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Real-Time Observations of Microstructural Evolution in Compressed Ice

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ABSTRACT

Understanding ice deformation under mechanical stress is crucial for ice engineering applications, yet real-time observations of microstructural changes remain limited. Previous studies have relied on post-test analysis or indirect methods, leaving gaps in the understanding of dynamic recrystallization and pressure melting processes as they occur. To address this, a novel experimental apparatus was developed to directly observe these phenomena in compressed ice. The apparatus enables real-time visualization of ice samples subjected to a constant 5 MPa compressive load at controlled temperatures ranging from -20°C to 0°C. Fourteen small-scale compression tests were conducted using 0.8 mm thick, 60 mm diameter ice samples, with in-situ observations captured via a borescope camera under polarized light. This paper reports the observations of dynamic recrystallization and pressure melting seen in these experiments.

Dynamic recrystallization was observed as a key deformation mechanism, with grain nucleation being the primary recrystallization process at temperatures below -3°C and grain boundary migration becoming the primary process at temperatures closer to the melting point. Pressure melting was documented within 0.1°C of the melting point, initiating at grain boundaries in localized parts of the sample and causing microstructural rearrangement under applied pressure. These findings provide new direct observations of ice behavior under mechanical stress, improving the understanding of ice failure mechanisms.

KEY WORDS: Ice mechanics; Dynamic recrystallization; Pressure melting; Compression testing.

1. INTRODUCTION

Ice deformation under mechanical stress plays a critical role in ice engineering, particularly in the design of offshore structures, icebreakers, and other maritime applications. The failure of ice under compressive loads involves complex microstructural changes, including dynamic recrystallization and pressure melting. While previous research has provided indirect evidence of these processes using methods such as microtomed thin-section analysis post-test (e.g., Mackey et al., 2007), real-time observations remain scarce. This study aims to address the gap in real-time observations using a novel experimental apparatus designed to capture in-situ microstructural evolution in compressed ice. This is accomplished by loading a cold, confined thin-section of ice under a constant pressure, then raising the temperature and observing microstructural processes in the ice as it approaches its pressure melting temperature.

In this paper, dynamic recrystallization in ice refers to the formation or evolution of new grains within the ice structure while it is undergoing mechanical deformation, particularly under compressive stress. Two main mechanisms are involved: grain nucleation and grain boundary migration. The process of grain nucleation refers to the formation of new, small ice grains in regions of high strain, that tend to be more dominant at temperatures below -3°C for these tests. Grain boundary migration refers to the process by which larger grains grow at the expense of smaller grains, which is more dominant at warmer temperatures closer to the melting point. Localized pressure melting here refers to localized areas within ice that reach their melting point due to the applied pressure, even if the bulk temperature is below 0°C, due to combined effects of mechanical and thermal energy. Thermal melting here refers to melting processes that occur in ice at atmospheric pressure conditions only and which may be attributed solely to thermal effects.

2. EXPERIMENTAL METHODOLOGY

2.1 Apparatus Design

While other apparatuses have been capable of in-situ recordings of ice under low shear-stress (Burg, Wilson, & Mitchell, 1986), the authors are not aware of any other device available to do the same under higher compressive loads. A custom-designed apparatus was developed to apply controlled compressive loads to thin-section ice samples while allowing real-time imaging under polarized light. The concept drawing of the apparatus is provided in Figure 1 (a). The device consists of an aluminum frame, fused quartz glass discs (22mm thick, 60mm diameter), a borescope camera, and was operated out of a temperature-controlled freezer. The applied pressure was maintained at 5 MPa using a hydraulic hand pump, and temperature was precisely controlled between -20°C and 0°C.

The ice sample (0.8mm thick, 60mm diameter) was prepared using deionized and de-aerated water to minimize impurities. The sample was frozen in place on top of the bottom glass disc, which is sunken into the frame by 0.8mm. A polished aluminum cylinder was then used to flatten the surface of the sample, making the ice sample flush with the surface of the frame. The upper glass disc protrudes 0.5mm from the frame, ensuring that all force was directed into the ice sample, and that the two parts of the frame would not come into contact. During testing, there was a visible gap between the upper and lower sections of the frame, indicating that only the ice was absorbing the applied load. The fabricated apparatus, along with the loading frame and hydraulic pump, is seen in Figure 1 (b).

