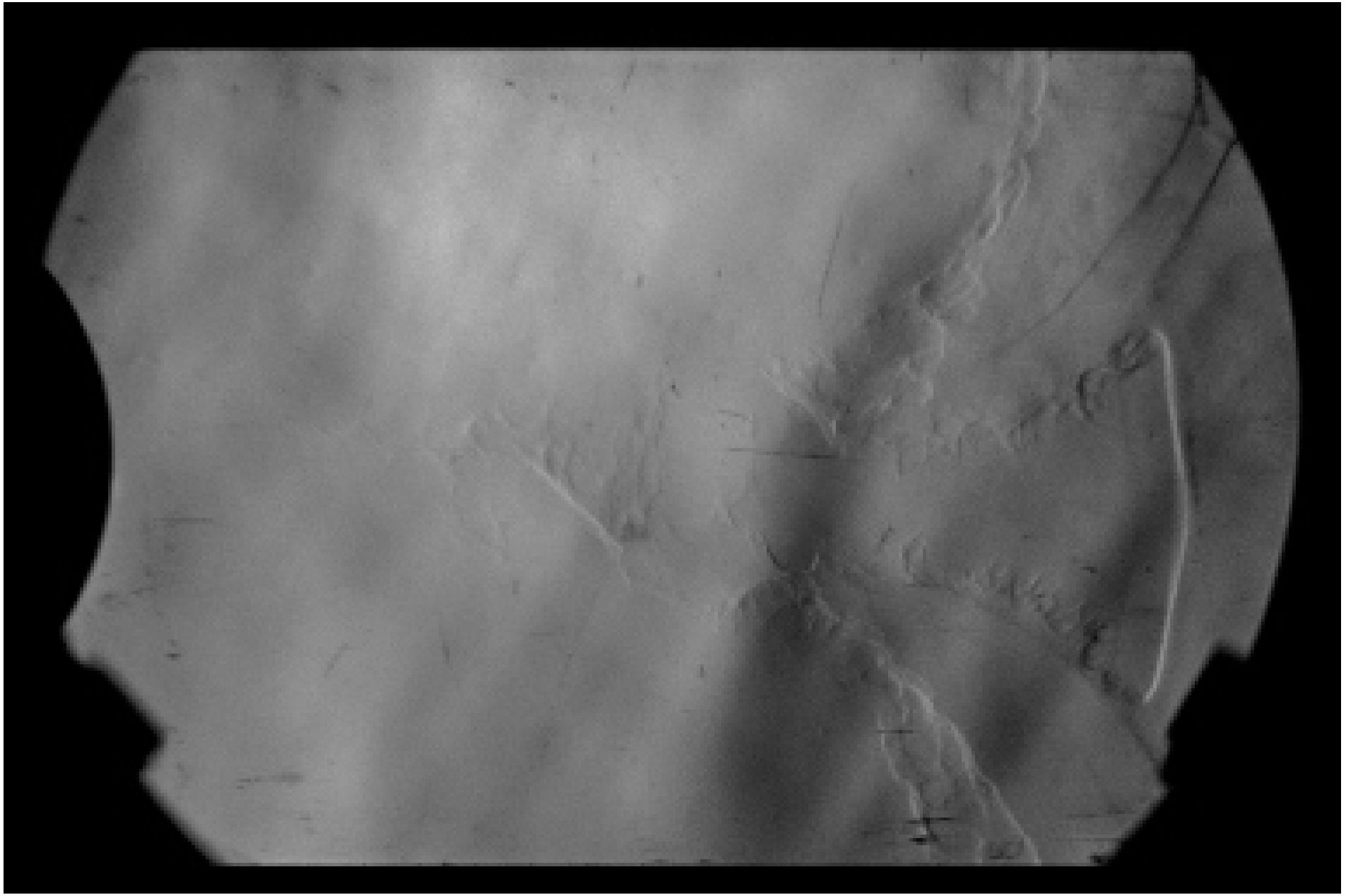

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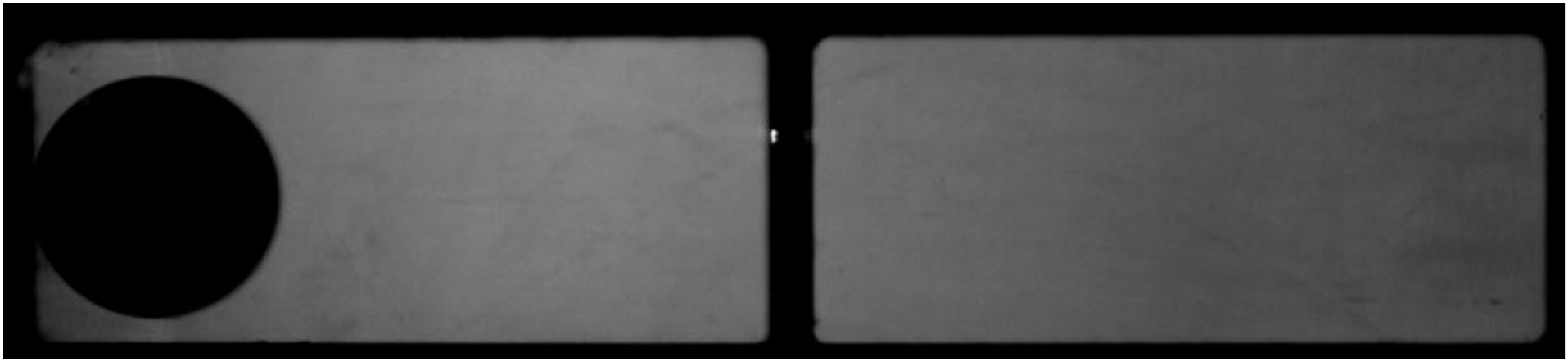
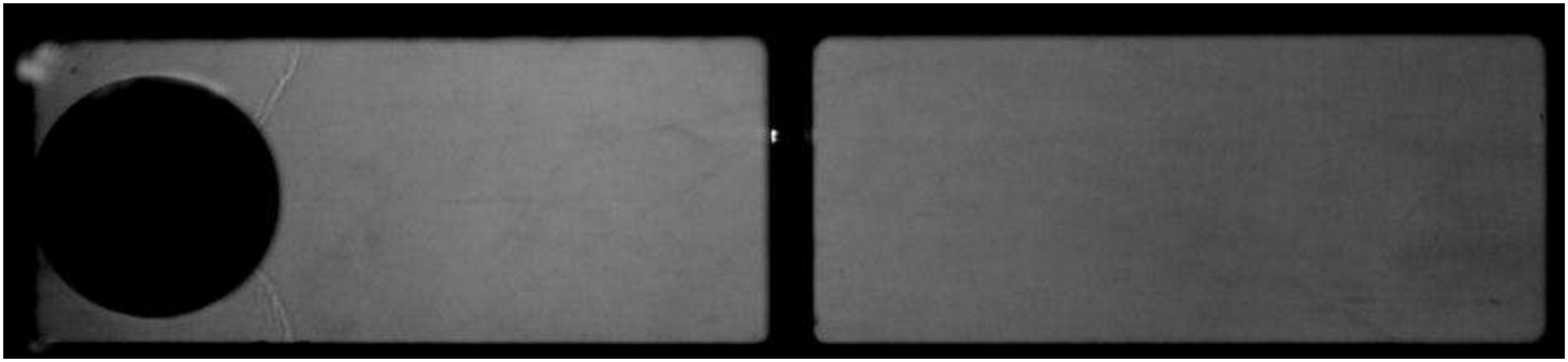


$2H_2 + O_2$ Po = 13.8kPa

Oxy-Hydrogen



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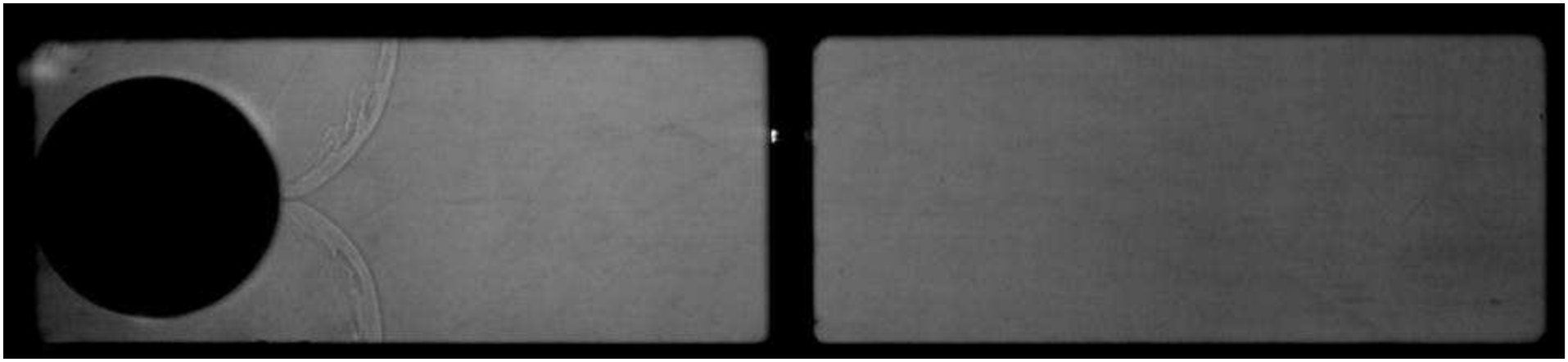

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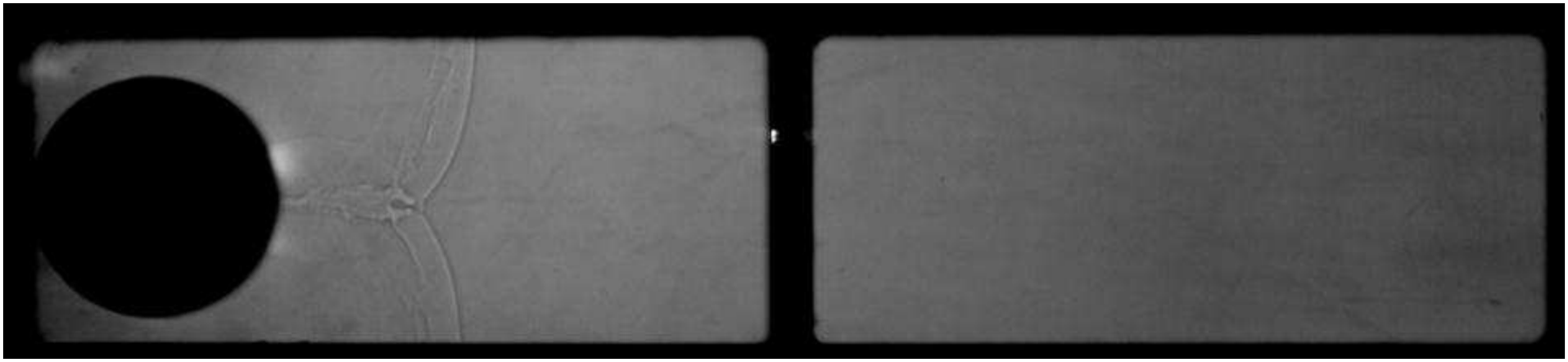
Oxy-Hydrogen



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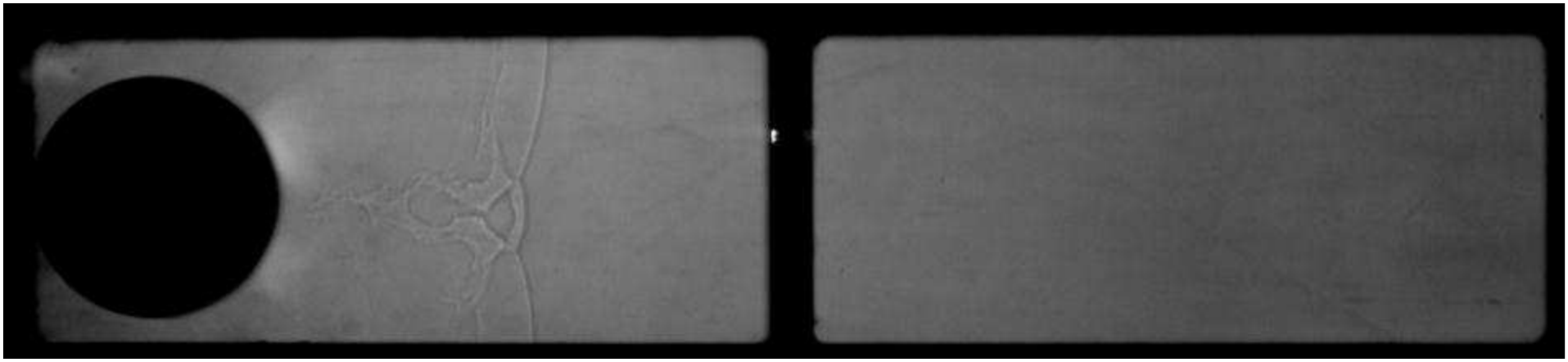
Oxy-Hydrogen



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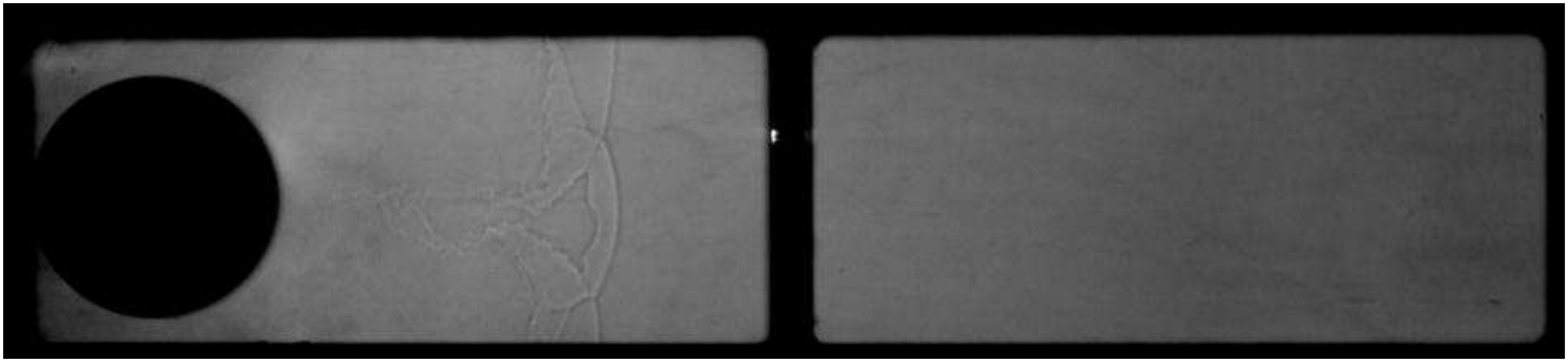
Oxy-Hydrogen



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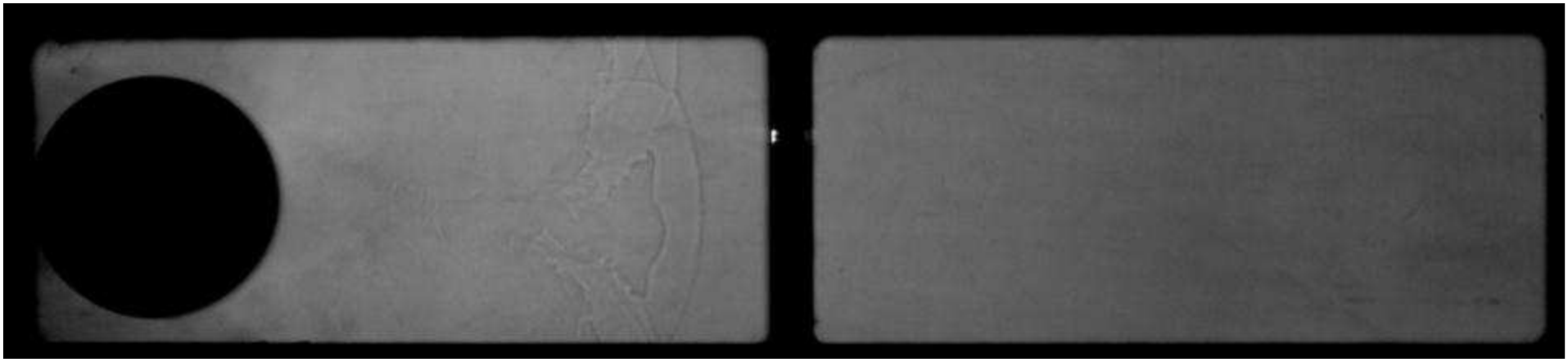
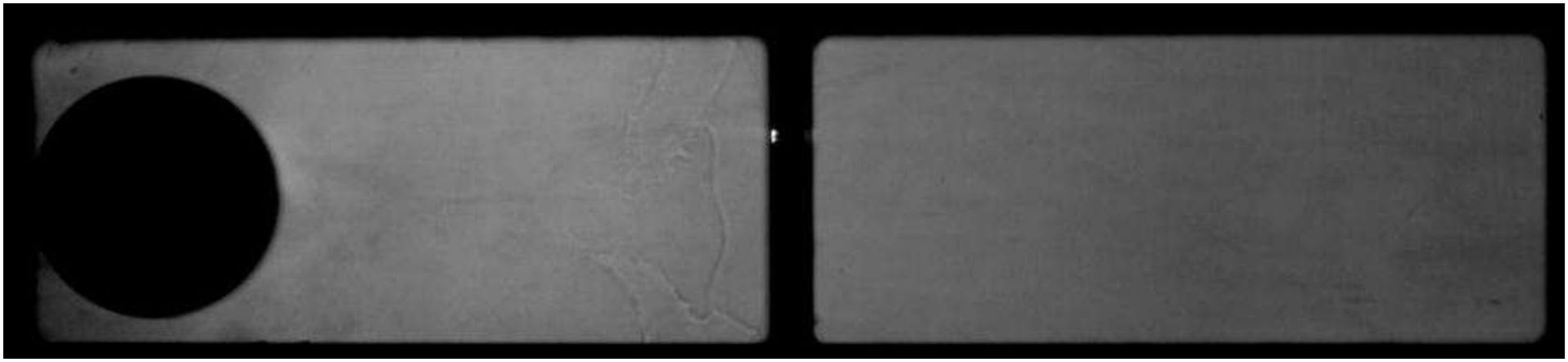
Oxy-Hydrogen



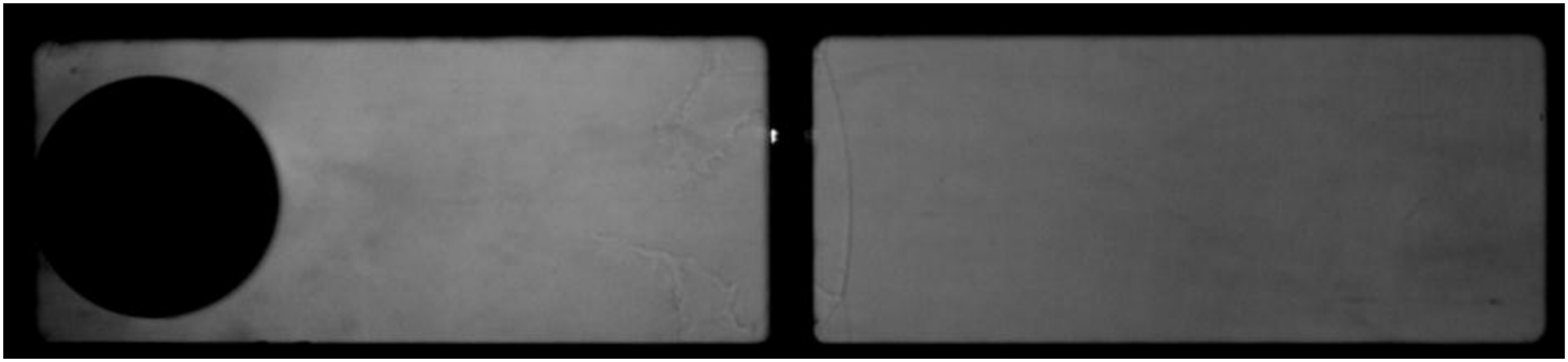
$2H_2 + O_2$ Po = 13.8kPa

Oxy-Hydrogen



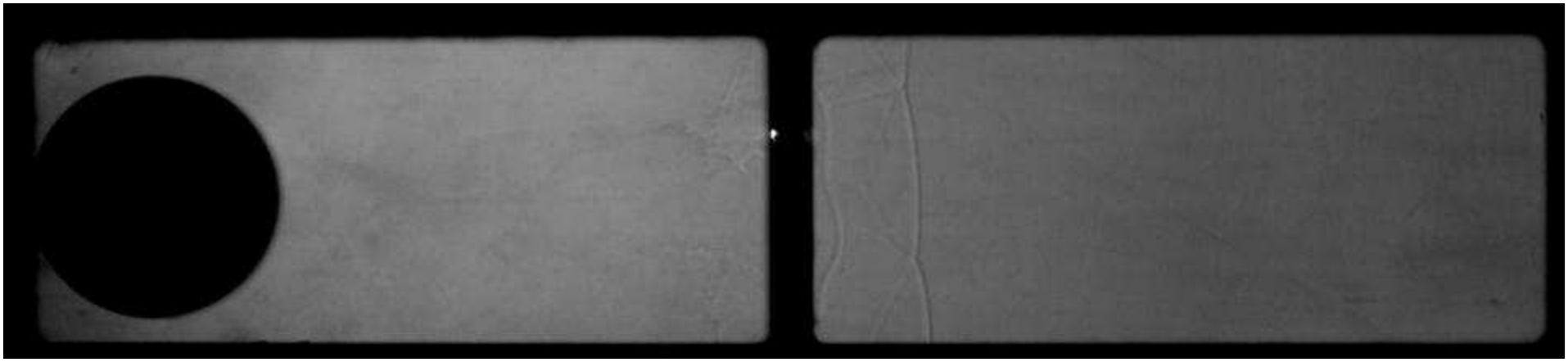
$2H_2 + O_2$ Po = 13.8kPa

Oxy-Hydrogen



$2H_2 + O_2$ Po = 13.8kPa

Oxy-Hydrogen



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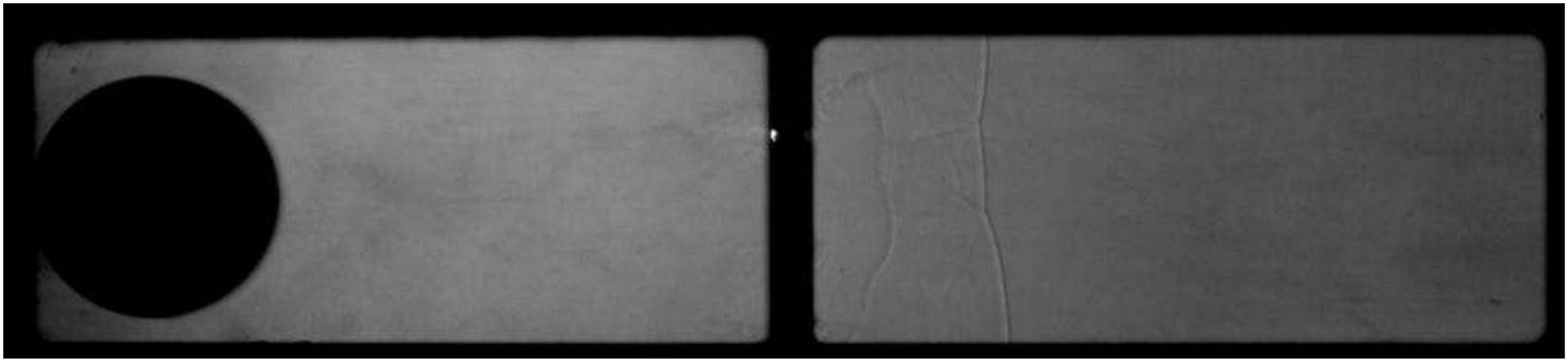
Oxy-Hydrogen



