Design, characterisation and performance evaluation of a Peltier-driven cryo-adhesive fixture for manufacturing operations

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Abstract
Workholding and fixturing is a critically important aspect of manufacturing that has direct implications for the quality of the manufactured component during processing as well as a direct impact on the cost of the component. The field of workholding is mature with numerous techniques employed, mostly using contact pressure, but also using magnetics and adhesives. Looking to nature for inspiration presents us with the use of ice as a mechanism for adhesion, referred to as cryo-adhesion. Cryo-adhesion offers some advantages over more traditional fixturing methods such as removing contact pressure and therefore reducing the dependence on the machining of complex, intricate bespoke fixtures. While the concept of ice adhesion is known, there is minimal research presented on the application of ice adhesion in manufacturing processes. This research reports on the development of a novel Peltier-based cryo-cooling fixture for workholding in manufacturing operations. The research provides insight into the main interactions that might be experienced in manufacturing type scenarios and presents findings on the cryo fixture's thermal and geometric characteristics, the use of the novel cryo fixture for holding various materials under tensile and shear loads, and a consideration of contact area and surface roughness on the cryo fixture performance.

Keywords
Ice adhesion; workholding; grasping; Peltier cooling; thermoelectric; manufacturing technology;

1. Background

The ability to hold and manipulate workpieces during manufacturing processes is critical to the production of high-quality product [1]. Traditionally, simple vices and other mechanical fixtures and clamps could be used to keep workpieces in place through contact pressure. For example, in recent decades milling, drilling, and grinding processes have been extended to progressively smaller and more delicate parts as the micro/precision manufacturing space has grown. Traditional clamping and fixturing principles based on contact pressure are often unsuitable for delicate manufacturing applications. This has led to the development of a variety of other clamping techniques and mechanisms, each with its unique set of benefits and drawbacks. A study of current manufacturing practices reveals that vacuum, magnetic, electrostatic, adhesive and nesting clamping techniques have already been adopted [2-4]. An alternative nature-inspired approach considers the use of ice as an adhesion mechanism. This research focusses on the development of an ice/cryo based fixture mechanism for manufacturing applications which is driven by Peltier cooling.

To date, the application of cryogenics in manufacturing has largely been focussed on cooling and stiffening workpieces during metal cutting processes as reported by Shokrani et al. [5] and Jawahir et al. [6]. Cryo adhesion has received little attention in this space. Cryo-adhesion is based on the formation of ice and it is known that when the temperature of a solid making contact with water falls below the freezing point, nuclei of solidified ice crystals begin to form as illustrated in Figure 1. Homogeneous nucleation occurs spontaneously throughout any water that has fallen below freezing. Heterogeneous nucleation, which occurs more frequently and rapidly, occurs against the cold solid surfaces and also against particles of impurities throughout below-freezing water [7]. The primary nucleation sites occur far from one another such that no significant interactions exist between them. Once lone ice crystals have formed in the water, they act as nucleation sites for further crystals to develop. Secondary nucleation is differentiated from later crystal growth by the fact that many ice crystals forming during this phase break free of the nucleation sites, and are left suspended in the water, possibly acting as further nucleation sites [8].

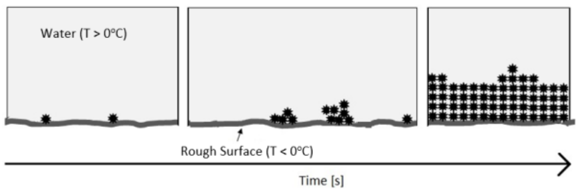


Figure 1: Primary and secondary nucleation, and bulk freezing, at the water-solid interface

The nucleation sites will grow in size and develop into multi-molecule grains. The grains will meet and join, forming ice crystals on a bulk scale. For the orientation described in Figure 1, a layer of ice will form from the bottom surface upwards.