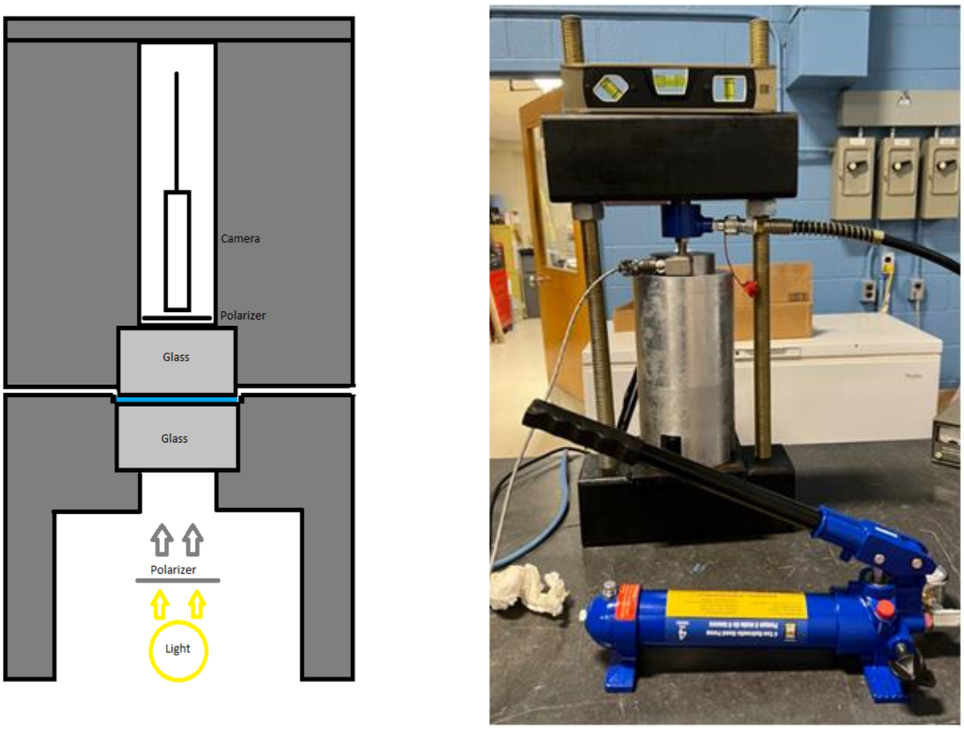

Figure 1 – (a) Conceptual design of the pressure melting observation apparatus; (b) Apparatus in loading frame with hydraulic hand pump.

The testing apparatus was designed to withstand a pressure of up to 15 MPa. A load cell was used to measure applied force to the sample, and a temperature probe embedded in the side of the apparatus to measure the sample temperature. The borescope camera provided a stable, high-resolution view of ice deformation in real-time. Unlike previous methods, which relied on post-test thin-sectioning, this system allows direct visualization of microstructural evolution and recrystallization events as they occur.

2.2 Testing Procedure

Each test followed a consistent protocol in which the sample was placed in the apparatus and allowed to equilibrate to the target temperature. A constant 5 MPa load was then applied, and microstructural changes were recorded using the borescope camera. Images and videos were analyzed to track grain evolution, recrystallization processes, and instances of pressure melting. The experiments lasted up to 24 hours, enabling the observation of both rapid and long-term microstructural changes. Temperature control was crucial, especially near the melting point, where small fluctuations could significantly impact the results.

3. RESULTS AND OBSERVATIONS

3.1 Dynamic Recrystallization

Dynamic recrystallization was identified as a key deformation mechanism in compressed ice. Two primary processes were observed, with the first being grain nucleation and the second being grain boundary migration. In all experiments, following the application of pressure onto the sample, fracturing and rapid internal deformation would occur for approximately 10 minutes. As the fracturing stopped and movement slowed, areas of high strain would develop orange and dark blue patches under the polarized light, seen in Figure 2.