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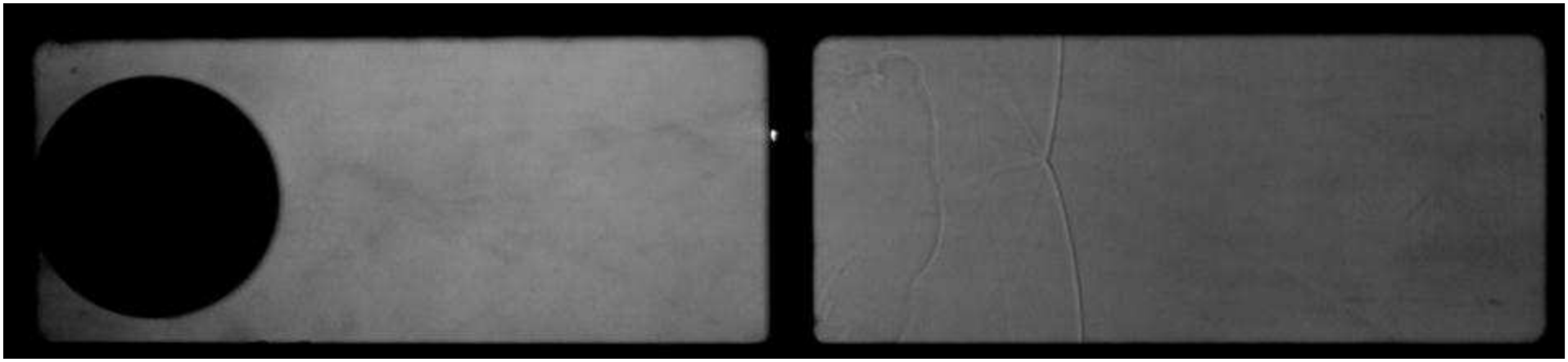
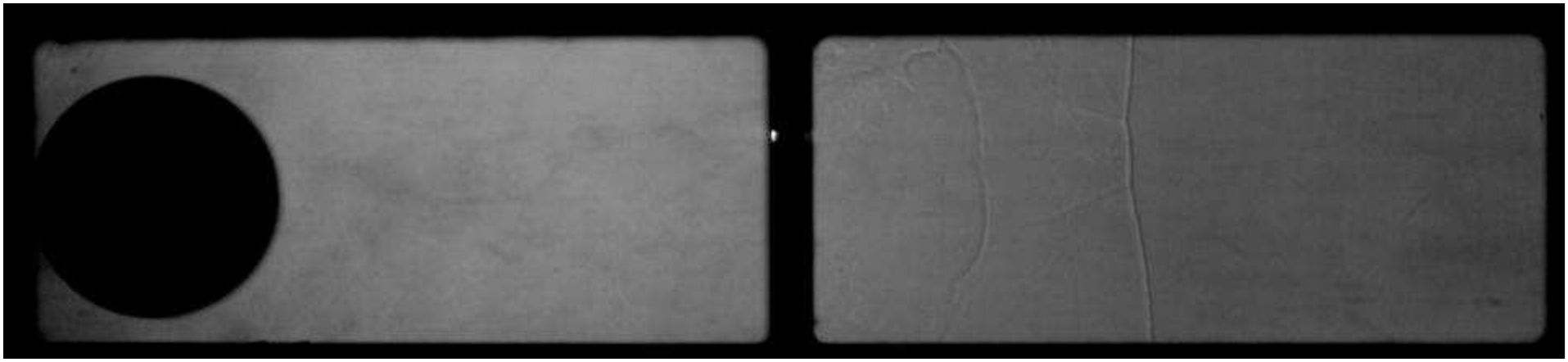
Oxy-Hydrogen



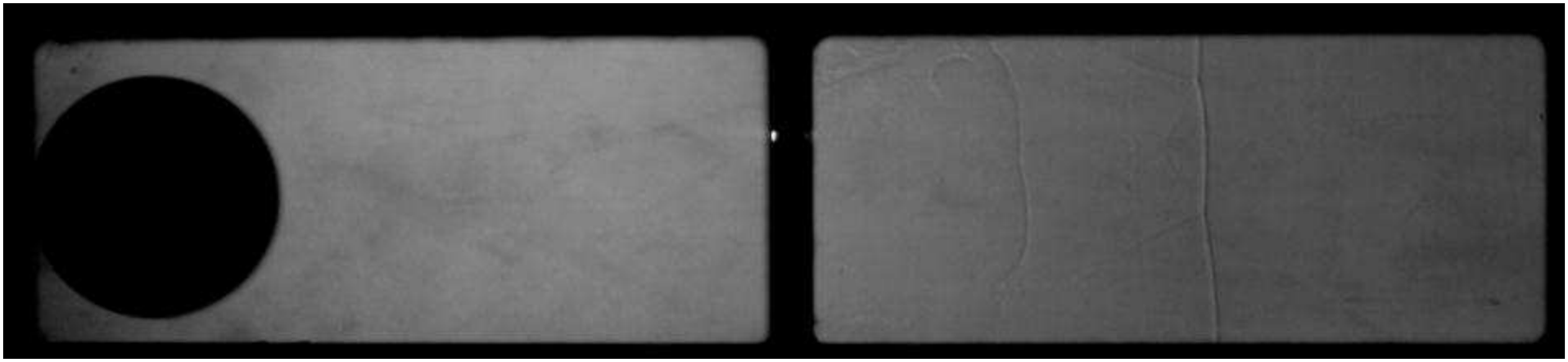
$2H_2 + O_2$ Po = 13.8kPa

Oxy-Hydrogen



$2H_2 + O_2$ Po = 13.8kPa

Oxy-Hydrogen



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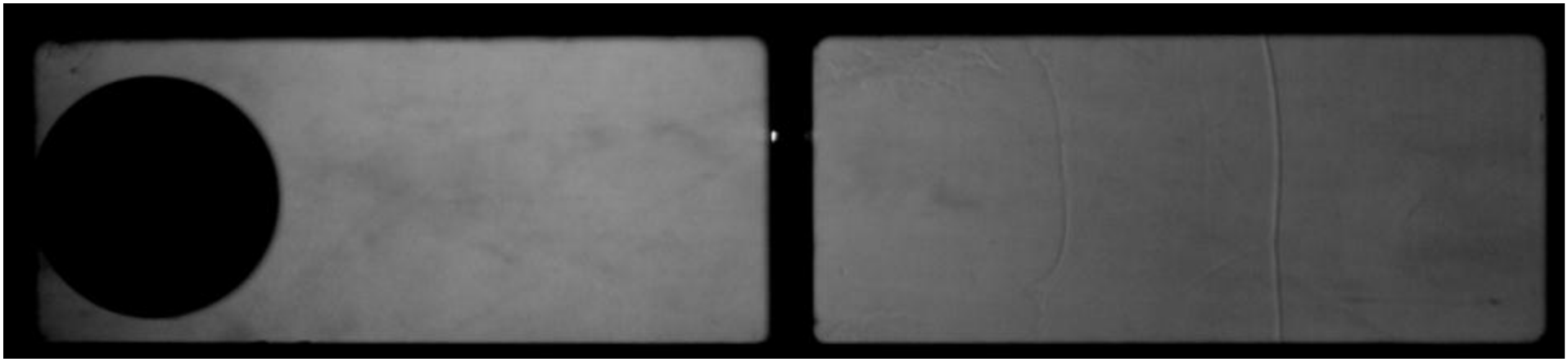
Oxy-Hydrogen



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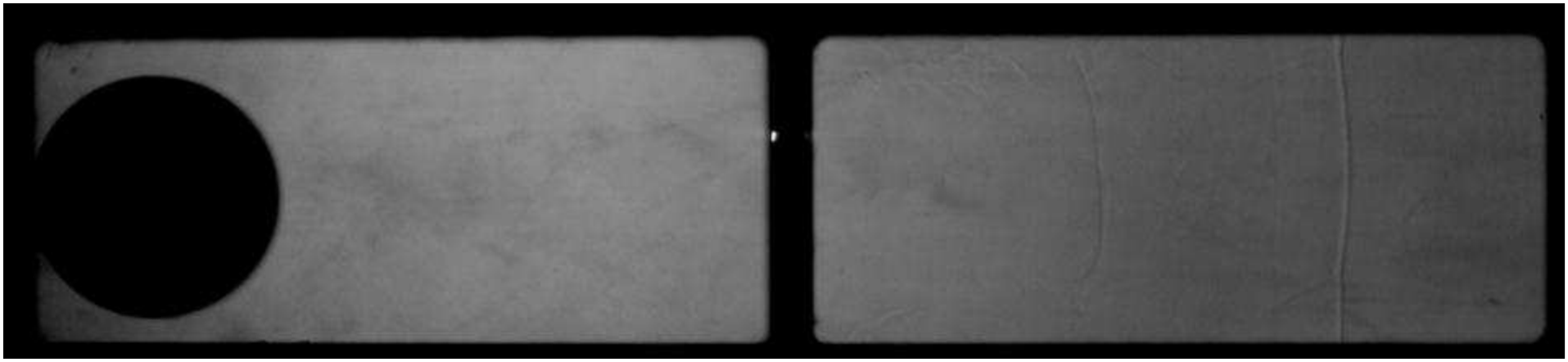
Oxy-Hydrogen



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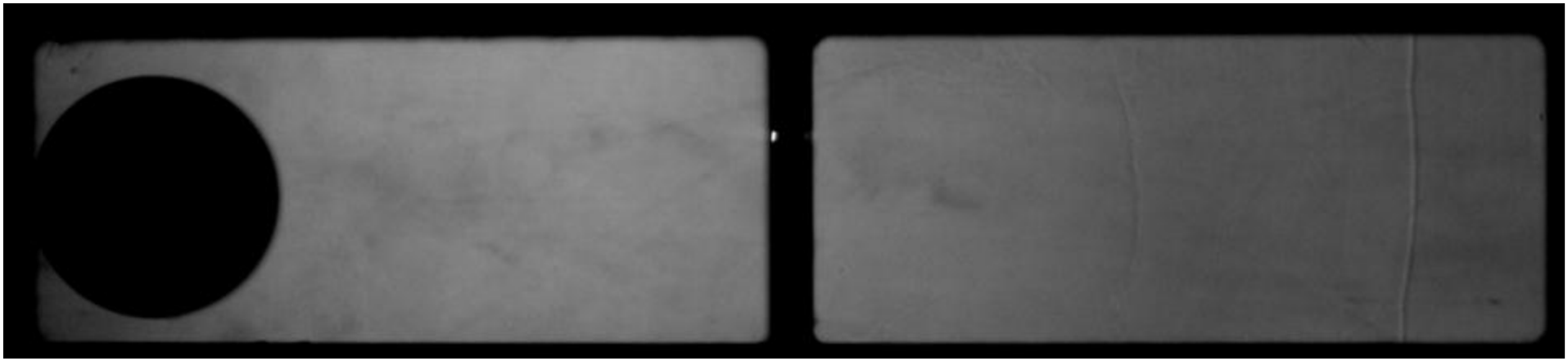
Oxy-Hydrogen



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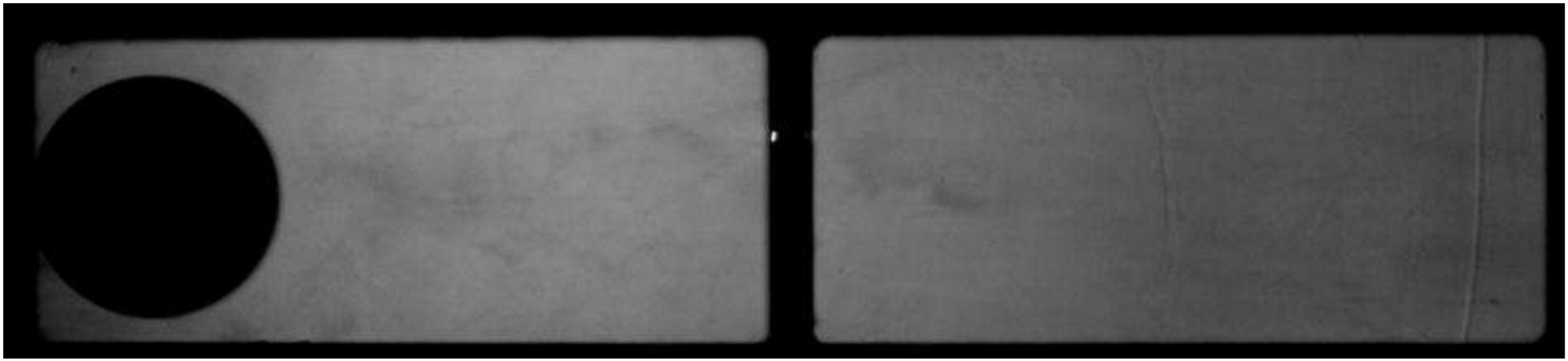
Oxy-Hydrogen



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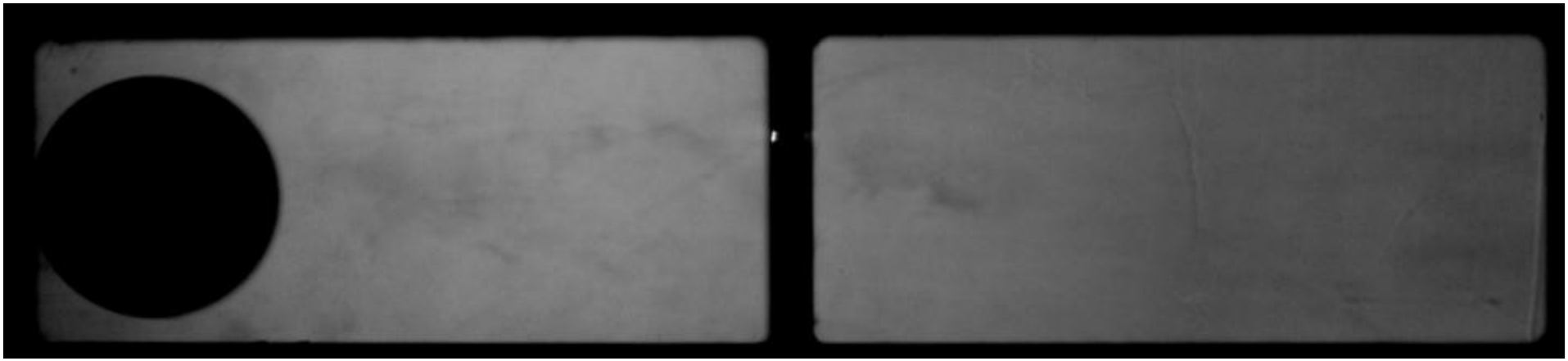
Oxy-Hydrogen



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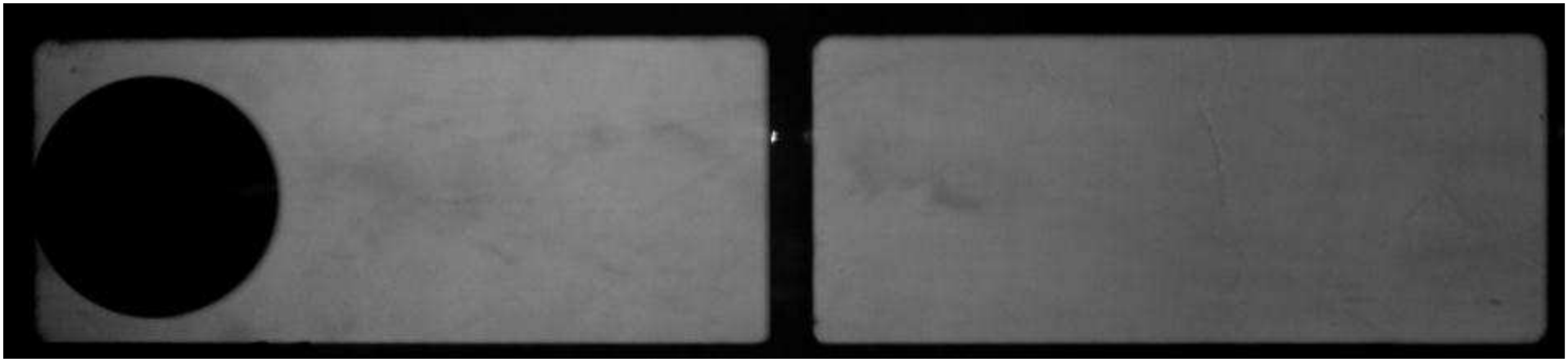
Oxy-Hydrogen