From the literature it would appear that predicting the adhesive force of ice is difficult. It has long been suggested that a thin, amorphous, liquid-like layer can be assumed to exist between ice and the substrate it is bonded to. Indeed Faraday proposed the concept in 1859. The theory was developed by Weyl [9] and subsequently formalised by Jellinek [10, 11]. Many subsequent researchers have partly based their theory on Jellinek's work [12-16]. The layer explains why ice-substrate interfaces are generally stronger in tension than shear, since surface tension forces must be overcome in tension as opposed to only frictional forces in shear. This layer is assumed to have a high viscosity. At lower shear rates, the ice and substrate move relative to each other. At greater shear rates, the layer does not have time to adjust to the required velocity, and fractures [10, 11].

In 2012, Makkonen [17] extensively reviewed the literature published on ice adhesion and concluded that, although trends can be identified, the mechanisms dictating adhesion strength are still poorly understood. Makkonen [17] states that the elastic modulus of ice strongly depends on its temperature. It is well established that the adhesive strength of ice increases as the interface temperature falls from freezing point downwards [18]. Raraty and Tabor [19] illustrated this theoretically and experimentally with a range of materials in shear. Combined with data from Jellinek [10, 11, 20], it was shown that the adhesive strength of ice increases with falling temperature only to a certain extent, after which the strength plateaus or decreases. Detach mechanisms were noted to fall into two categories; adhesive and cohesive. Adhesive detach/breakages refer to those where the fracture occurs at the ice-solid interface, and cohesive detach/breakages occurs within the ice bulk. The breakage type can be identified by the presence or absence of ice left on the solid post-fracture. It is thought that at this temperature, the adhesive strength of ice, which grows with decreasing temperature, surpasses the cohesive strength which either falls [11], or plateaus [19], with decreasing temperature.

The research examining the relationship between stress or strain rate and the adhesive strength of ice is limited. Sonwalkar et al. [16] proposed that ice-metal interfaces are sensitive to strain rate, while ice-polymer interfaces are strain insensitive. Jellinek [10, 11, 20] tested the effects of stress rate on steel and polystyrene in tension, and the effects of rate of travel on steel in shear. It was found that the stress rate did not have any effect on the tensile adhesive strength, and that shear adhesive strength increased with increased rate of travel.

The work of adhesion of ice has also previously been estimated in terms of contact angle, providing a measure of the wettability of the interface and thereby providing measure of likelihood of a strong ice bond to the substrate [17]. Several researchers have attempted to relate the contact angle of water with the adhesive strength of ice on various surfaces. Landy and Freiberger [14] and Sonwalkar et al. [16] found weak correlations between contact angle and adhesive strength. However, Meuler et al. [15] found a strong relationship between the equilibrium angle (based on advancing and receding contact angles) and adhesive strength.

Landy and Freiberger [14] also attempted to correlate the adhesion strength of ice with various properties of the substrate. The substrates tested were a range of polymers including Teflon, nylon, polycarbonate, and Plexiglas. No clear correlations were found between adhesive strength and the substrates' coefficients of linear expansion, tendency to absorb water, or relative permittivity. However, it was determined that decreasing substrate flexibility increased adhesive strength, with two alternative methods being tested: increasing substrate thickness and using substrates with greater flexural moduli. The results were later disputed by Archer and Gupta [12] who claimed that in such tests it was impossible to discriminate between the effects of variables separately. Makkonen [17] suggested that the failure mechanism at the interface may vary with the flexibility of the interface.

The adhesive force per unit area between ice and a substrate is weaker when the true interface area is less than the apparent one [17], and stronger when the true interface area is greater than the apparent one. For the former, this can occur when there are very small air bubbles located at the interface, or when micro-pores of the substrate are not filled with water due to hydrophobicity. For the latter, roughness on the microscopic scale can lead to increased adhesion. Several researchers have investigated the relationship between substrate surface roughness and adhesive strength. Jellinek [20] showed both shear and tensile strength decreasing as a stainless steel substrate was smoothened, a result that was supported by the work of Hassan et al. [21] who found a strong positive correlation between shear adhesive strength and the surface roughness of an aluminium substrate. These authors concluded that increasing substrate roughness generally increases strength, as water flows into substrate pits and pores before freezing, leading to strong mechanical interlocking. It is known that increasing the surface roughness of a substrate does not always increase wetting [22]. According to the Wenzel wetting model, water molecules fill all bumps and crevices on a surface, increasing the solid-liquid interface area. On the other hand, the Cassie model postulates that gas remains trapped in the crevices, underneath the water droplet, restricting the interface area. Determining the conditions under which either the Cassie or Wenzel state is dominant, and understanding the mechanisms behind the transition between the two, is currently of interest to researchers [22].