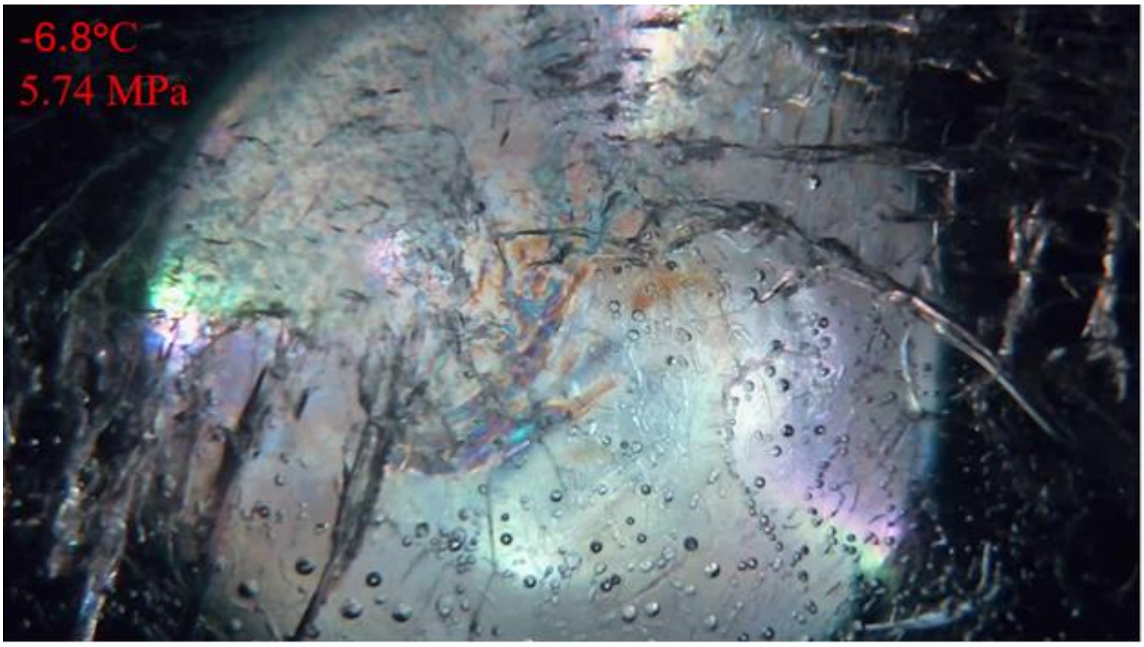

Figure 2 – The blue and orange discoloration of the sample under polarized light indicates an area of high stress 18 minutes following application of pressure.

Grain nucleation results in the formation of new grains within the existing ice structure. In these high-strain regions, continuous dynamic recrystallization in the form of grain nucleation would occur, which aligns with research conducted by Duval et al. (1983) and Jordaan et al. (1999). The initial grains were observed to be less than 1mm in diameter, having little time to grow before being consumed by the nucleation of newer grains. This process effectively resets the grain structure, maintaining a fine-grained texture as long as nucleation processes continue to dominate. However, as the sample reaches an equilibrium state, nucleation slows, and the overall grain size increases as new grains form less frequently, allowing existing grains to expand through grain boundary migration at the given temperature conditions.

Shear stress in ice has long been associated with dynamic recrystallization and grain growth (Burg, et al., 1986). It is observed that when movement—and thus shear—is present in a test sample, grain nucleation continues to occur. As movement slows, nucleation also decreases, eventually ceasing after a sufficient period when the sample reaches a steady state. At higher temperatures closer to the melting point, these processes are observed to occur faster.

Temperature plays a critical role in the balance between grain nucleation and grain boundary migration. At lower temperatures, particularly below -3°C, continuous nucleation appears to be the dominant process, with grain boundary migration occurring at a comparatively slower rate. Figure 3 illustrates this observation. Continuous nucleation is evident, resulting in a visibly different structure each hour. Over time, two factors contribute to a shift in the dominant recrystallization process from nucleation to grain boundary migration. The first is that the sample is gradually compacting and approaching a steady state, reducing the amount of shear stress on the sample. The second is that the temperature is increasing, creating better conditions for grain boundary migration to occur. Thus, as seen in Figure 3, grain boundary migration becomes increasingly dominant resulting in larger grains over time.