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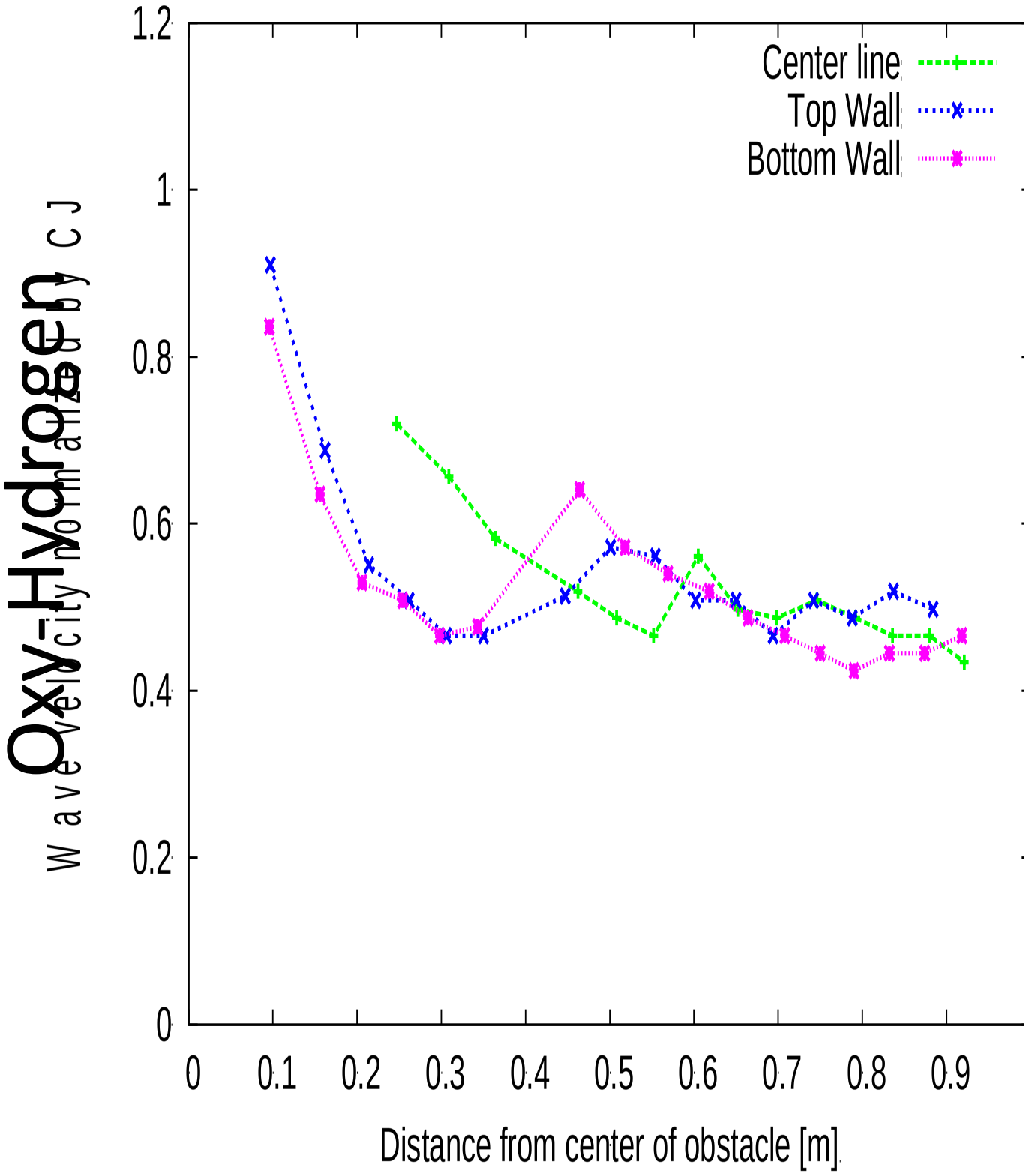
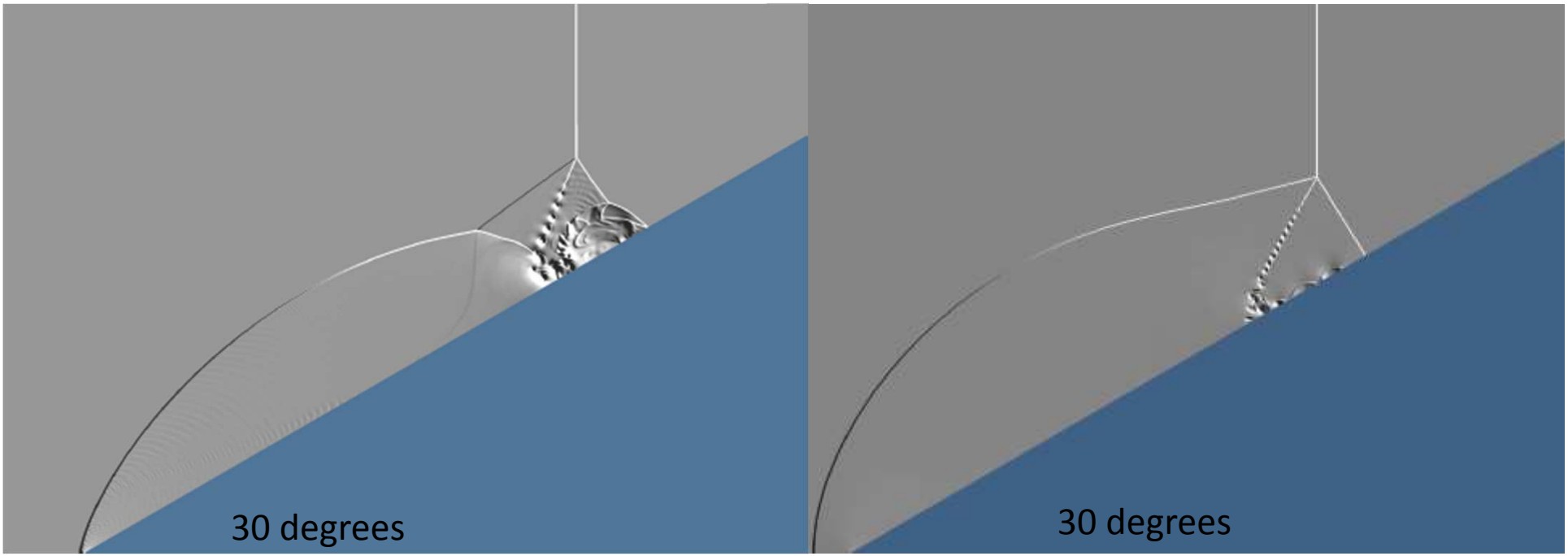

Oxy-Hydrogen
Wave Velocity normalized by C J
1.2
1
0.8
0.6
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Distance from center of obstacle [m]
Center line
Top Wall
Bottom Wall

Discussion

CI 2011 - Mach and Radulescu have correlated low gamma and forward jetting

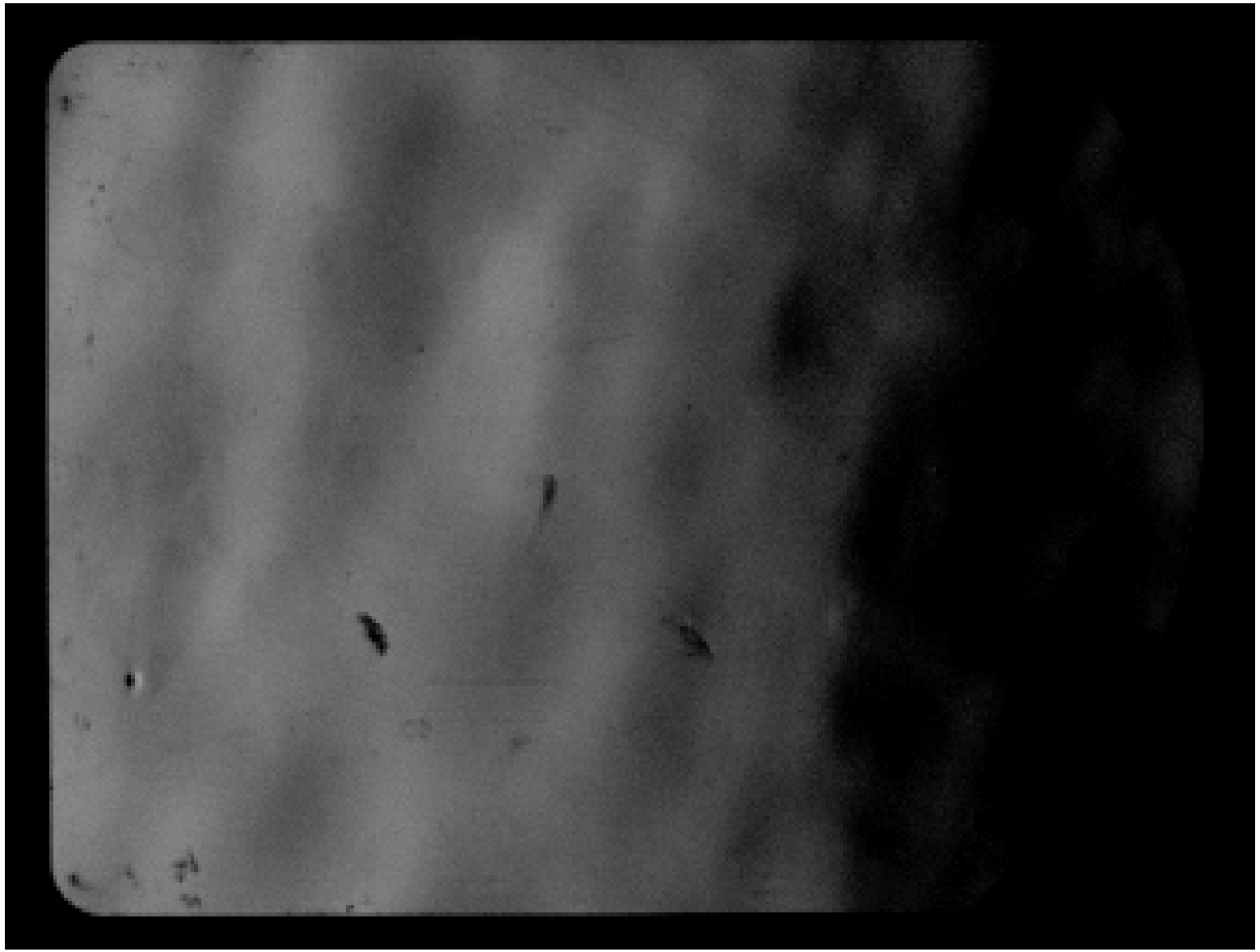


$CH_4 + 2O_2$
Gamma = 1.2
Mach=3.2

(1/2 Mcj)

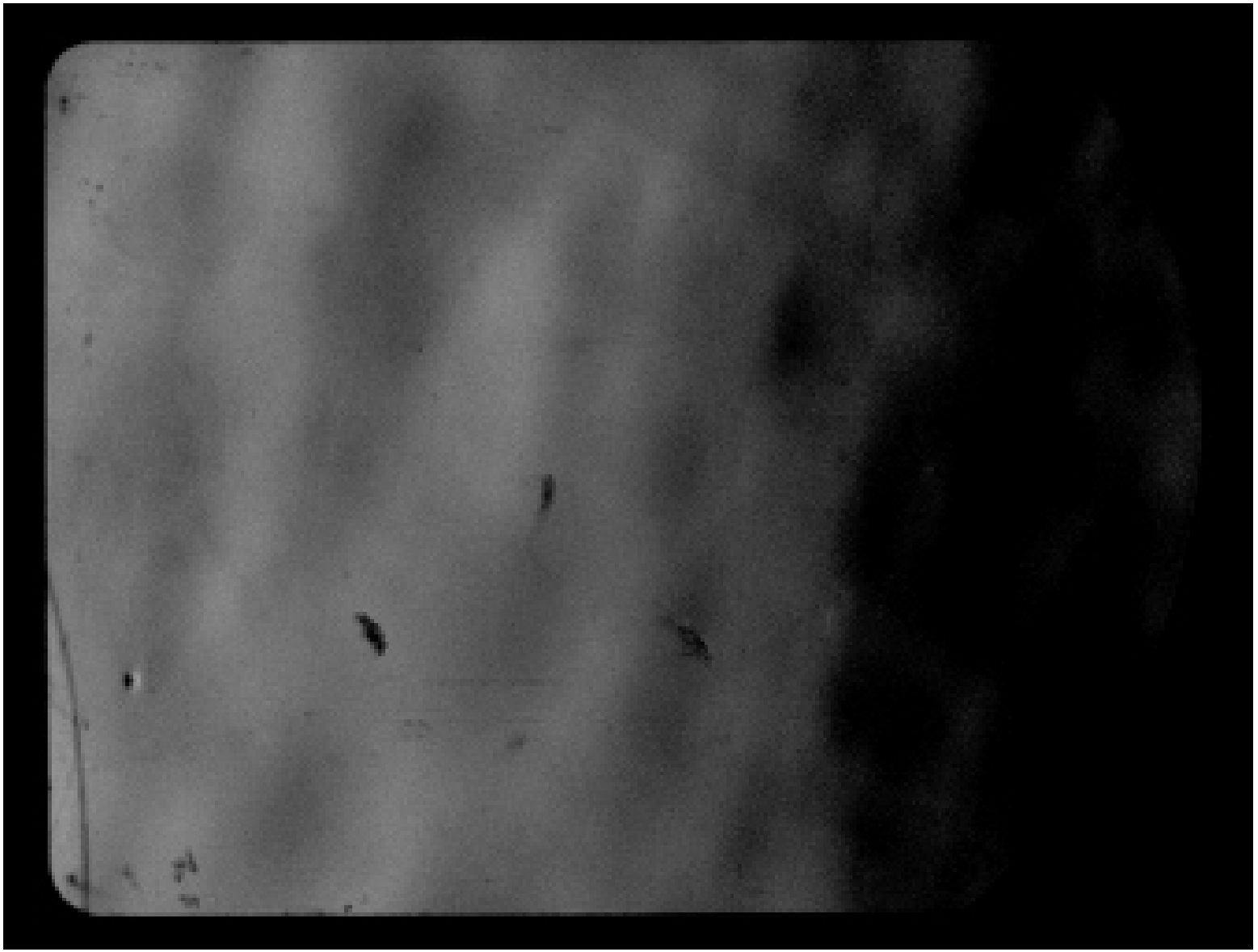
$2H_2 + O_2$
Gama= 1.36
Mach=2.5

A hot stop in Oxy-Methane



$CH_4 + 2O_2$ P_o = 8.4kPa

Fast Flame Behaviour



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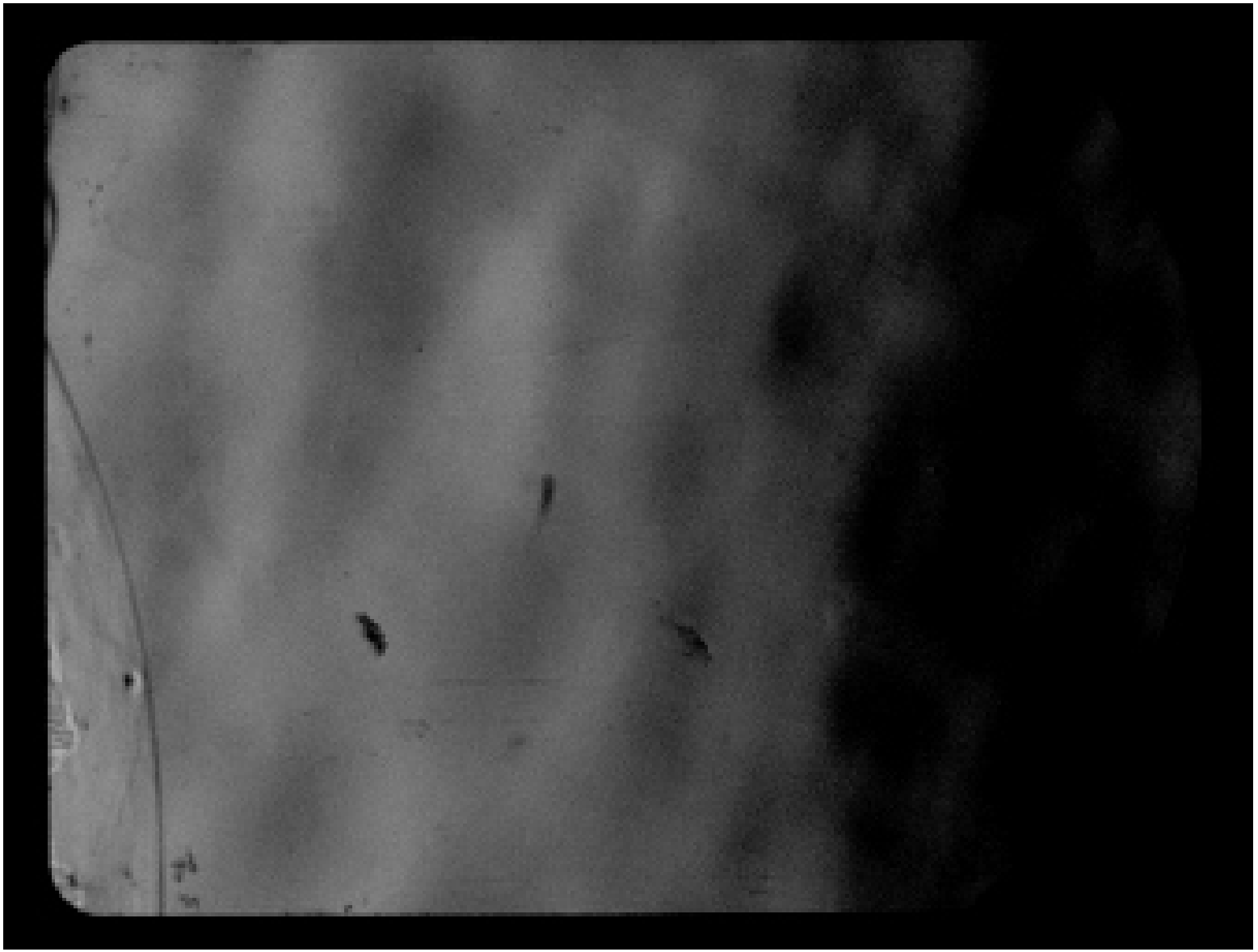

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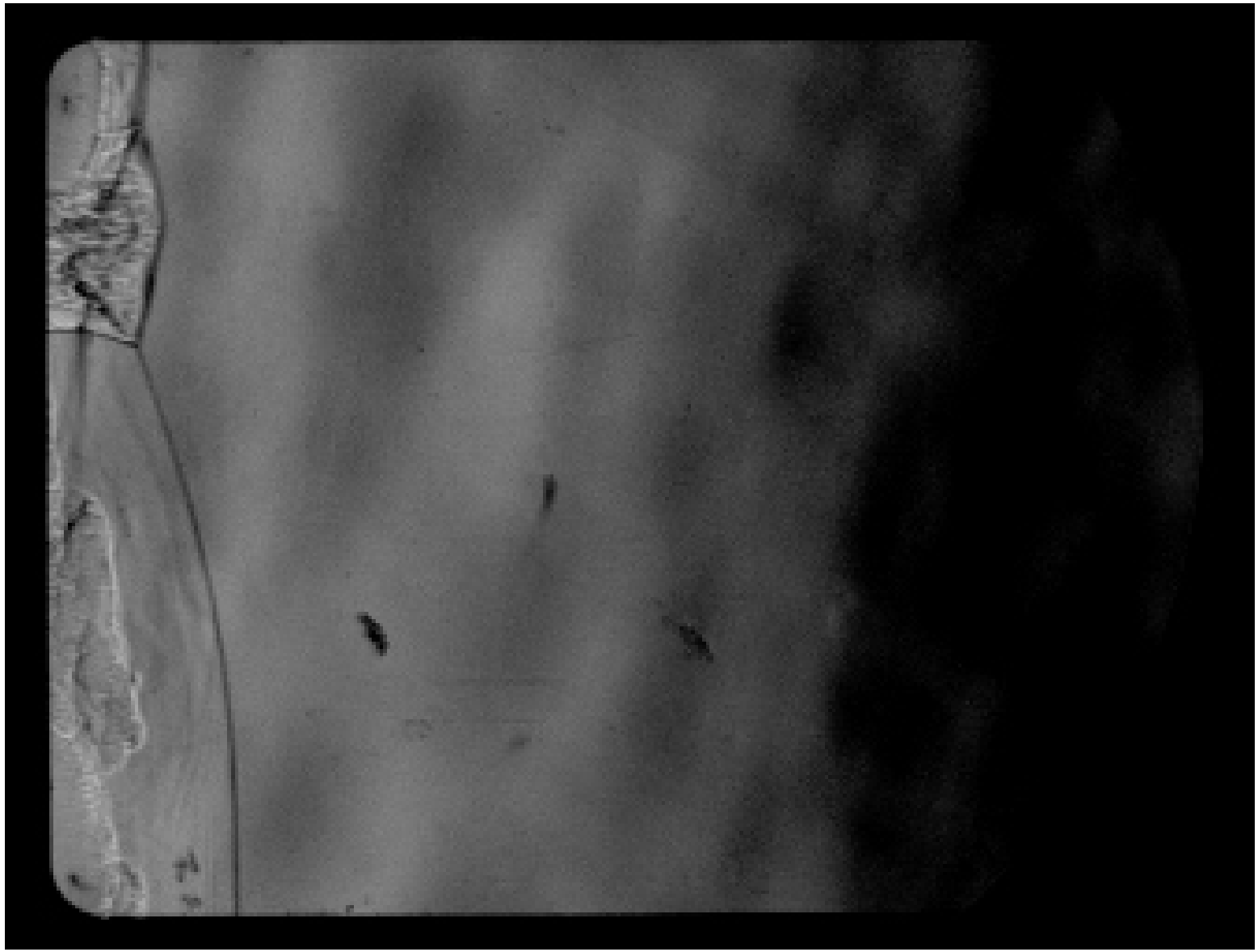

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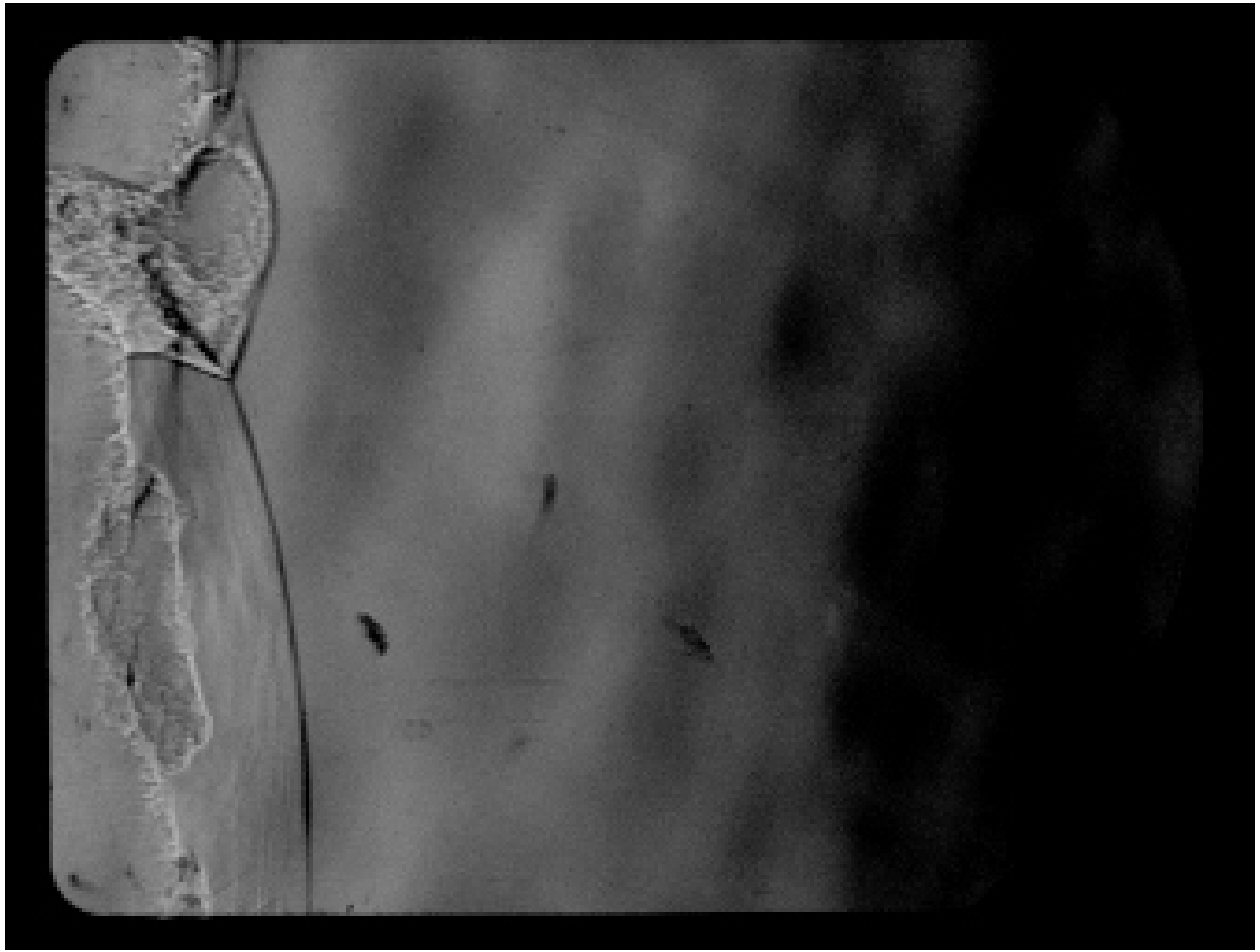