The influence of surface contaminants on ice-solid adhesive strengths is substantial [23]. Very thin films of oil-based lubricants can greatly reduce adhesive forces. It was found that, in the absence of proper cleaning to remove contaminants, leaving water to sit on the surface for a few hours before freezing can restore adhesive strength.

1.1 Cryo based workholding

There exists a limited number of published studies of cryo fixture technologies for manufacturing available in scientific and engineering literature. Ice gripping has been explored in relation to grasping and holding materials in the micro-manufacture industry, such as those in [24-26].

A small number of authors have studied the potential of ice gripping devices in macro-manufacturing. Jou [27, 28] studied the optimal design of a Peltier module freeze chuck. In the design, water was pumped through channels to cool the hot side of the Peltier modules. It was found that the Peltier modules could reduce the top of the plate to a low and stable temperature more rapidly with greater mass flow rate through the cooling channels, and greater turbulence. Smooth channels resulted in the longest time to steady-state, whereas transversely-ribbed channels resulted in the shortest cooling time. The research suggested that altering the coolant temperature will not significantly reduce the time taken to reach steady-state, but will affect the value of the steady-state temperature.

Kitajima et al. [29] studied the potential of a freeze chuck system for manufacturing thin and brittle parts such as silicon wafers. Also using Peltier modules for surface cooling, the researchers compared the cooling characteristics using steel and molybdenum surfaces. It was found that the molybdenum plate surface cooled to a much lower temperature (-18°C) than steel (-6°C), using identical electric and coolant parameters. The molybdenum plate also fell below zero far faster than the steel.

An alternate method of cooling the Peltier modules was proposed by Kashimura et al. [30] who used an FEM model to suggest that high-velocity compressed air may be used as the cooling fluid in a Peltier-driven freeze chuck. The researchers attached a set of aluminium fins to the hot-side, and blasted it with air to successfully remove heat.

Bahar et al. [31] studied the feasibility of submerging a workpiece in a water container before freezing the container to secure the piece in position. A cylindrical tank just under 1 litre in volume was filled with distilled water at an ambient temperature of 25°C. The tank had hollow walls through which a denatured alcohol of 95% ethanol was pumped. This coolant was maintained in liquid form at -20°C throughout the tests. The tank was placed in an ice-water bath of 0°C, and a workpiece was partially submerged in the distilled water. After 90 minutes of coolant being pumped through the hollow walls of the tank, the distilled water had frozen, and the workpiece was securely clamped in place.

1.2 Research objectives

Clearly, much work has been published on the fundamentals of ice and ice adhesion but far less on their potential application to new technologies, in particular those relating to ice clamping and the use of ice for workpiece holding in manufacturing. Due to the inconsistencies in published results relating the adhesive strength of ice to various parameters, it is clear that much research is required to enhance the technology's suitability for use in mainstream manufacturing. This study aims to further knowledge on the subject of ice adhesion for complex workpiece manufacturing by

- designing and constructing a novel cryo fixture system.
- performing a series of experiments to characterise its thermal behaviour.
- experimenting with different parameters to assess the cryo-fixture's suitability for manufacturing purposes.

2. Cooling fundamentals

There exists a range of cooling technologies which could be used as the cold source for a cryo fixturing device. A typical method of rating the efficiency of refrigerators or coolers is the coefficient of performance, COP, which is defined as

$$\mathrm{COP} = \frac{Q_C}{W} \qquad (1)$$

Here Q_C represents the rate of heat removed from the cold reservoir and W is the work consumed by the heat pump. Higher COPs equate to lower operating costs.