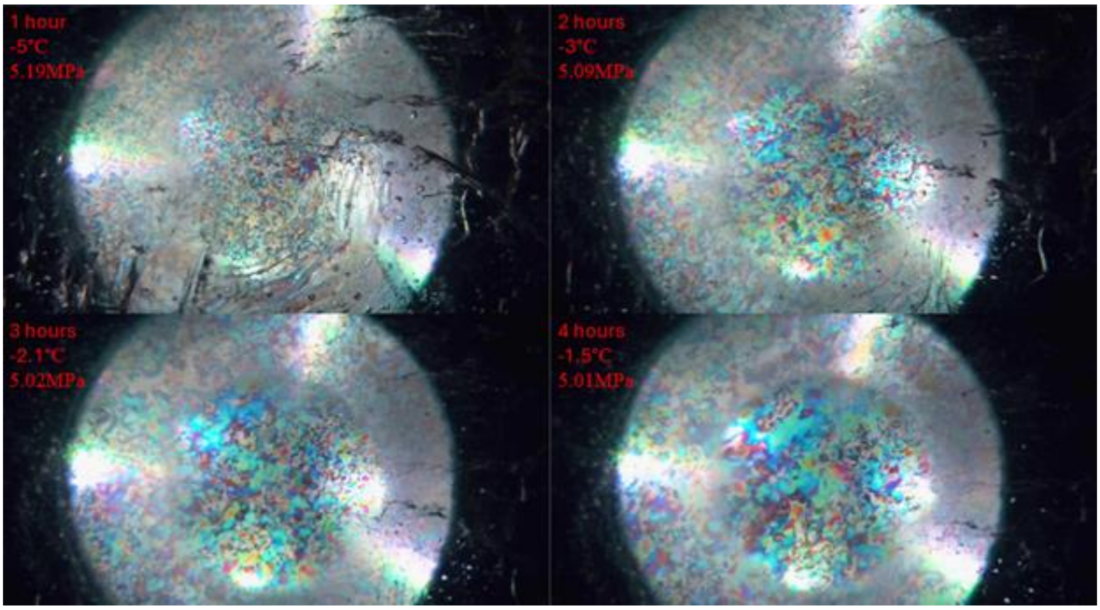

Figure 3 – Progression of grains over 4 hours. As nucleation slows, the grains grow slightly larger – typically occurring once temperatures exceed -3°C.

Grain boundary migration, the second recrystallization mechanism, occurs when larger, more energetically stable grains grow at the expense of smaller, less stable neighboring grains. This process is driven by the reduction of grain boundary energy and becomes more dominant at higher temperatures, particularly observed above -3°C during these experiments. As movement of the sample slows and nucleation rates decline, grain boundary migration becomes the dominant recrystallization process and leads to a coarser grain structure, characterized by fewer, larger grains, as shown in Figure 4. Here, a single grain grew to dominate the surrounding structure as nucleation ceased and existing grains began to consume their neighbors.