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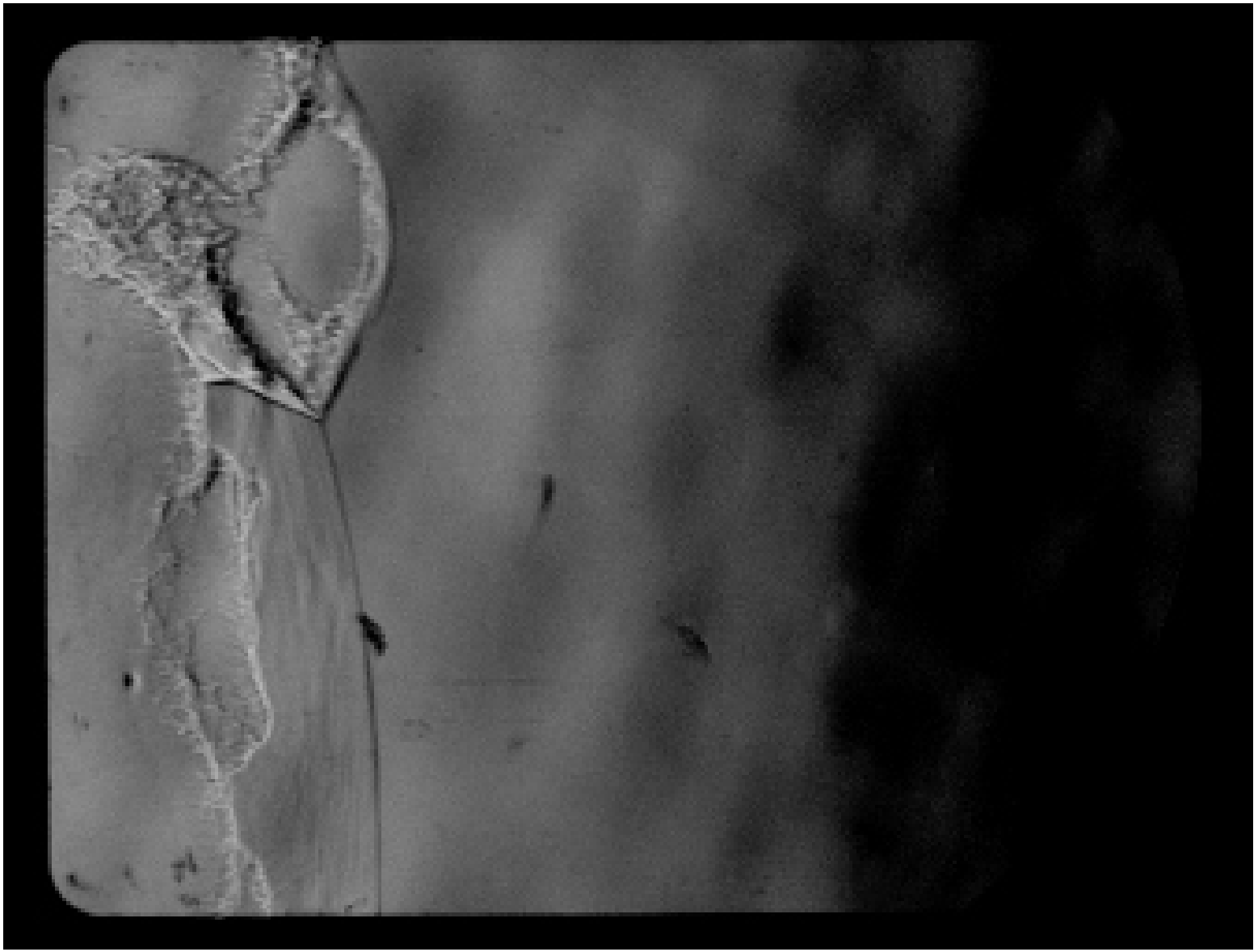

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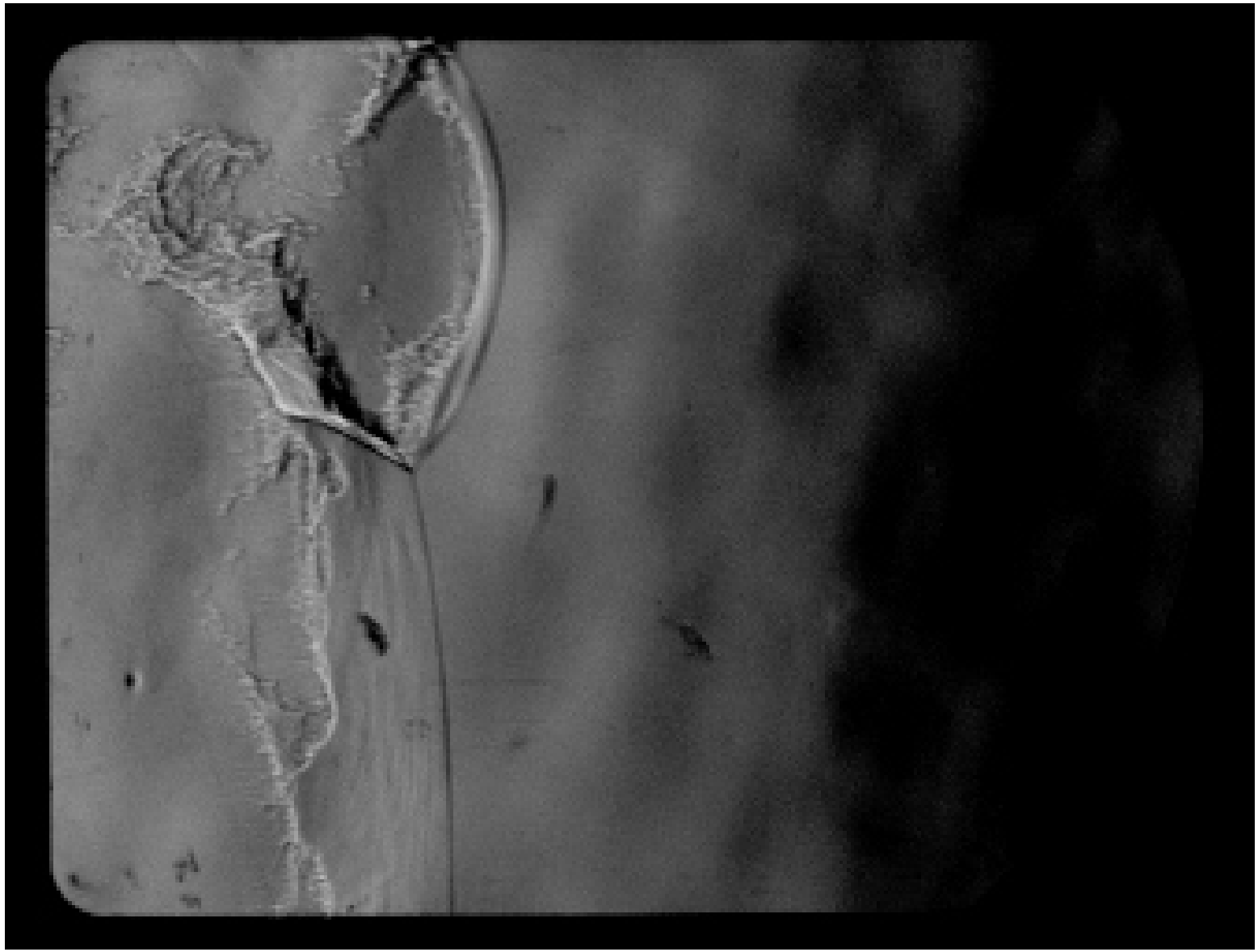

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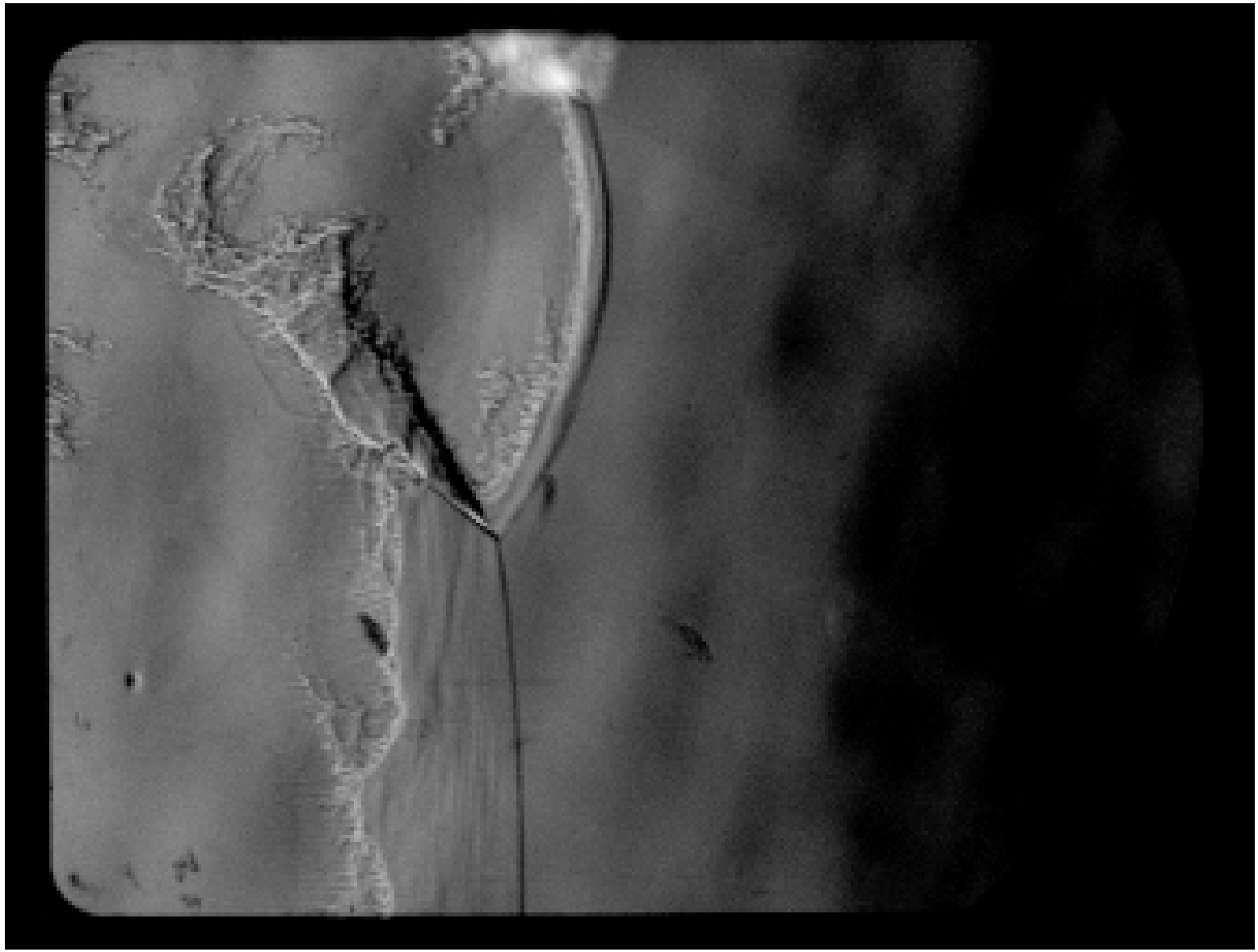

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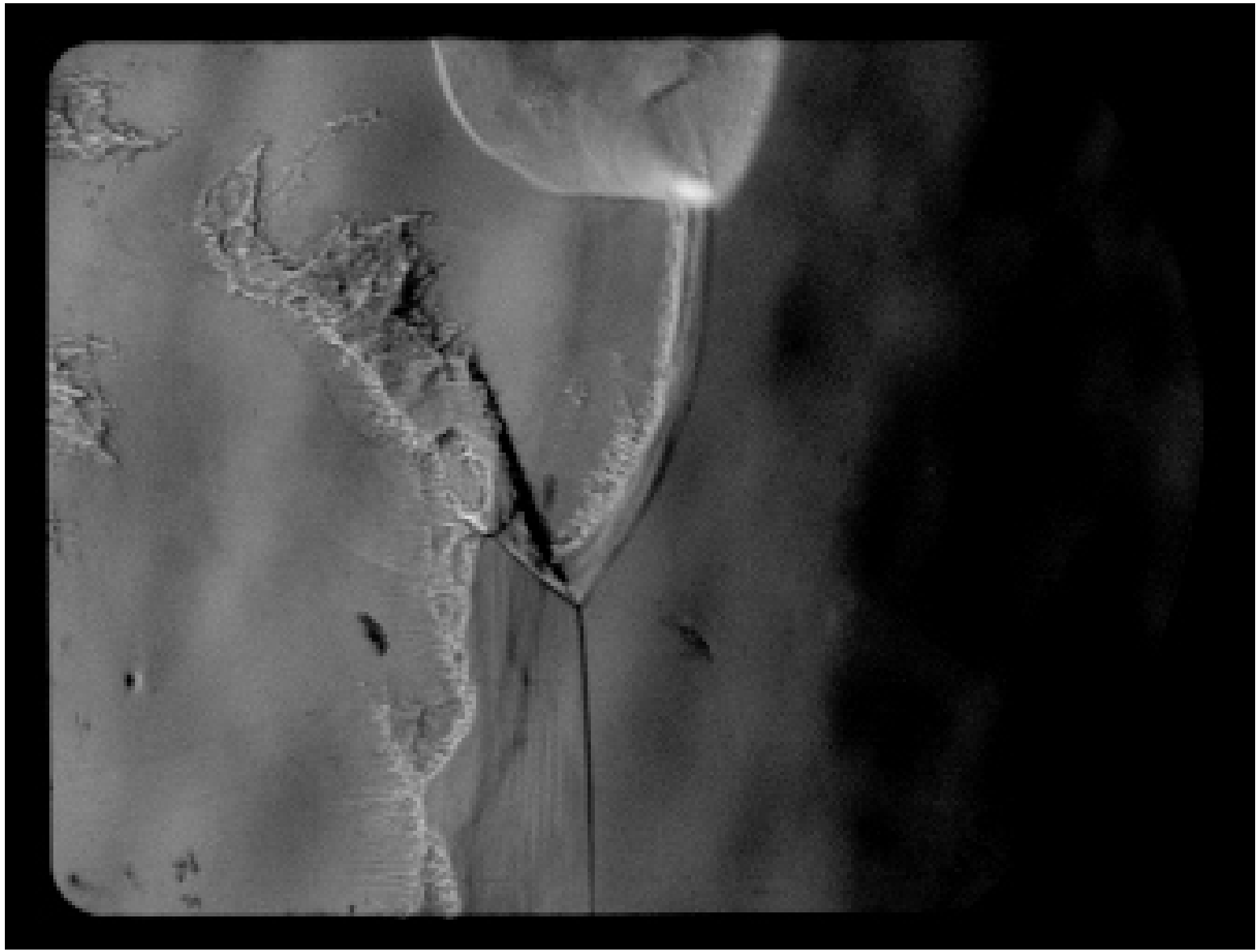
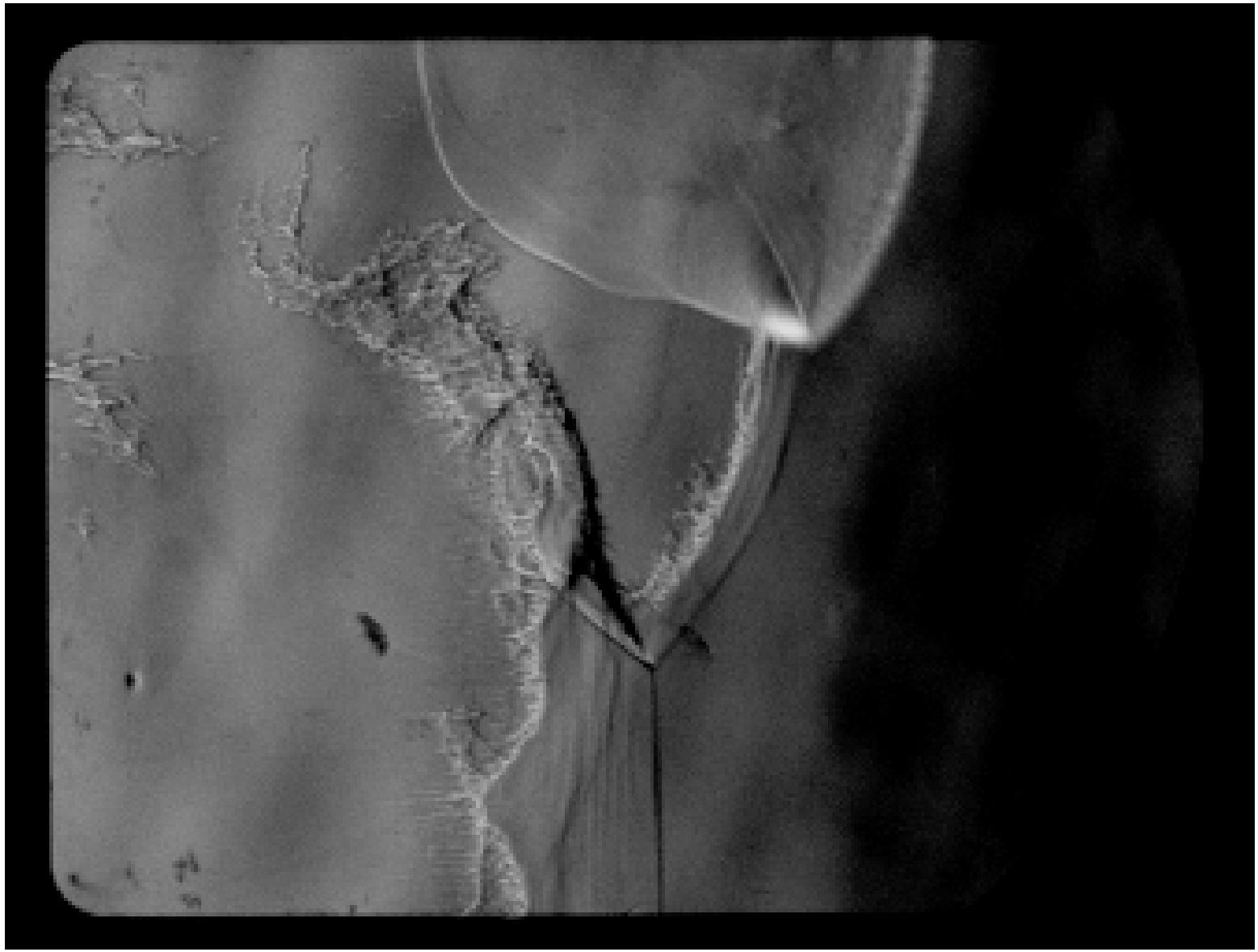