2.1 Thermoelectric theory

A Peltier cooler, also known as a thermoelectric cooler (TEC), is a solid-state heat pump which transfers heat from one side of the device to the other with the consumption of electrical power. Heat flow through the TEC can be directed by controlling the magnitude and polarity of the current. Although these devices can be used as both coolers and heaters, in practice they are more frequently used in cooling applications.

The term 'thermoelectric effect' actually comprises three separately identified effects: the Seebeck, Peltier, and Thomson effects. The Seebeck effect is the conversion of heat directly into electricity at the junction of different types of wire. The Peltier effect is the presence of heating or cooling at an electrified junction of two different conductors. The Thomson effect describes the heating or cooling of a current-carrying conductor with a temperature gradient.

TECs typically have two ceramic faces and when connected to an electrical power source, heat is transferred from one face to the other, thus decreasing and increasing the temperature of the respective faces. TECs are comprised of arrays of p-n semiconductor junctions, arranged thermally in parallel and connected electrically in series. A sketch of a TEC is provided in Figure 2. The performance characteristics of the device depend primarily on the construction materials [32]. The COP of a thermoelectric cooler ranges from approximately. 0.3 to 0.6, increasing with the heat sink's ability to extract generated heat from the hot side of the junction [33]. Peltier-based ice plates are only recently available in the industrial marketplace [34].

Peltier modules have no moving parts, and, excluding the support cooling system to remove heat from the hot junction, no moving fluids. The temperature of the cold side can be set to within a fraction of a degree given suitable control systems. The modules have very long life expectancies, and require near-zero maintenance when operated under stable thermal and electrical conditions. However, the achievable heat flux and maximum temperature gradients are often too small for industrial applications. Commercially available TECs move heat across the junction at a rate of 50 to 150 W, creating a temperature difference of up to 70 K [35].

The pressure must be applied evenly on both faces of the modules. Slight pressure variations across the surfaces are enough to crack the brittle ceramic layer. Since the p-n junctions within the module are connected electrically in series to provide the output, the device cannot usually withstand the breakage of even a single junction [36, 37].

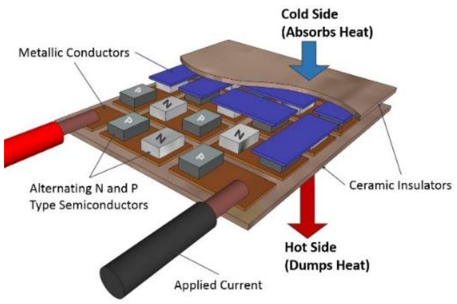


Figure 2: Peltier cooler operation

An applied voltage induces a flow of current across the junction of the semiconductors which causes a temperature difference. Heat is absorbed on the ‘cold’ face and moved to the ‘hot’ face, which is usually connected to some kind of heat sink or heat exchanger.

To describe the cooling process mathematically, various factors must be taken into account. The total amount of heat transfer into the cold side of the TEC, as shown in Figure 3, consists of the algebraic sum of three heat loads:

1. heat pumped by the Peltier effect
2. heat transferred by conduction through the TEC due to the established temperature difference between the hot and cold sides
3. half of the total Joule heating caused by current flow through the device.

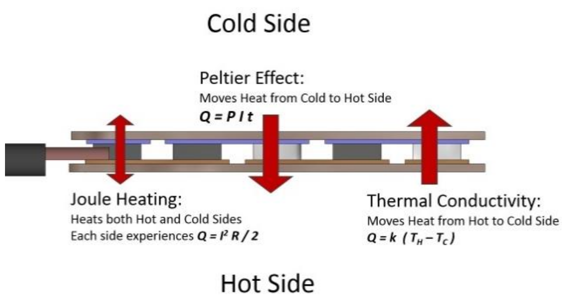


Figure 3: Heat transfer through a TEC

Mathematically, the heat pumped by the cold side, Q_C, is given by

$$Q_C = \alpha_M T_C I - \frac{I^2 R_M}{2} - \kappa(T_H - T_C) \qquad (2)$$

Where α_M, is the module Seebeck coefficient in *V/K* , *I* is the current flowing through the module, R_M is the module resistance in Ohms, κ is the module conductance in W/K, and T_h and T_c are the hold and cold junction temperatures respectively. The input voltage to the module is the sum of the voltage generated due to the Seebeck effect and the voltage drop across the module’s resistance once current is flowing.