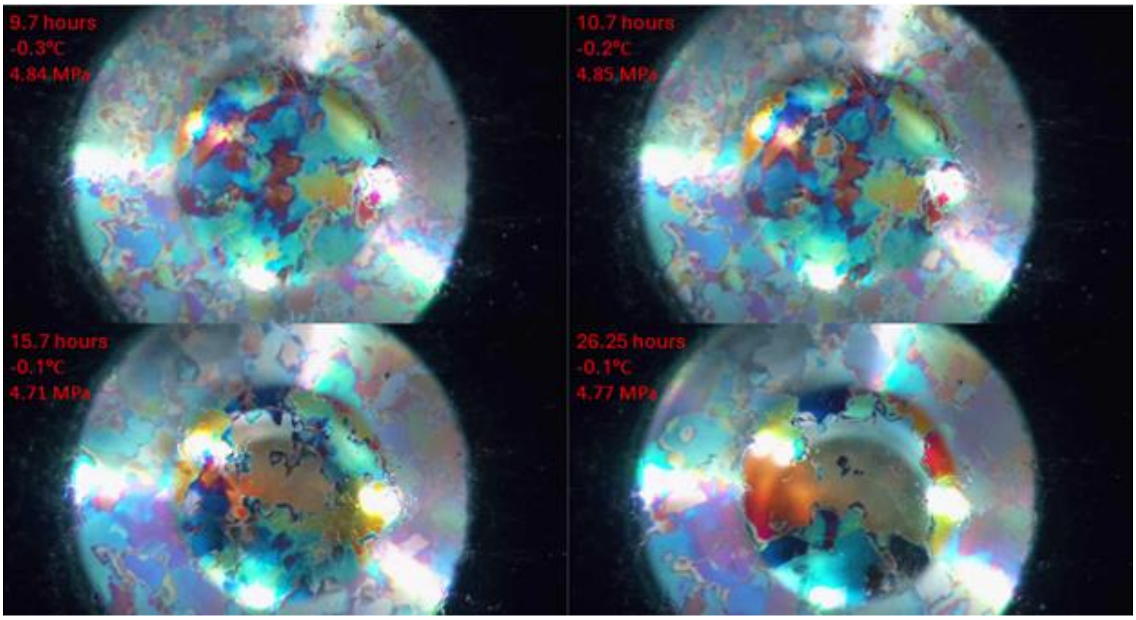

Figure 4 – Grain boundary migration occurs at temperatures near the melting point, resulting in fewer, larger grains.

Temperature appeared to be a key factor in which process, either grain nucleation or grain boundary migration, was dominant in the formation of the grain structure. To demonstrate this, a test was conducted where the temperature was held at approximately -18°C (left in Figure 5). After 24 hours under a pressure of 5 MPa, the grain structure consisted of many small, less than 1mm in size, grains. This suggests that there was minimal, if any, grain boundary migration under these testing conditions. In contrast, a warmer sample maintained between -0.1°C and 0°C (right in Figure 5) exhibited rapid initial nucleation followed by aggressive grain boundary migration, producing fewer, significantly larger grains after 22 hours. These results demonstrate the strong temperature dependence of dynamic recrystallization processes in compressed ice – with the final grain structure differing based on whether grain nucleation or grain boundary migration is the dominant process. In colder cases where grain nucleation remains the dominant recrystallization process, a fine grain structure is produced, featuring many small grains. In warmer tests, while grain nucleation dominates the initial grain structure, it is quickly overtaken by grain boundary migration, which results in a coarse grain structure with relatively fewer, larger grains.

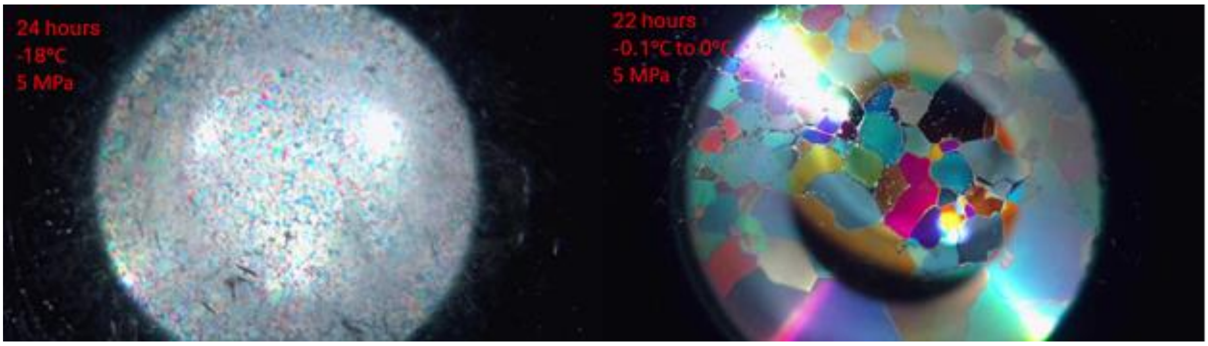

Figure 5 – Comparison of maintained cold temperature (left) and warmer temperature (right) to demonstrate prevalence of grain nucleation vs. grain boundary migration at different temperatures.

3.2 Pressure Melting

Localized pressure melting (LPM) refers to smaller-scale instances of melting that may occur due to high-pressure conditions within ice-structure interactions, potentially leading to recrystallization and pressure softening (Jordaan, 2001). The significance of pressure melting as a failure mechanism in combination with dynamic recrystallization is supported by Gagnon (1998), who performed medium-scale indentation experiments on Hobson's Choice Ice Island, producing visual records of ice behavior during crushing. These observations revealed significant surface spalling and the development of highly crushed ice zones beneath the indenter. Although internal grain structures could not be resolved in those tests, the visual evidence suggested the formation of a slurry-like material at the contact interface. This behavior was attributed to intense crushing and the wetting of grain boundaries, implying that localized melting or pressure-induced softening may occur during the process. Further support for this interpretation was again provided by Gagnon (2002), who reported strong experimental evidence of dynamic recrystallization and localized melting during high-strain ice crushing. The resulting microstructural changes and fine-grained zones pointed to the presence of a thin liquid layer within the crushed region—formed through grain boundary wetting and high-pressure melting—which contributes to local softening and may influence the macroscopic failure response.