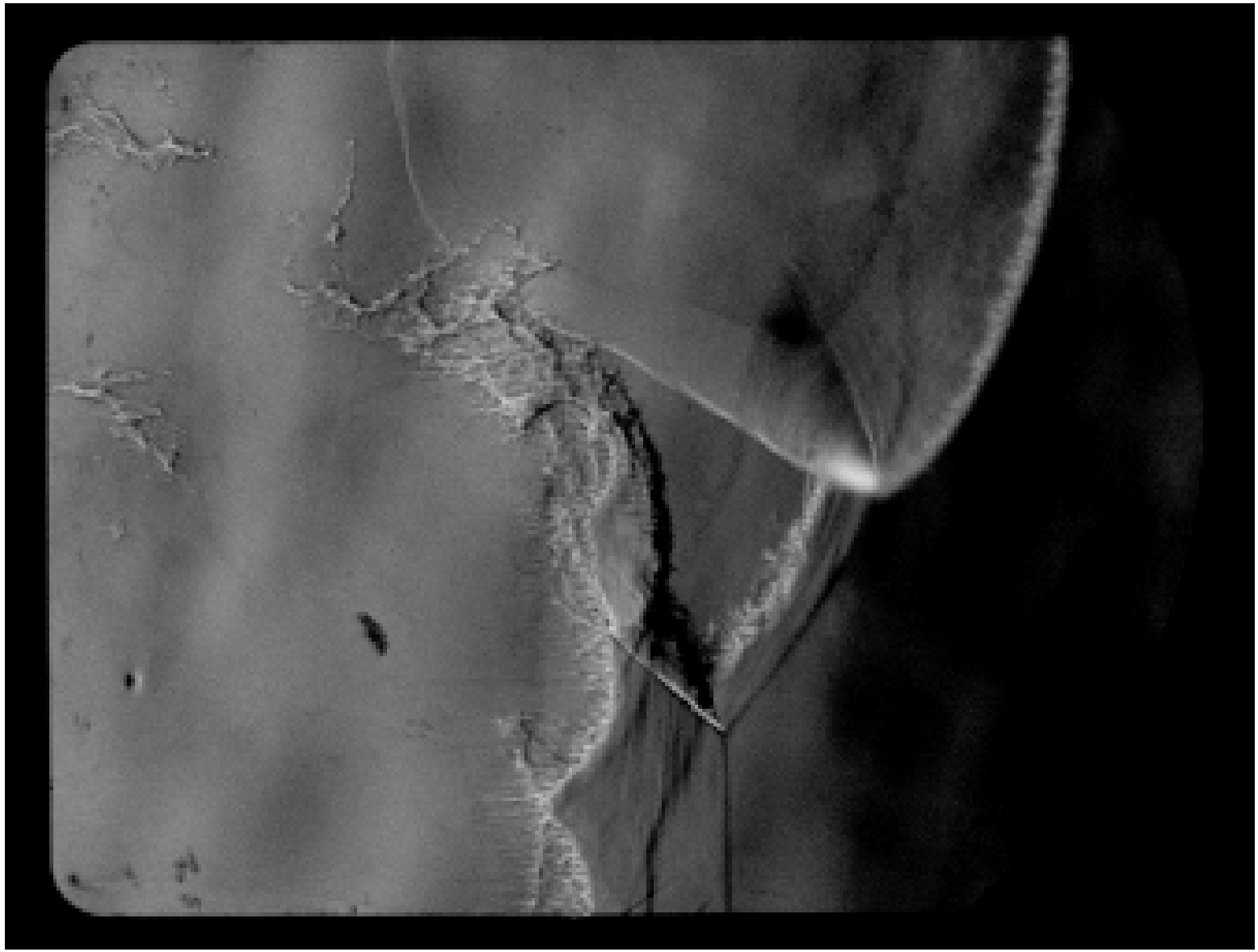
$CH_4 + 2O_2$ P_o = 8.4kPa

Fast Flame Behaviour



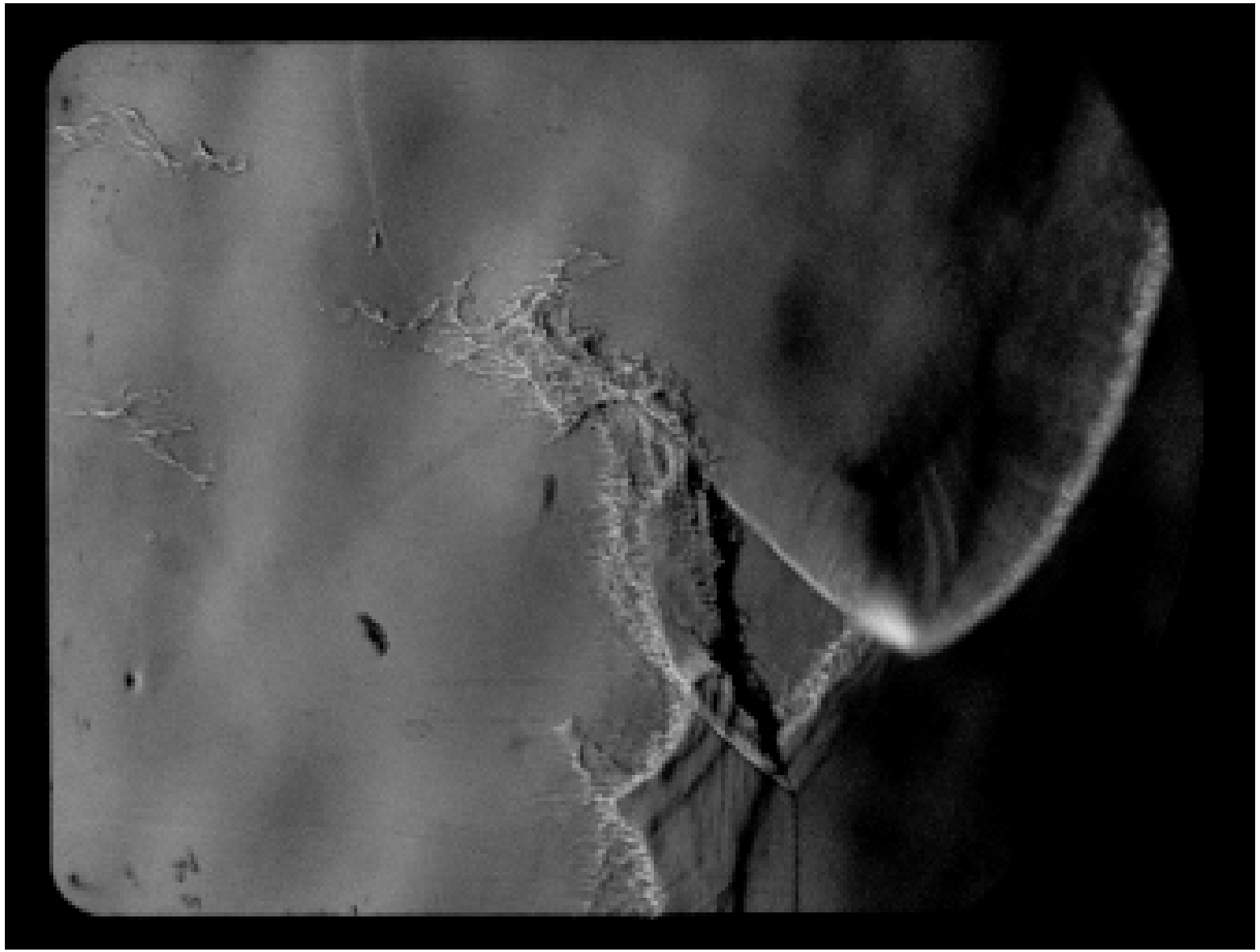
$CH_4 + 2O_2$ P_o = 8.4kPa

Fast Flame Behaviour



$CH_4 + 2O_2$ P_o = 8.4kPa

Fast Flame Behaviour



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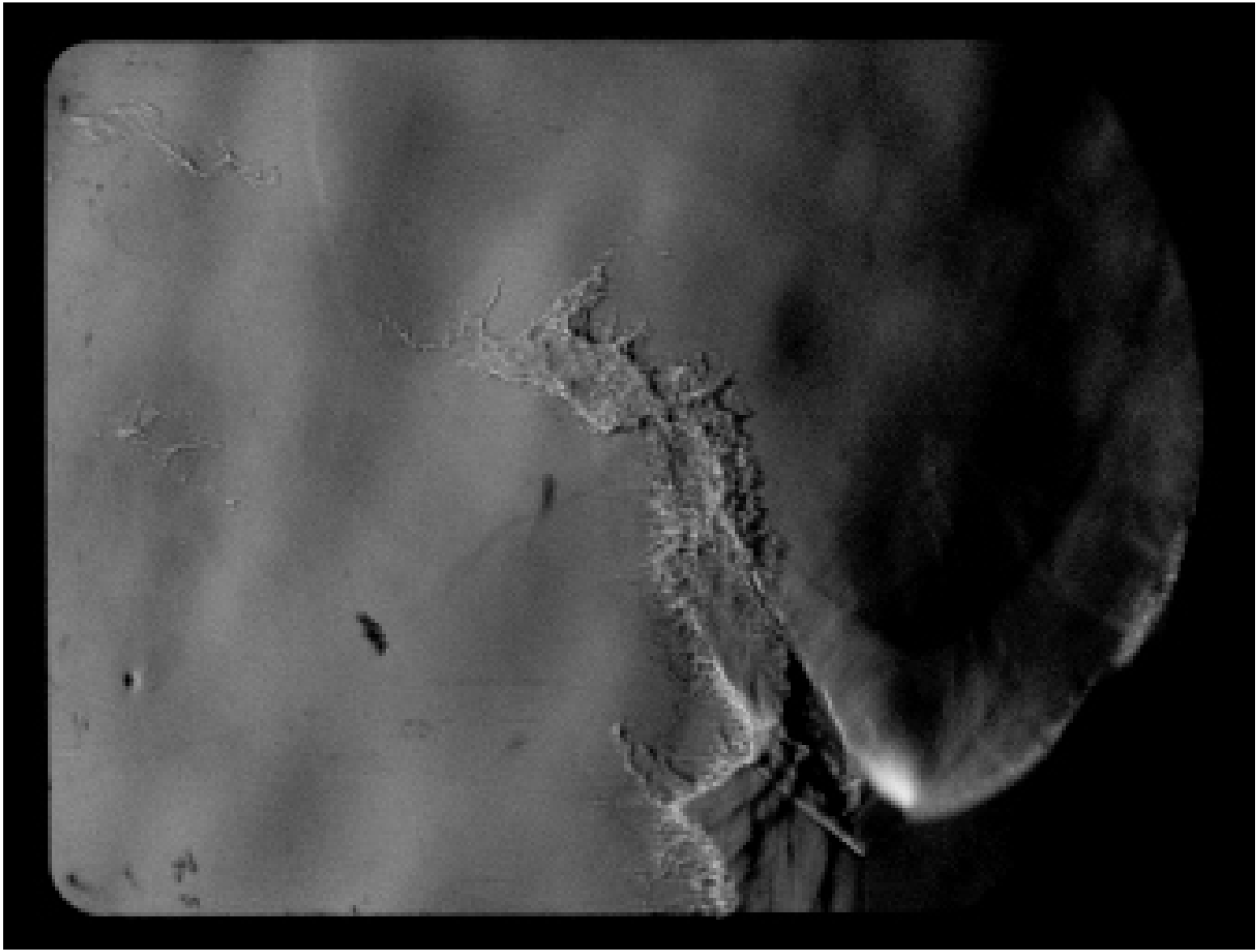

$CH_4 + 2O_2$ P_o = 8.4kPa

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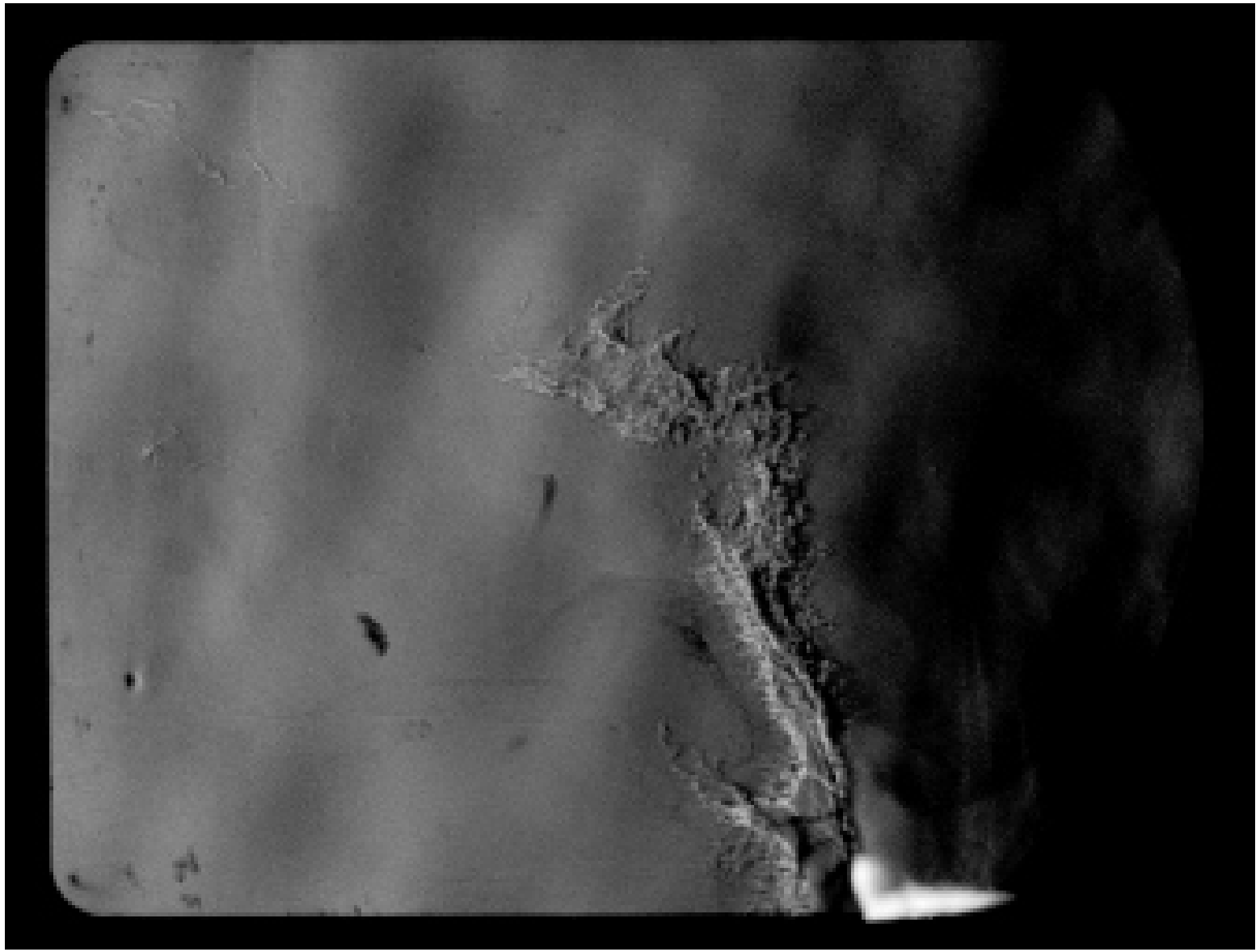

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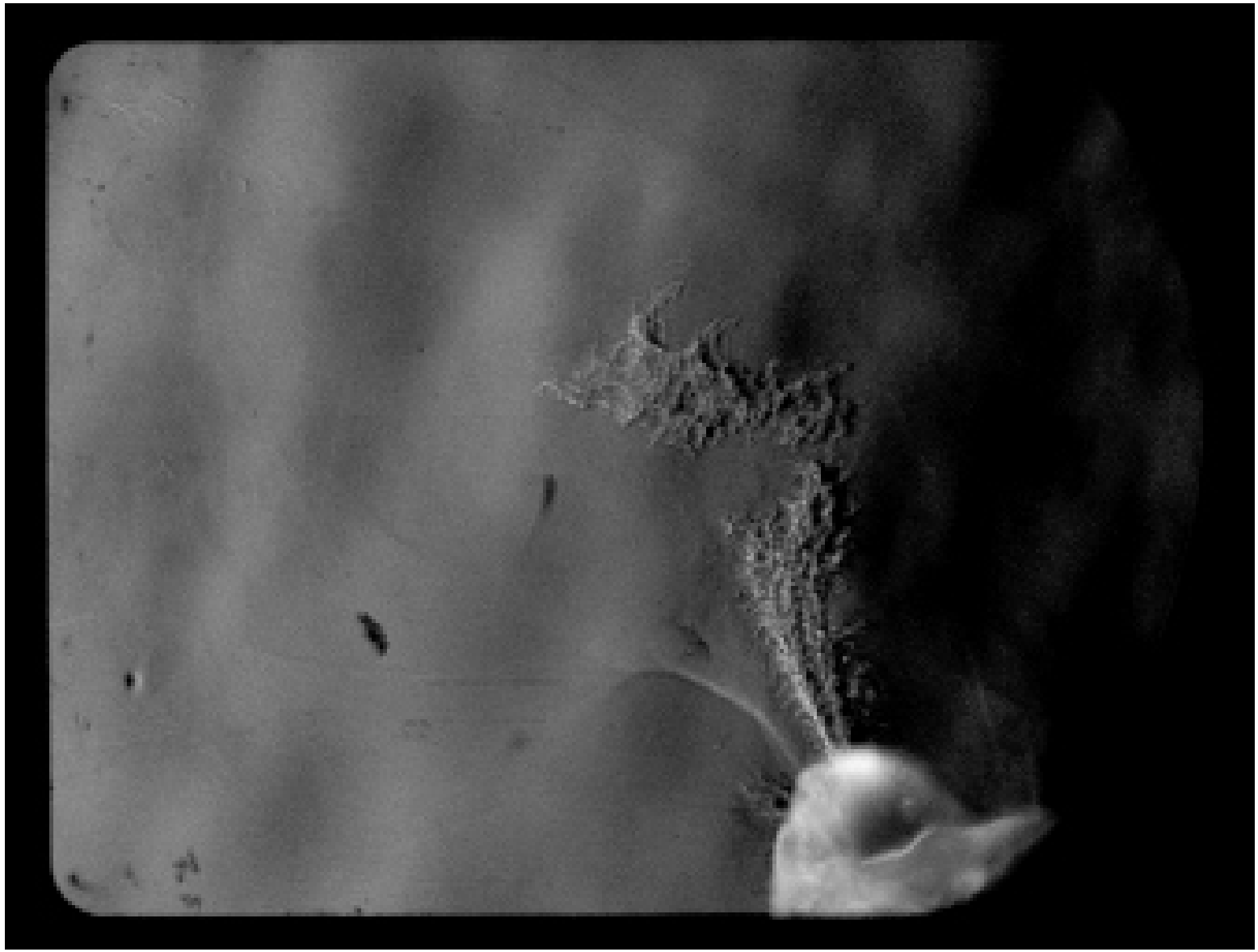

$CH_4 + 2O_2$ P_o = 8.4kPa

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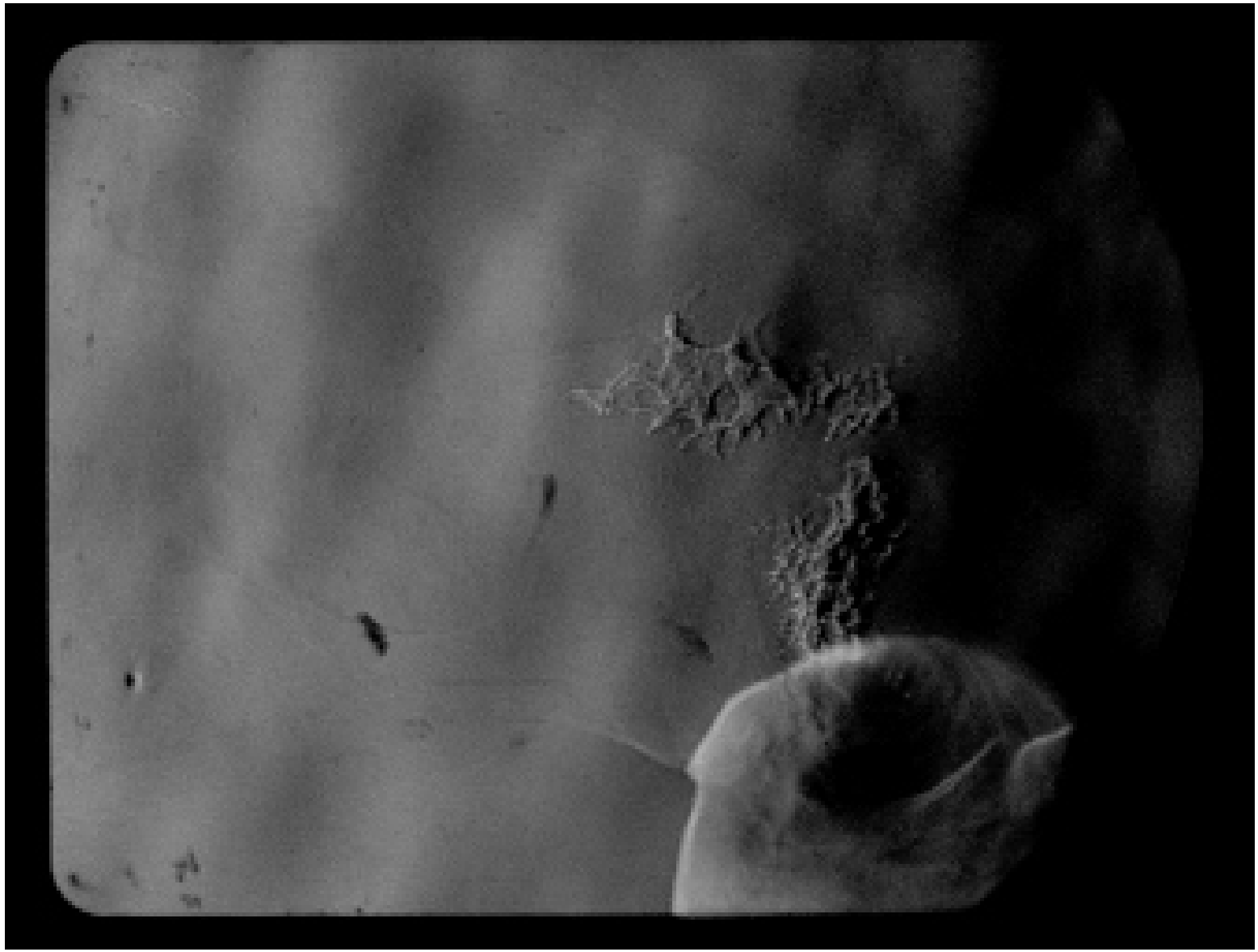