$$V_{IN} = \alpha_M(T_H - T_C) + IR_M \qquad (3)$$

Equation 3 leads to the calculation of the electrical input power, P_{IN}.

$$P_{IN} = V_{IN} I \qquad (4)$$

The heat rejected from the module at the hot face is the sum of the electrical input power and the heat absorbed at the cold face:

$$Q_H = P_{IN} + Q_C \qquad (5)$$

3. Cryo fixture design

The cryo fixture presented in this study was designed and manufactured in Trinity College Dublin, Ireland. An illustration of the cryo fixture design is shown in Figure 4. Aluminium was selected due to the thermal properties and manufacturability. Ice adhesion requires a sub-zero surface to hold the workpiece in place. To achieve this, the cryo fixture uses four Multicomp MCTE1-12712L-S Peltier modules to cool the top surface below 0 °C. The modules are arranged in a two-by-two grid 6mm below the top surface and are electrically connected in parallel. The modules are separated from one another by 10 mm. Each module is capable of 110 W of cooling. Further Peltier module specifications are listed in Table 1.

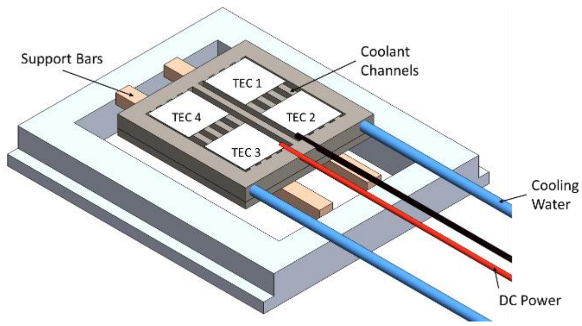


Figure 4: Cryo fixture design

Electric power to the modules is supplied by an AimTTi EX2020R power supply, with a maximum power rating of 400 W. In the current configuration, providing electrical power to the Peltier modules results in a cold upper surface and simultaneously a hot lower surface. To maintain a steady cooling rate, the heat generated on the lower surface of the modules must be dissipated. To this end, the cryo fixture contains a series of channels through which coolant flows, as shown in Figure 4. These channels not only direct the flow of coolant but also increase the effective area for heat transfer. The coolant (distilled water) is supplied by a Fisher Scientific Isotemp 250LC recirculating chiller. This chiller has a cooling capacity of 250 W at 20 °C and an internal reservoir temperature resolution of 0.001 °C. This closed loop cooling method is employed to regulate the temperature on the hot side of the Peltier modules.

Table 1: Peltier module specifications

Dimensions	40 mm x 40mm x 3.7mm
Power Rating	110 Watts
Internal Resistance	1 Ohm
Voltage/Current Max.	15.4 Volts/12 Amps
Temp. Diff. Max.	68 °C
Operating range	-40°C to +90°C

4. Thermal characterisation of the cryo fixture

The cryo fixture creates a ‘cold zone’ measuring approximately 95 mm x 95 mm and verified using a FLIR E50 infra-red (IR) camera, as shown in Figure 5. This camera has a maximum thermal sensitivity of 0.05 °C, and a resolution of 240 x 180 pixels. Since the aluminium has a reflective surface, the fixture was sprayed with a thin layer of black matt paint with a known emissivity of 0.95 to obtain the images shown in Figure 5. The paint was removed using a cleaning agent before further testing, with care taken not to scratch or damage the surface. Figure 5 shows that the cooling is quite localised to the vicinity of the Peltier modules. This results in thermal gradients from the outer edge of the cold zone to the edge of the fixture.