In high pressure zones, or areas of high pressure within the ice sample, the melting point is expected to drop by approximately -0.5°C based on the Clausius-Clapeyron equation at a pressure of 5 MPa (Taylor, 2010). Throughout the experiments, there were multiple incidents of observable local pressure melting. In most cases, this occurred in experiments in which pressure is applied on the ice at a relatively warmer temperature of between -1°C and 0°C.

During all experiments in which pressure was applied near 0°C, LPM was observed. Upon loading, melting occurred in localized areas where the pressure was sufficiently high, as the ice's initial thermal state provided enough energy to trigger the phase transition. This resulted in individual pockets of melt within the ice sample, which formed approximately 30 minutes after pressure application and continued to expand until 2.5 hours following pressure application. Much of the ice remained as is, presumably due to these areas being under less local pressure. This can be observed in Figure 6.

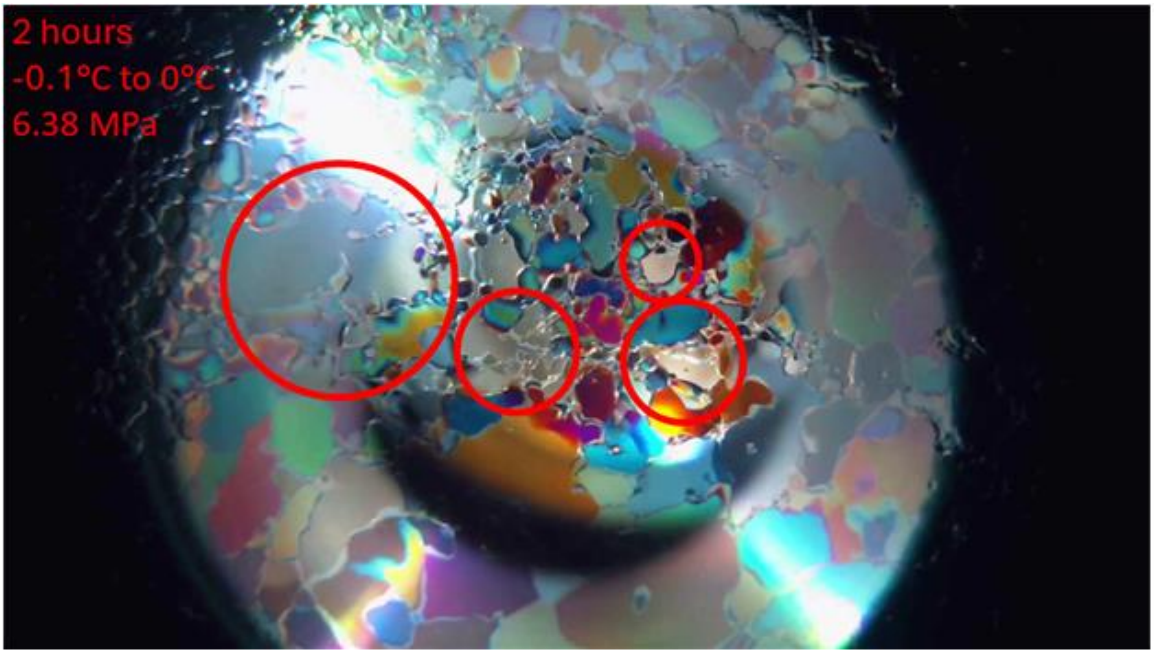

Figure 6 – Localized pressure melting was observed (circled) when pressure is initially applied on a sample near melting point.