$CH_4 + 2O_2$ P_o = 8.4kPa

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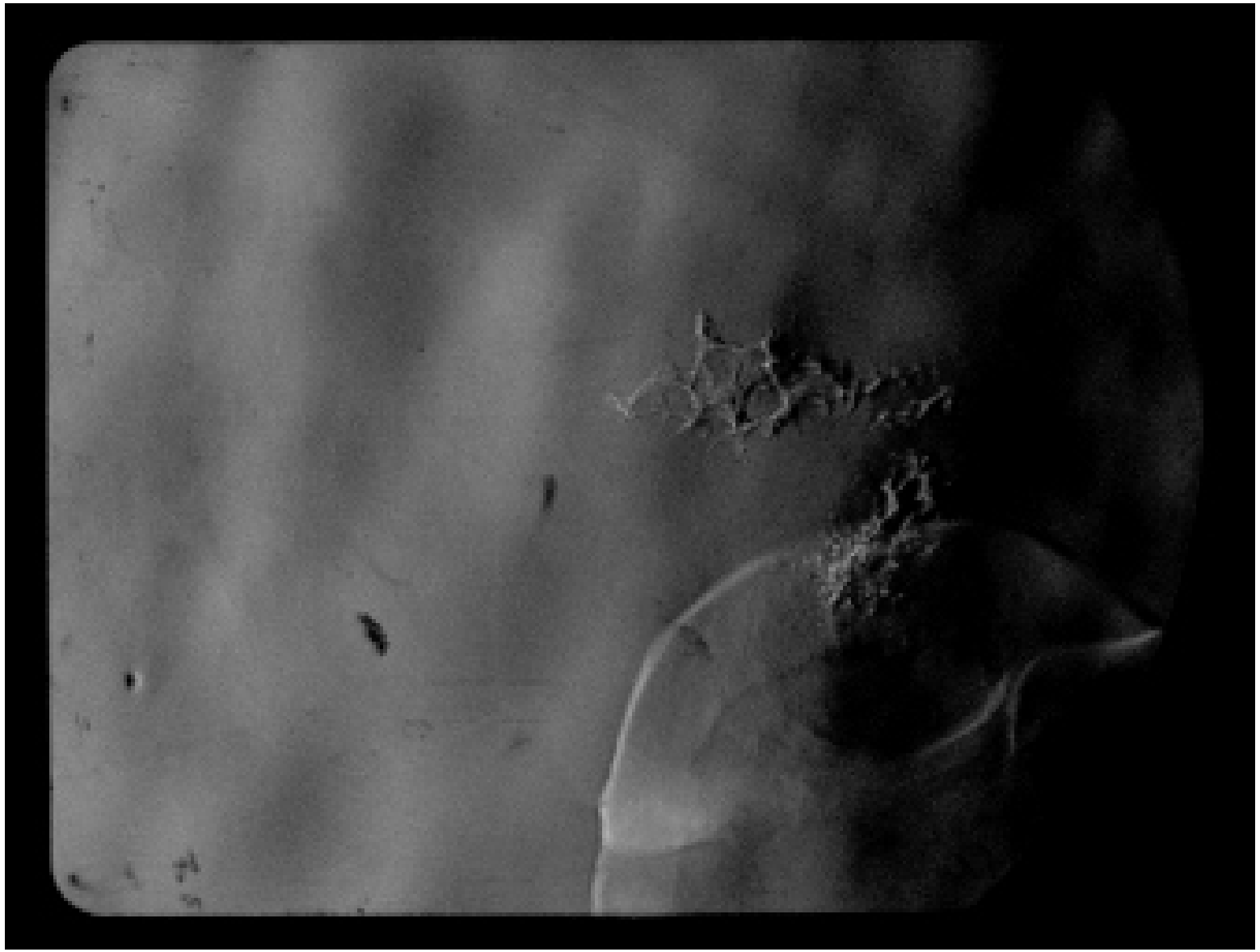
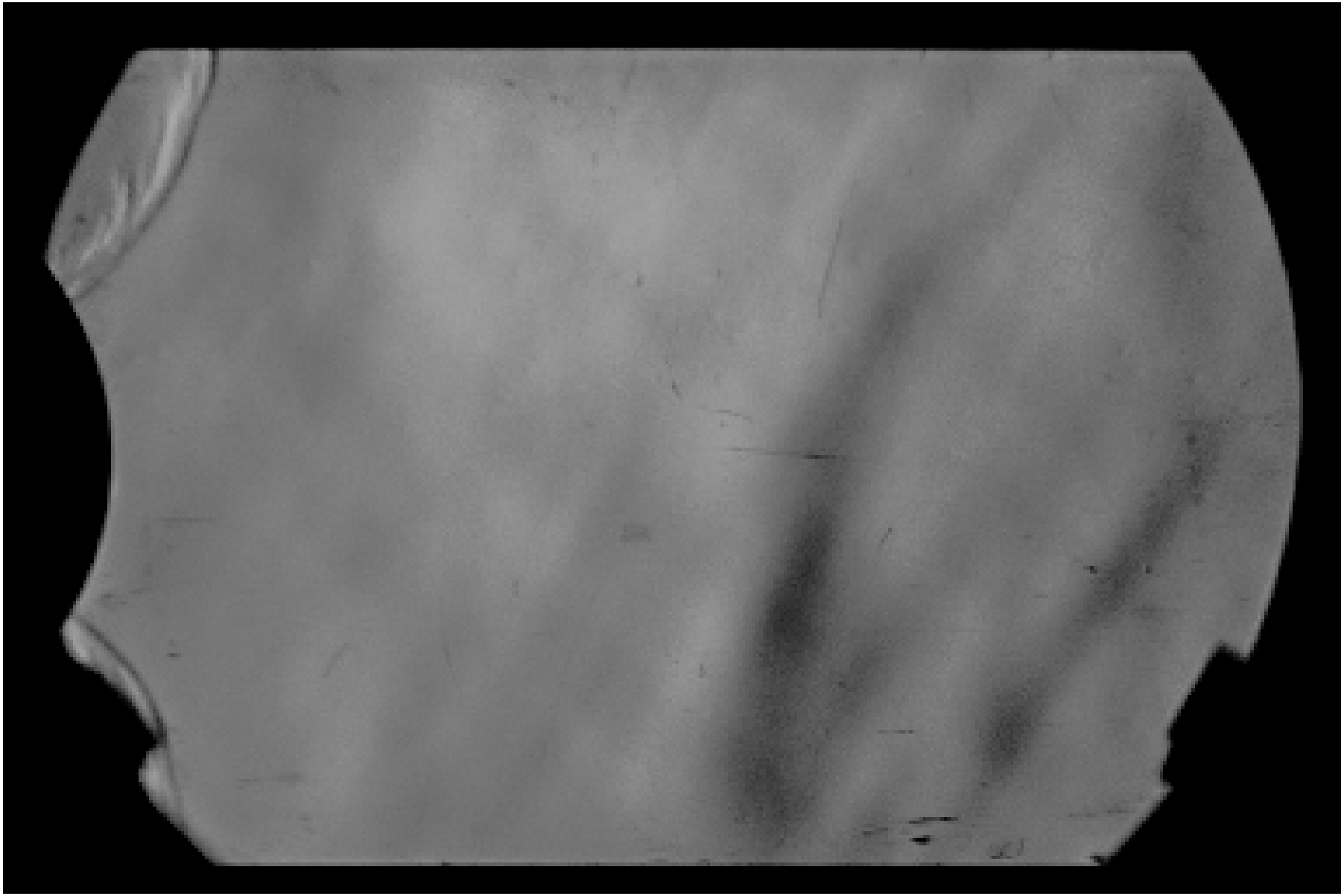


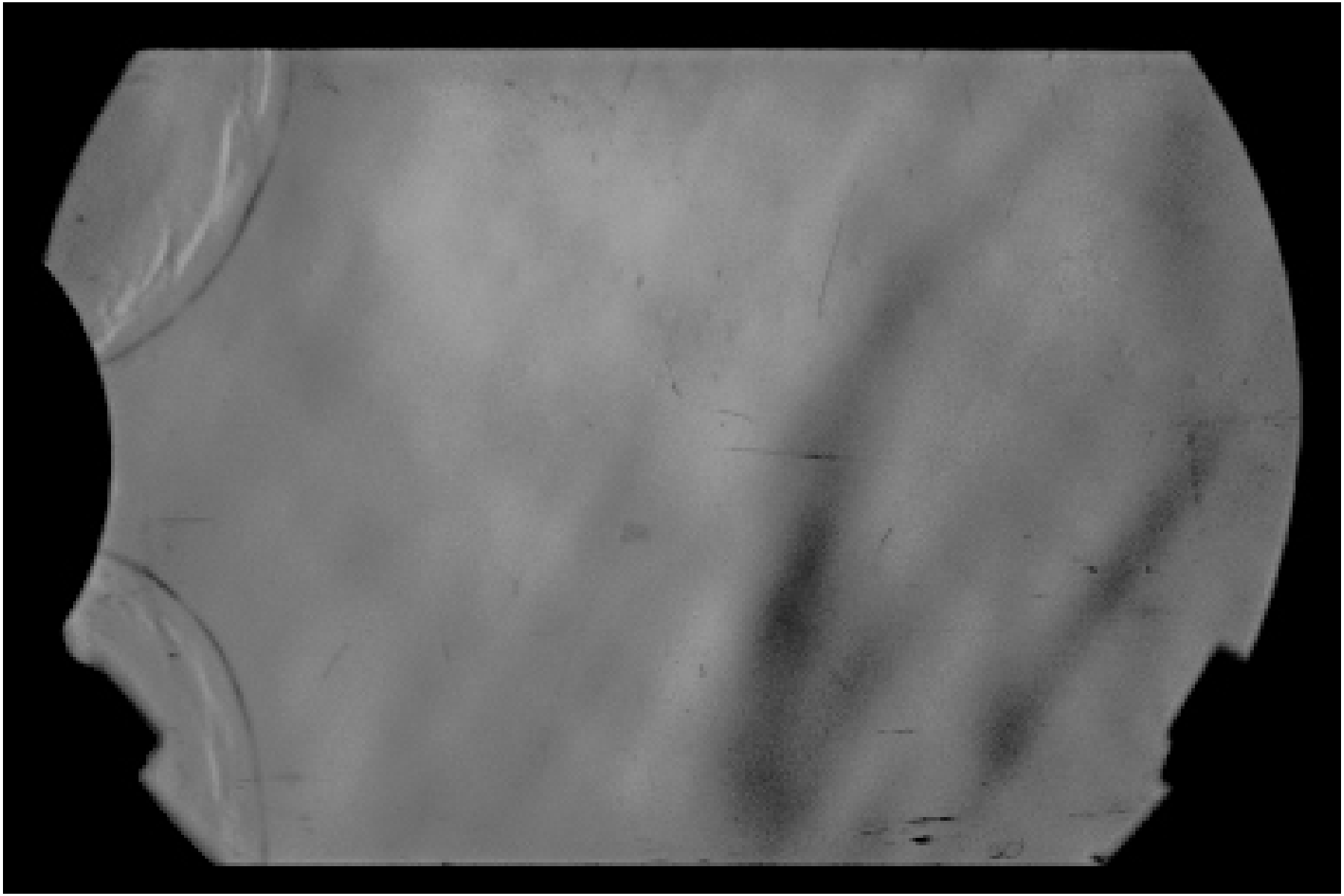
$CH_4 + 2O_2$ P_o = 8.4kPa

Oxy-Hydrogen Inert Reflection



$2H_2 + O_2$ P_o = 10.3kPa

Oxy-Hydrogen Inert Reflection



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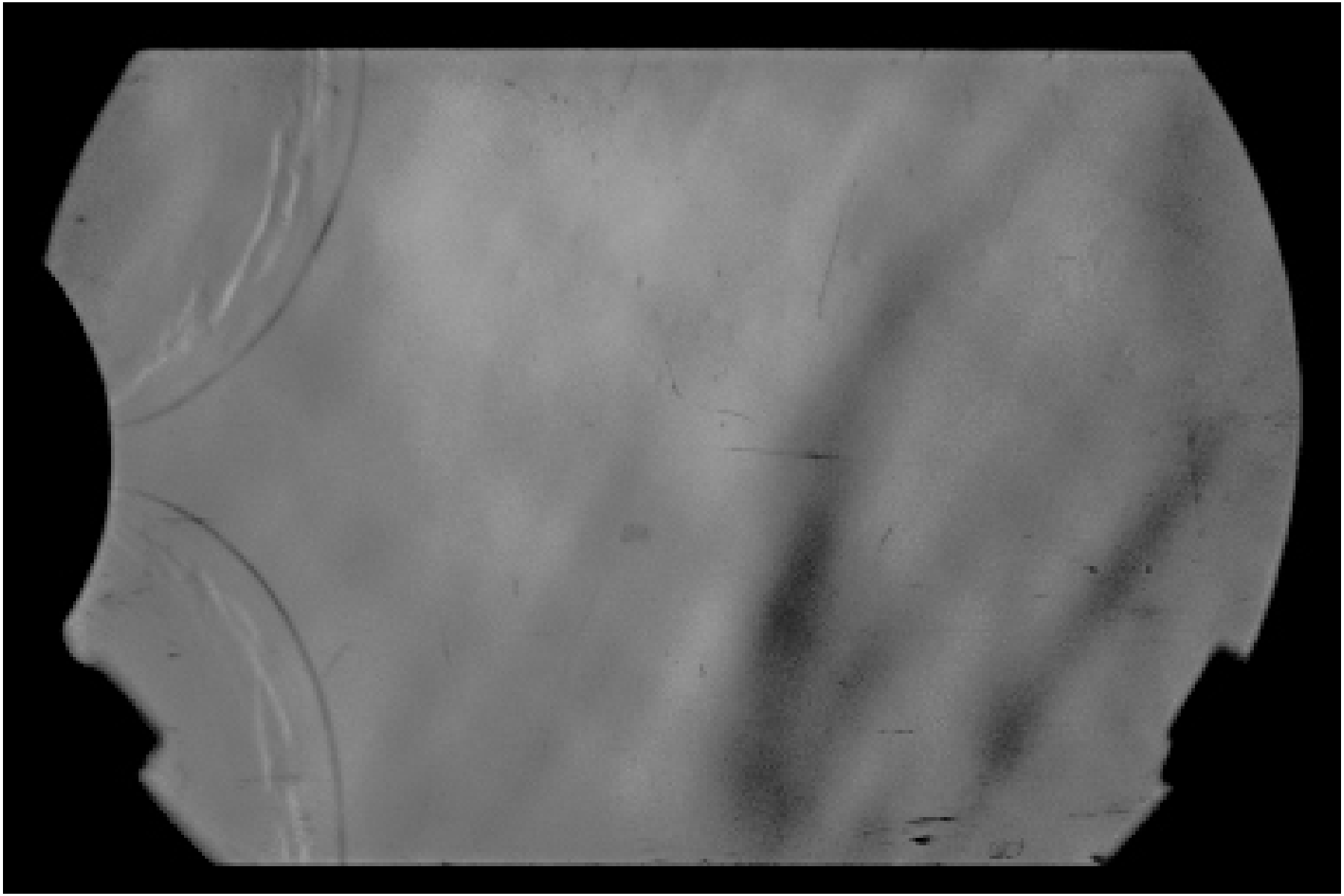

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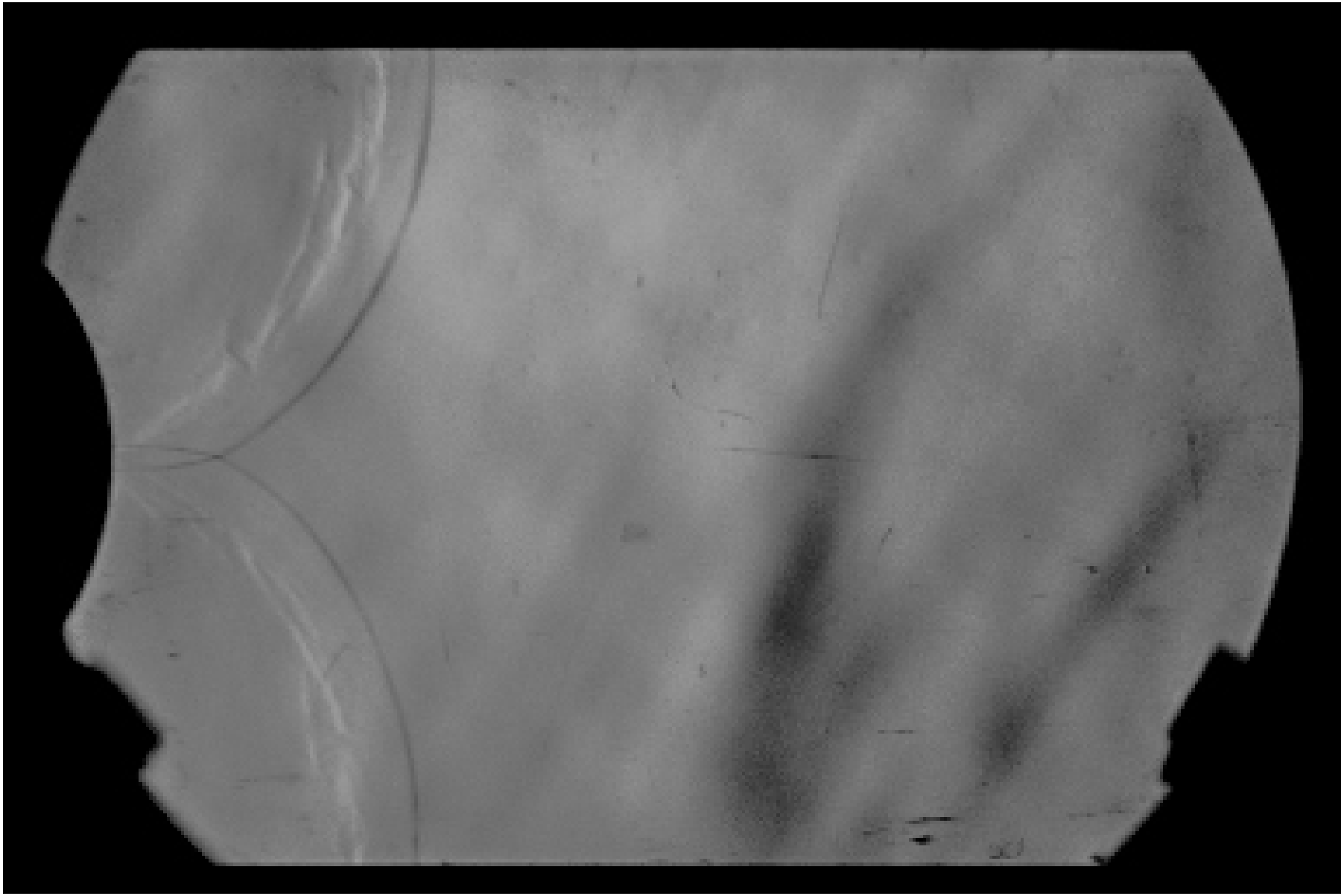

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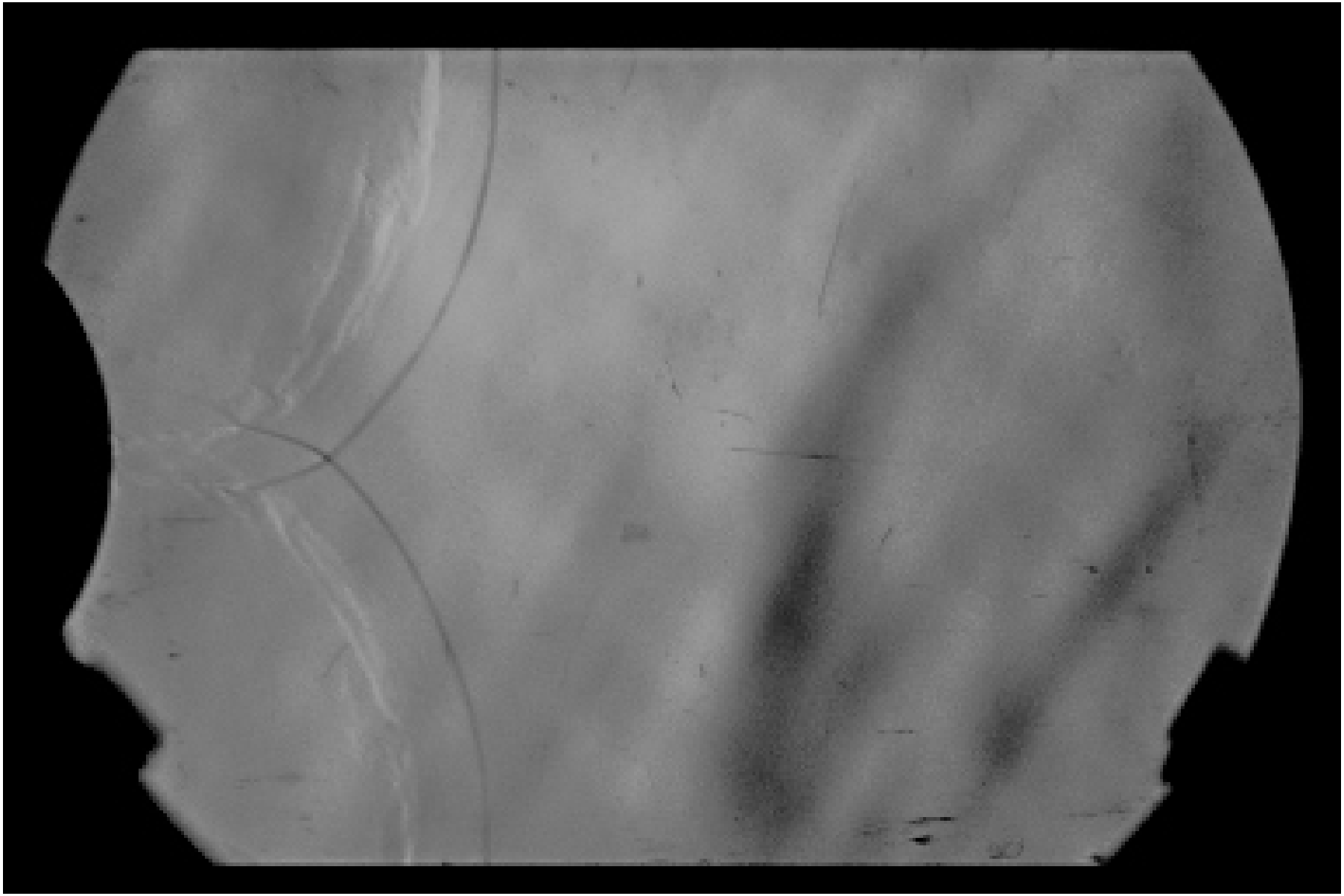

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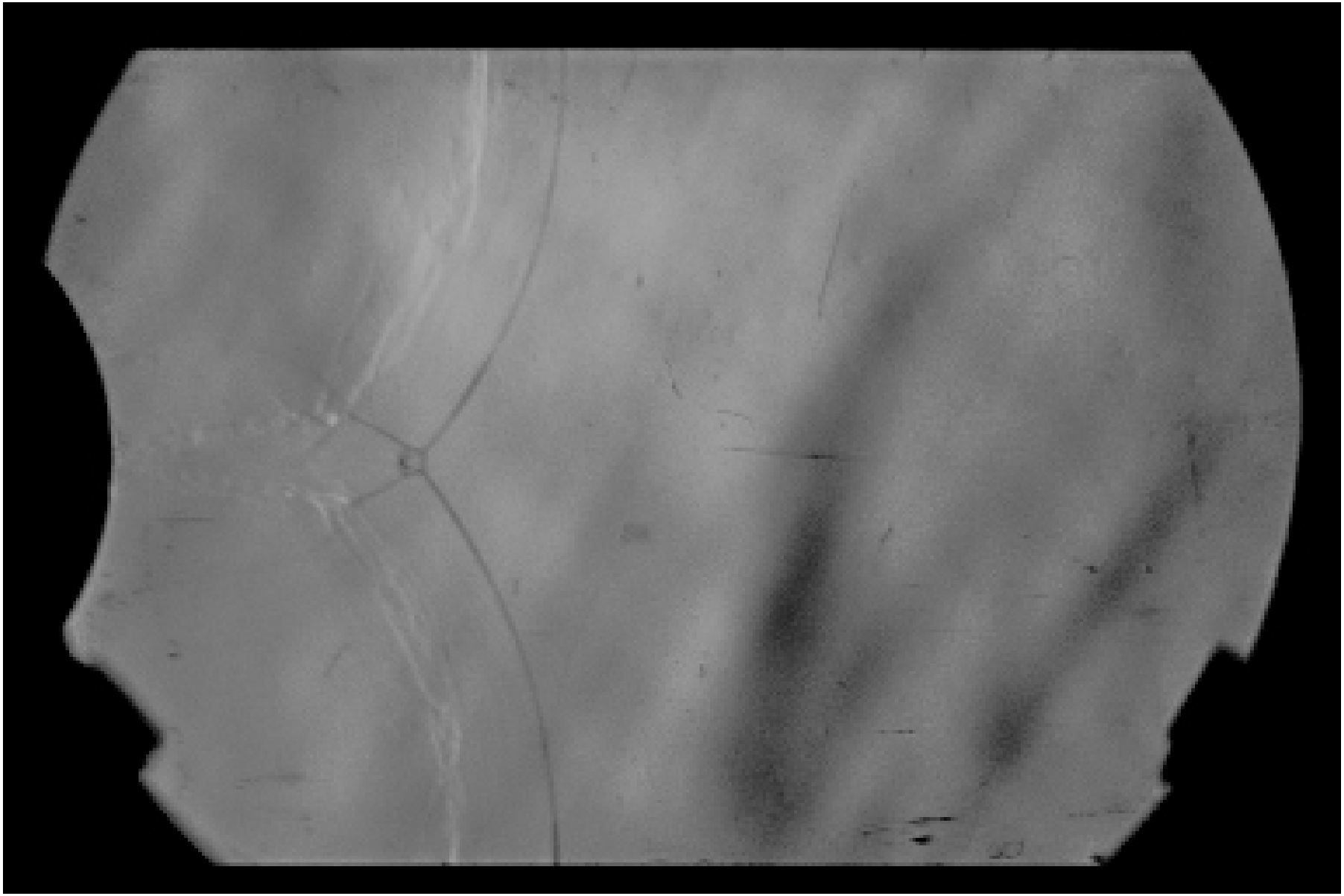

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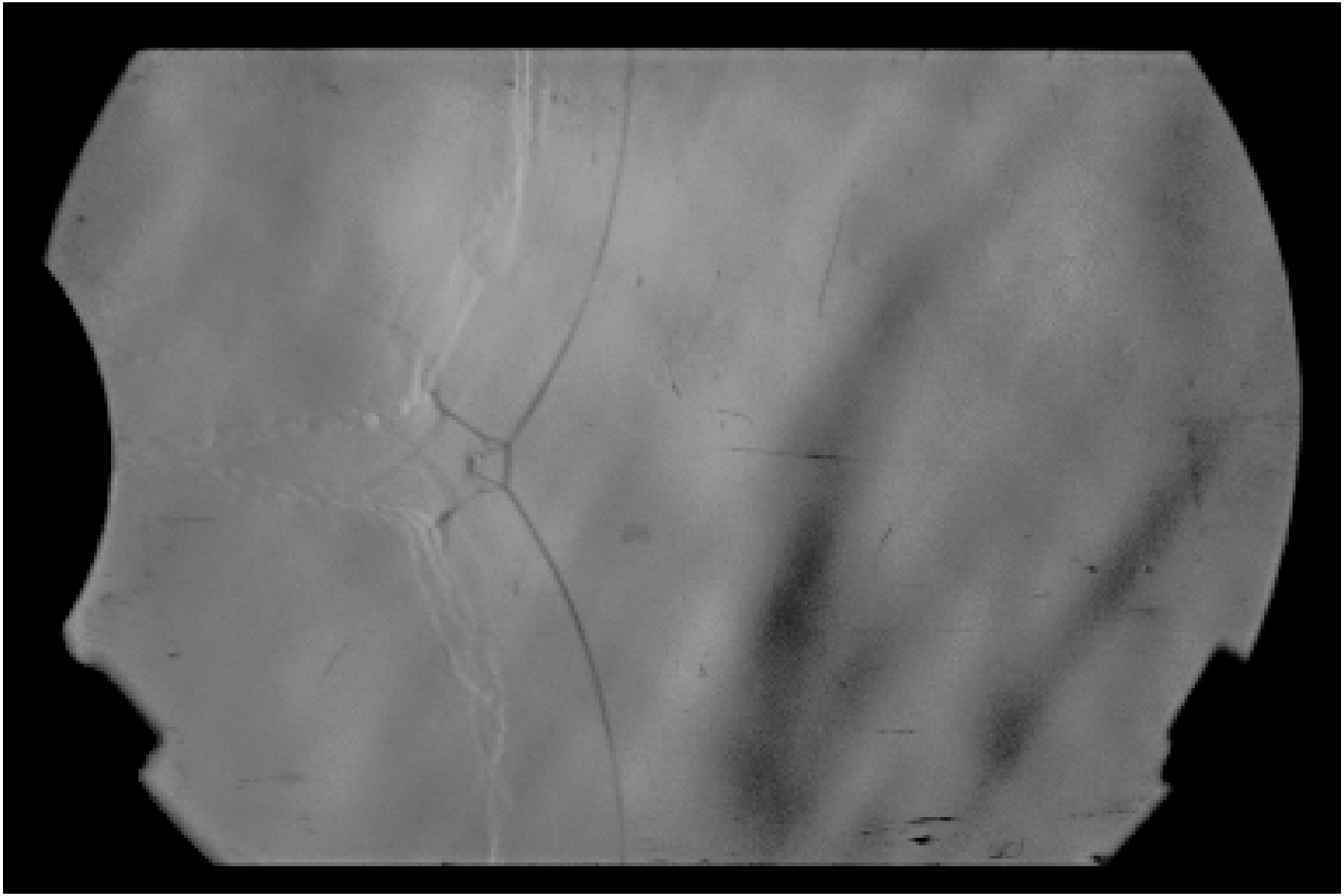

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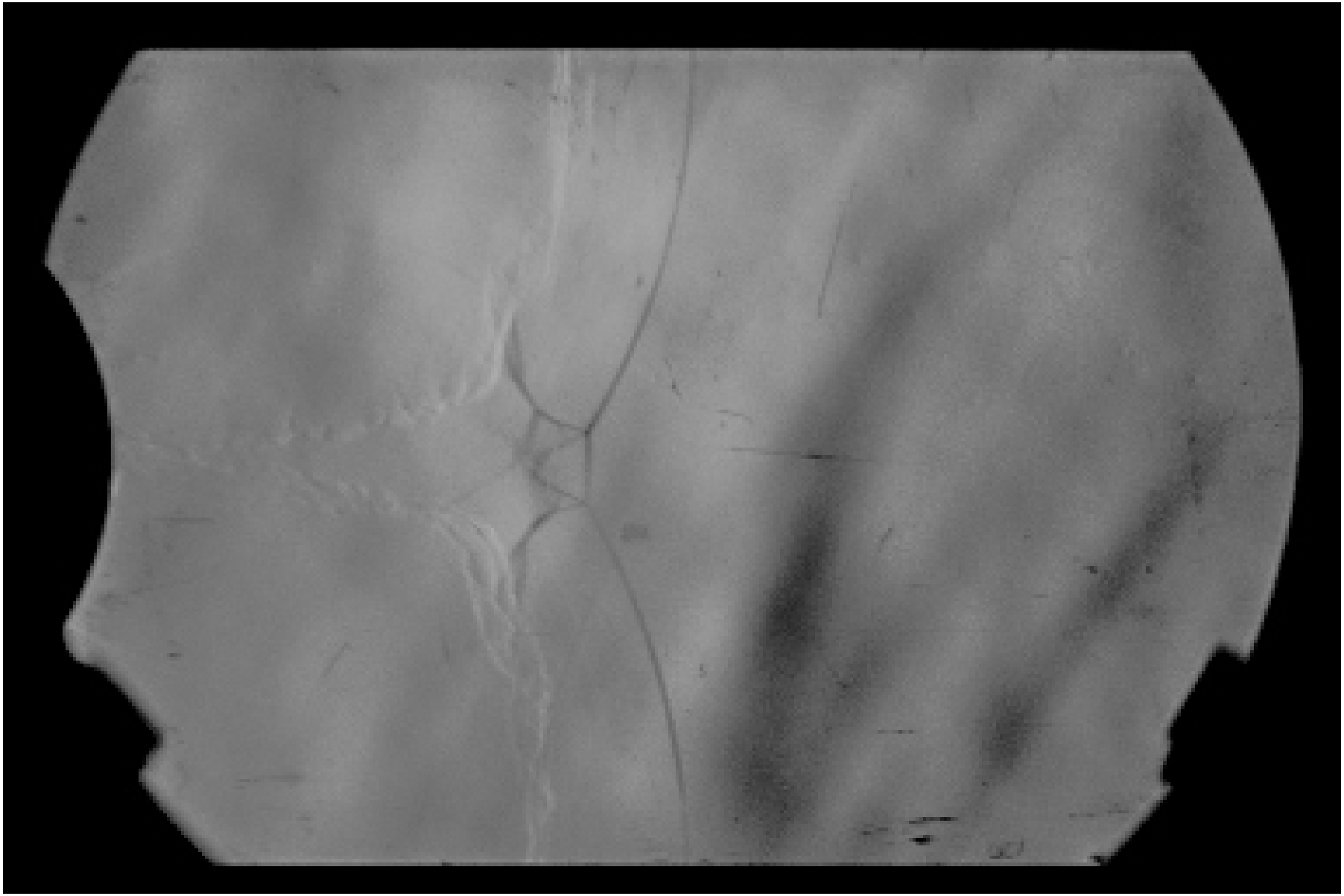

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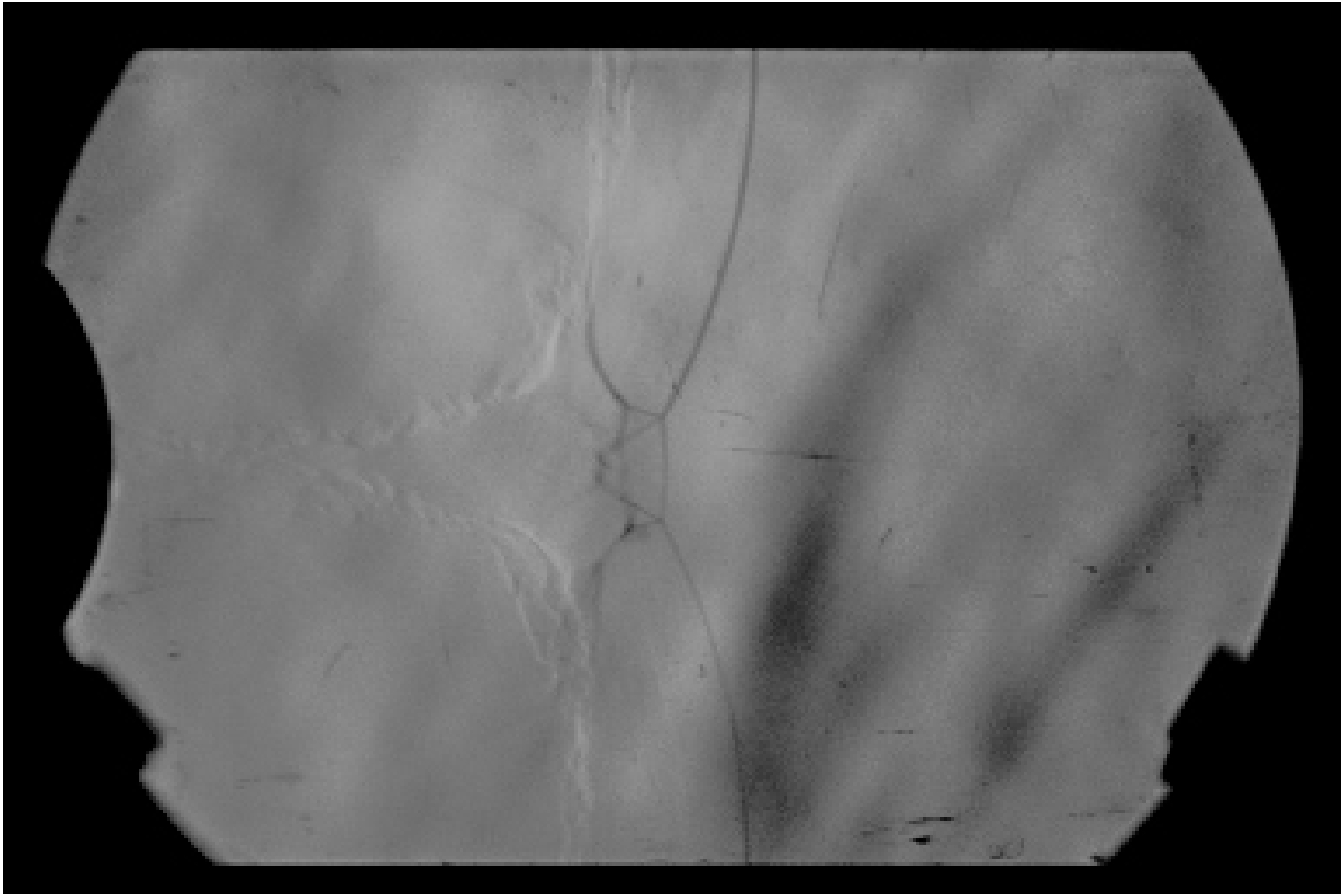

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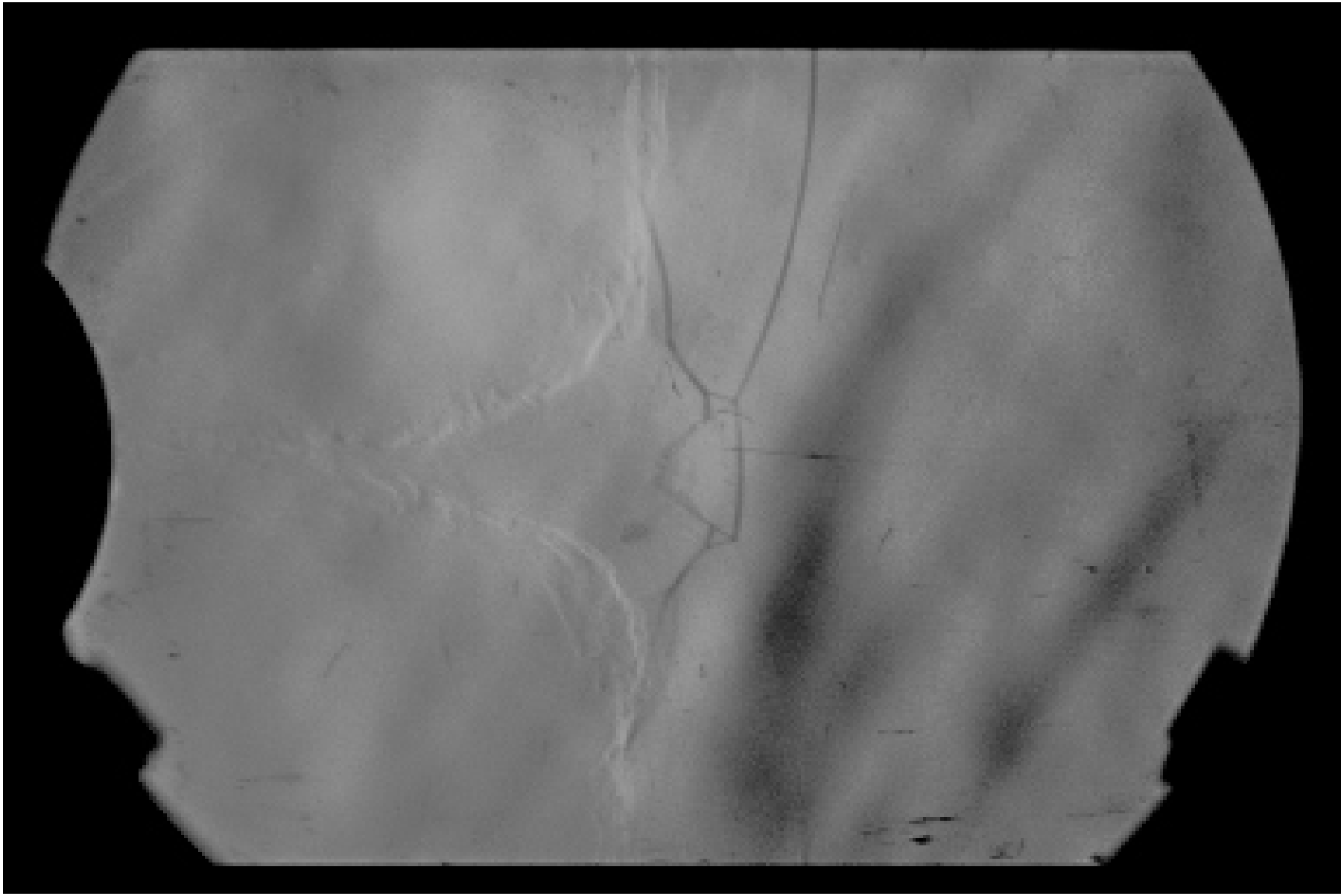