Following the instances of LPM, there was observable refreezing. That is, the growth of new ice crystals within the melt as well as the growth of surrounding grains into the melt. An example of this is circled in Figure 7. In this case, once the pool of water stopped expanding at the 2 hour and 30 minute-mark, the pool of melt slowly began to shrink as the surrounding grains started to refreeze and expand into the melt. At the same time, some of the small pieces of ice floating within the melt acted as nucleation sites for new ice crystals. These processes continued until all of the melt had turned back into solid ice around the 10-hour mark. The temperature of this experiment was between -0.1°C to 0°C and pressure at 6.2 MPa. These values remained consistent throughout the experiment, suggesting that the melting and refreezing were due to internal processes occurring in the ice sample rather than any external factors. It is likely that the ice relieved stress and pressure by melting, which allowed the redistribution of these forces to other parts of the ice, a mechanism supported by past research (Barnes & Tabor, 1966). Once the localized pressure dropped, the melting point and freezing point rose, and the water was able to freeze back into ice over time.

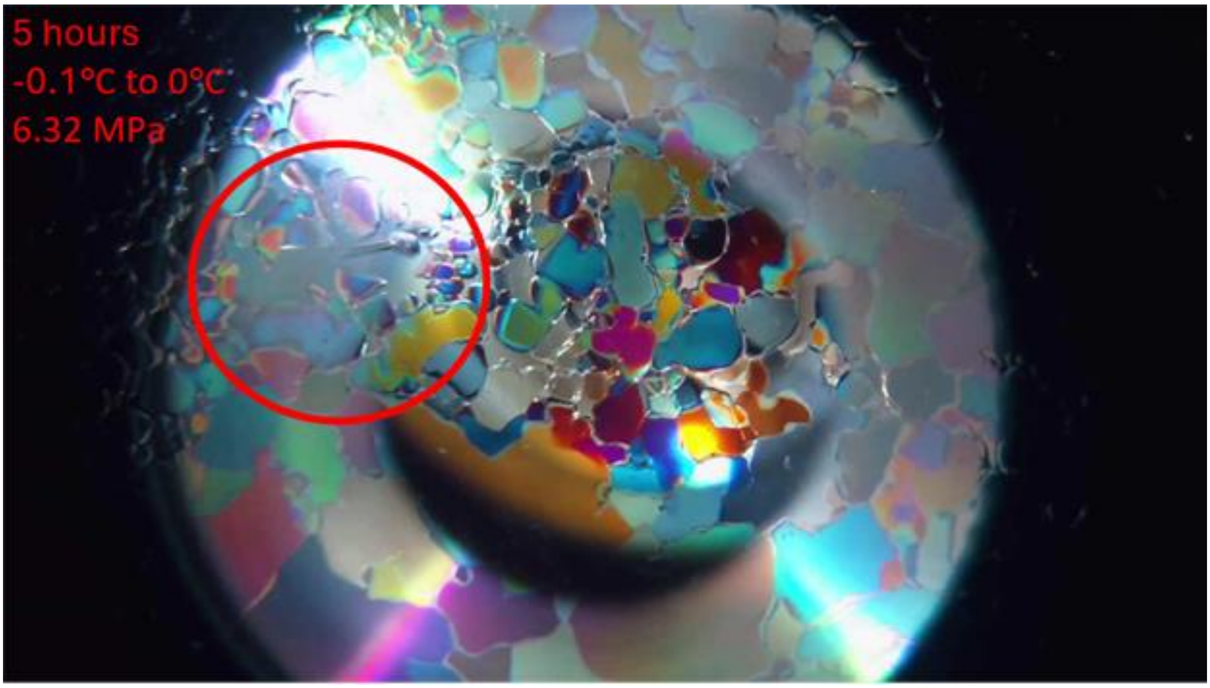

Figure 7 – Refreezing (circled) following localized pressure melting at constant pressure and temperature.

4. CONCLUSIONS

This study presents real-time observations of microstructural evolution in compressed ice, offering key insights into dynamic recrystallization and pressure melting. The results reveal that continuous grain nucleation with minimal grain boundary migration dominates at lower temperatures, while rapid nucleation followed by significant grain boundary migration occurs near the melting point. Pressure melting is identified as a mechanism for stress redistribution, observed primarily under conditions where the applied pressure coincides with temperatures close to the melting point. Overall, temperature plays a critical role in controlling the rate and nature of dynamic recrystallization, with faster and more extensive processes occurring at higher temperatures. Future work is recommended to incorporate stereographic analysis and to explore the integration of an automatic ice fabric analysis system into the experimental apparatus. These enhancements would allow for more precise quantification of evolving ice fabric and texture, and support the development of theoretical models describing these microstructural processes.

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