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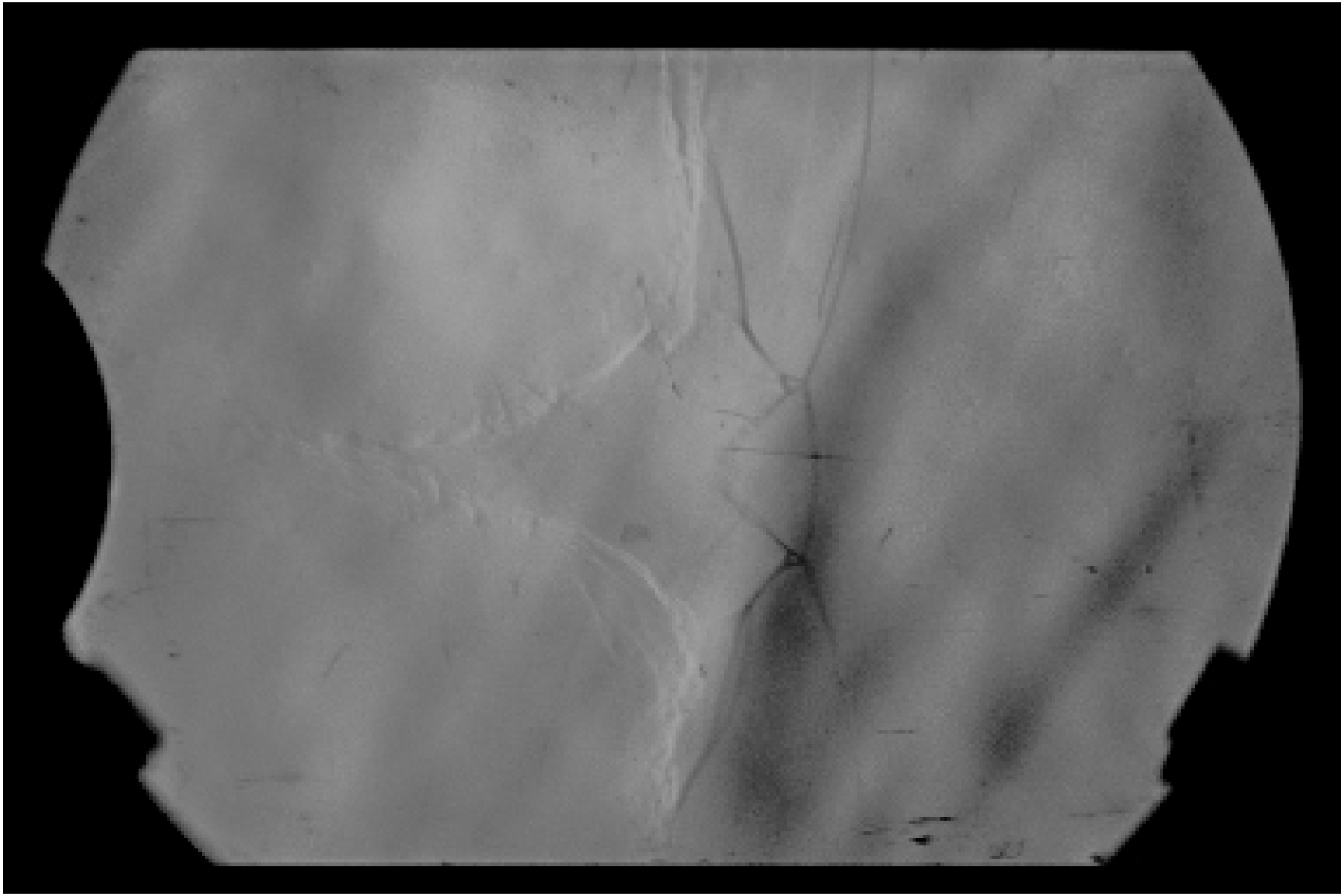

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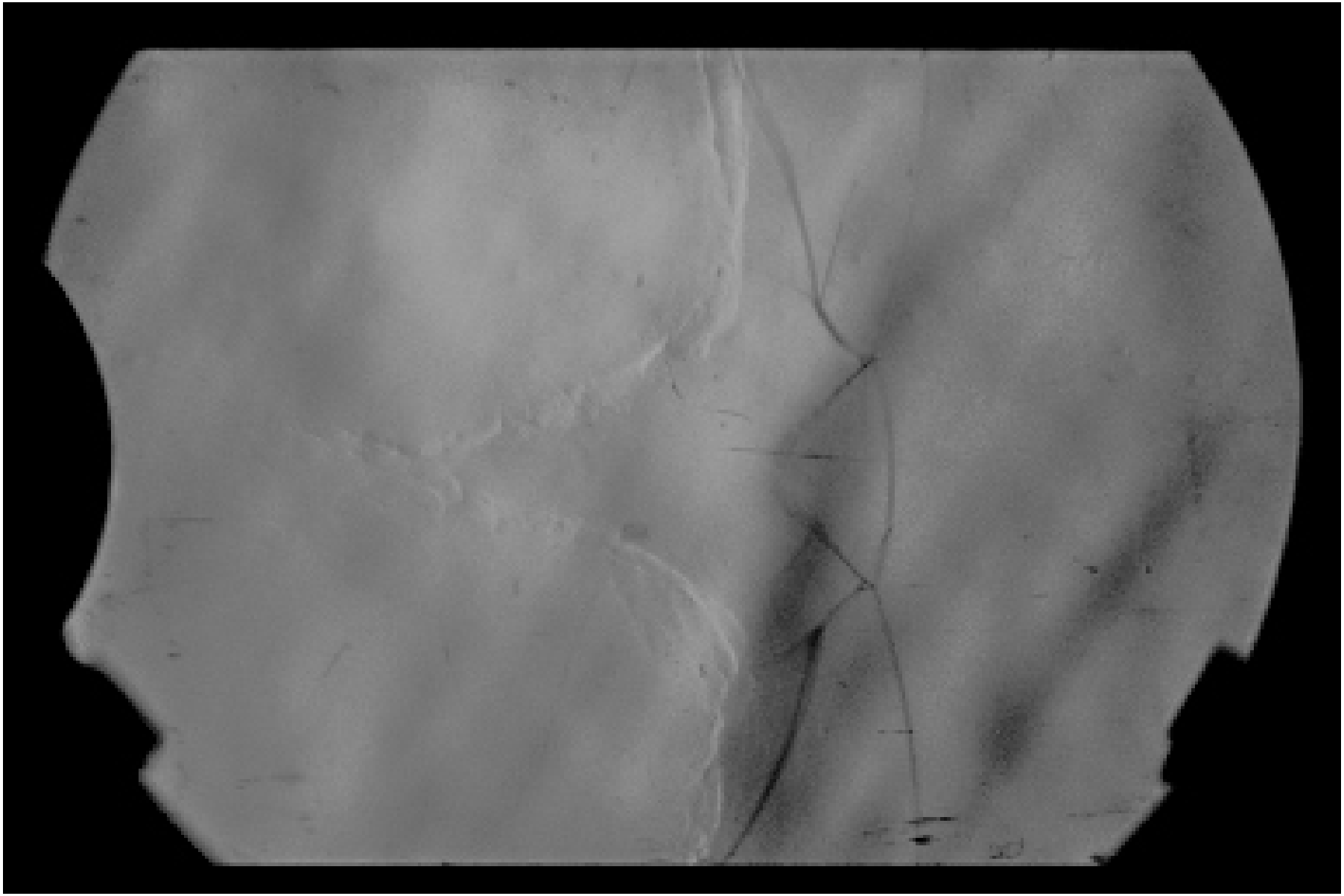

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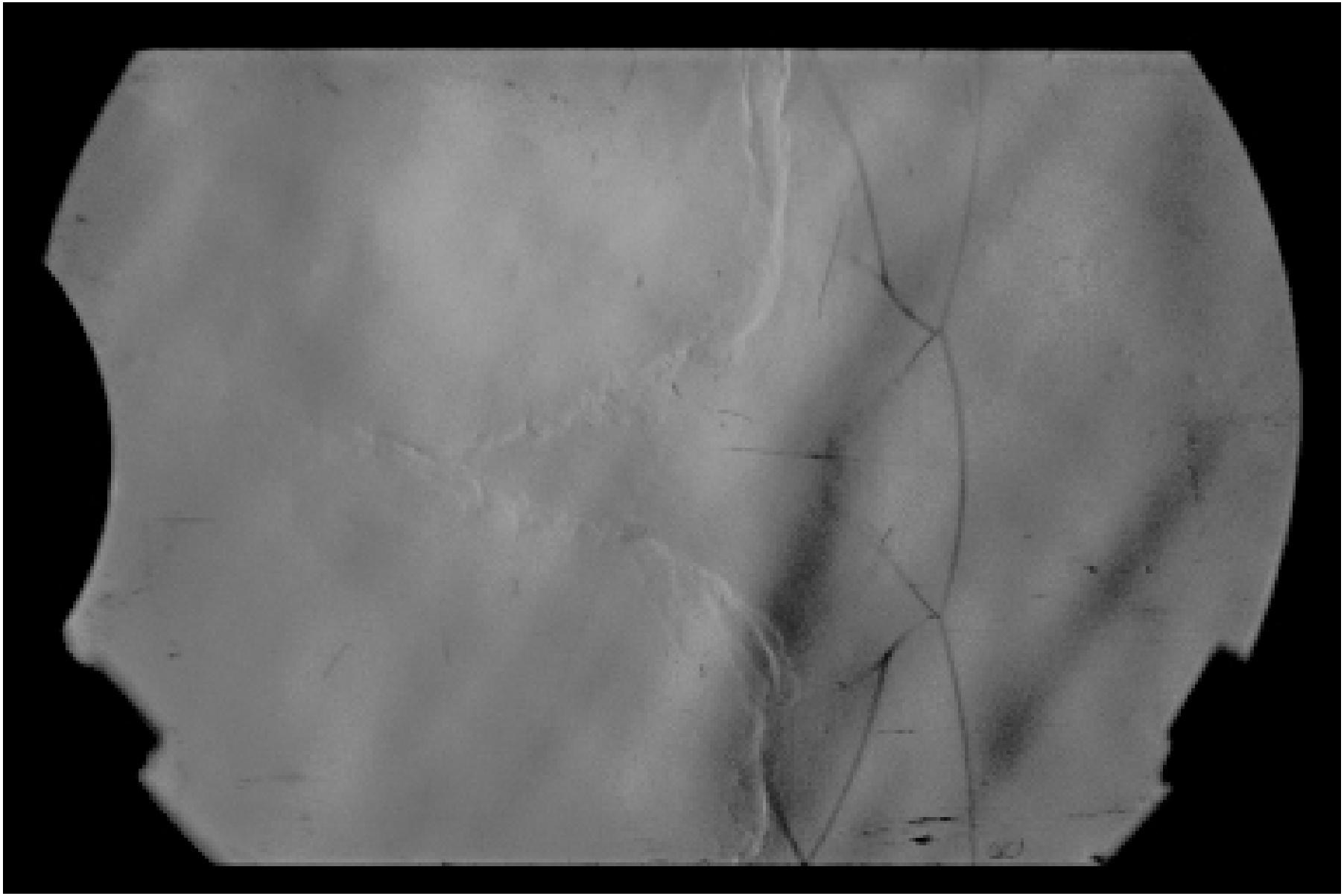

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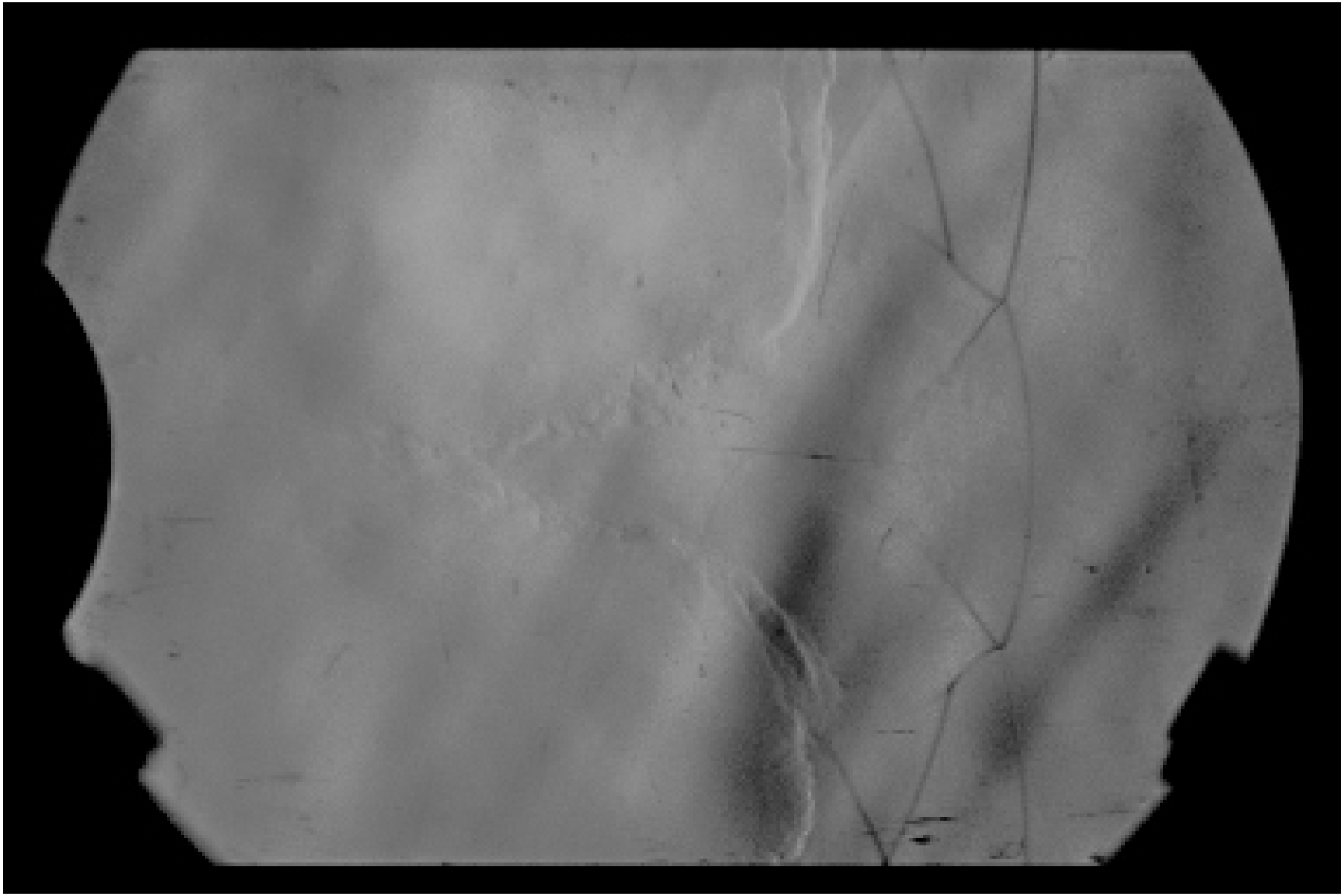

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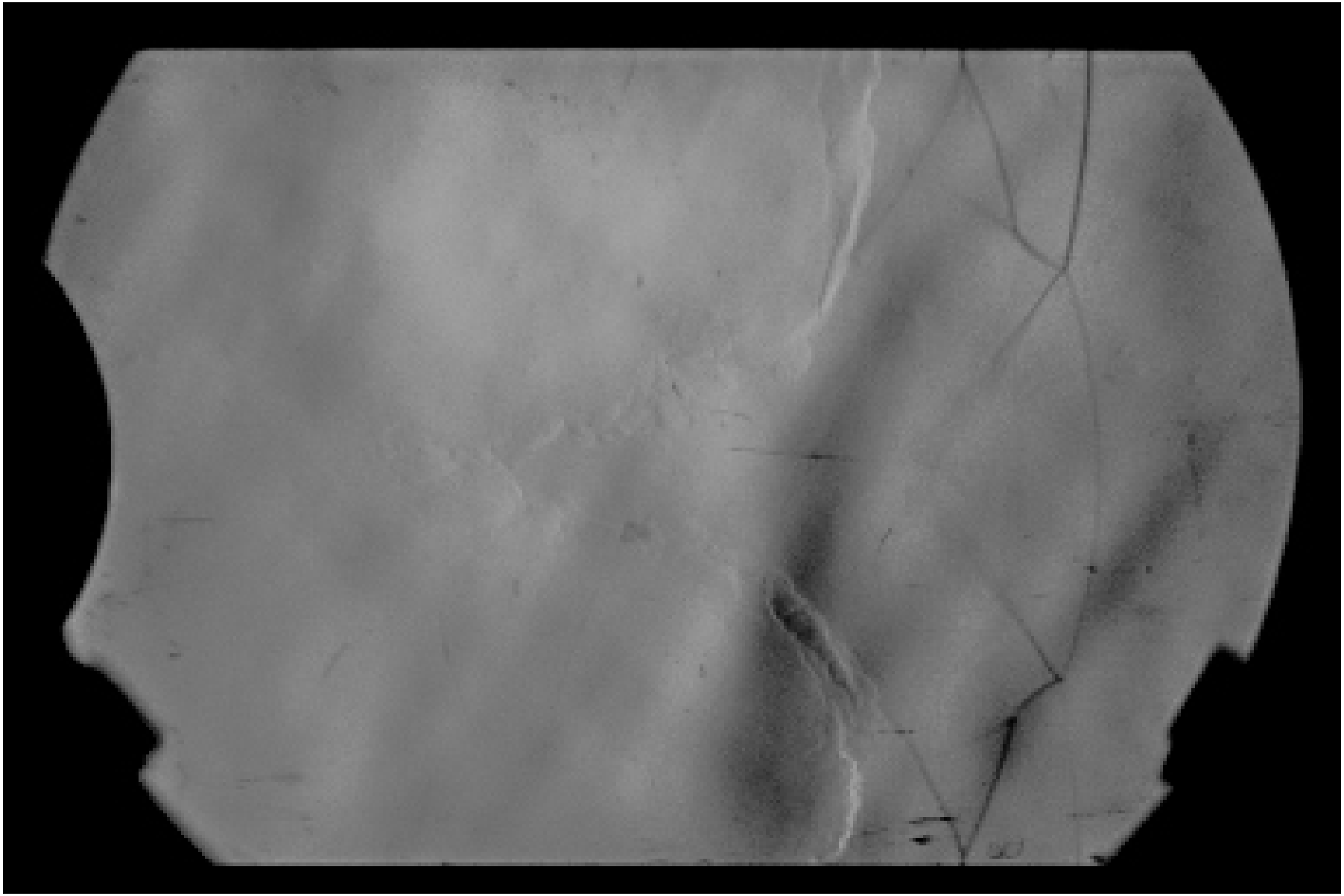

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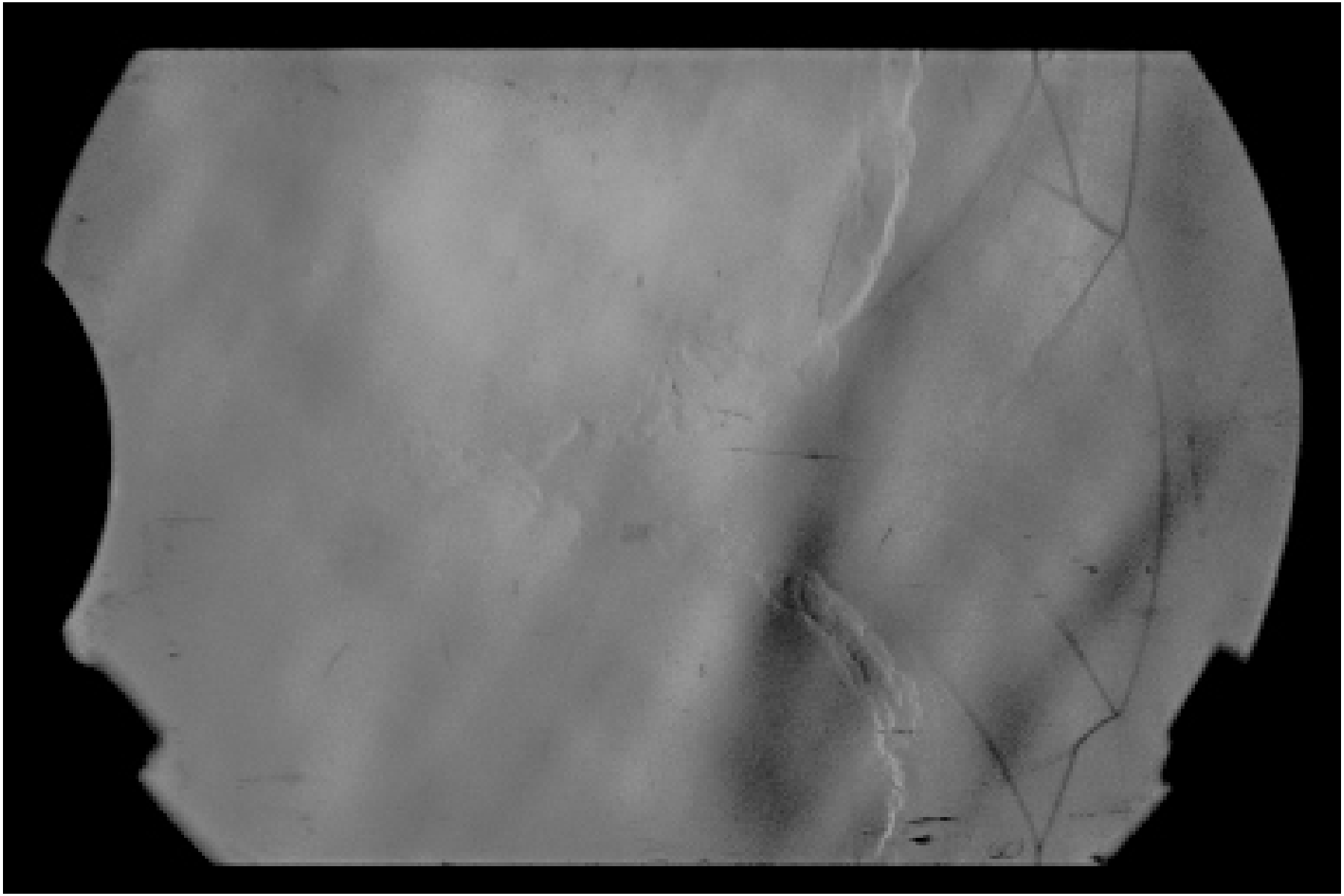

$2H_2 + O_2$ P_o = 10.3kPa

Conclusion

The hydrodynamics causing the forward jet behind the Mach reflection are seen to be responsible for the fast flame acceleration leading to detonation ignition.

Oxy-Hydrogen has been seen not to display this hydrodynamics behavior as hydrocarbons to resulting in a smaller range of conditions for detonation ignition.

Thank you