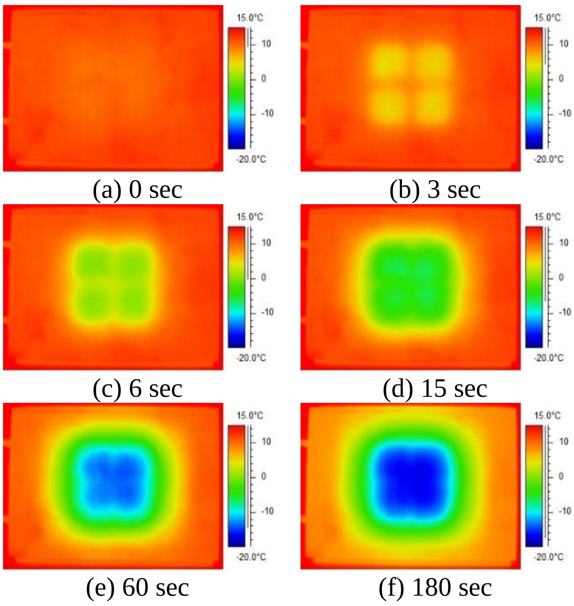


Figure 5: IR images of aluminium surface during transient cooling

Figure 6 plots the surface temperature along a horizontal line taken at the midpoint of the cooling zone as viewed by the IR camera; i.e. between the four Peltier modules. Expectedly, the fixture temperatures display an approximate symmetry.

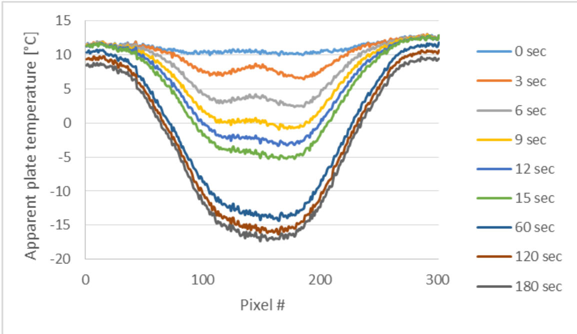


Figure 6: Horizontal line plot of fixture surface temperatures during transient cooling

4.1 Cooling performance characterisation

In order to quantify the cooling performance of the cryo fixture, four calibrated miniature type-T welded bead thermocouples were fixed to the top surface using thermally conductive adhesive. The thermocouples were positioned along a diagonal line through the cooling zone. The thermocouple readings were taken using two Fluke 52 Series II dual input digital thermometers.

The supply power to the Peltier modules was varied to study the effect upon surface cooling. The surface was cleaned using acetone prior to each test, except for the small areas near the thermocouples. Ambient air temperature in the laboratory was monitored but not controlled, and typically remained within the range 20 °C +/- 3°C. Due to the poor heat transfer rate associated with natural convection to/from a horizontal flat surface, the ambient air does not appear to significantly warm the fixture surface during testing within the range stated. Once power to the modules was initiated, the surface temperature was observed to drop rapidly and consistently across the cooling zone. All thermocouple readings remained within a 1 °C range at all times. When the surface temperature dropped below the dew point, a small amount of moisture condensed from the ambient air and settled on the surface. This moisture froze as the surface temperature was lowered below 0 °C.

The chiller was set to circulate water at 5 °C. This temperature provided the maximum cooling of the hot faces of the Peltier modules, and resulted in increased Peltier cooling performance. As shown in Figure 7, this resulted in the coldest plate surface temperatures using the current cryo fixture design. Since the coolant in the reservoir can be controlled to less than 0.1°C and is operated at a constant flow rate, and the TECs are operated at constant input power, the thermal performance of the cryo-fixture is extremely repeatable and surface temperature measurements were found to be accurate to 0.5°C±0.4°C, even allowing for small fluctuations in ambient air temperature.

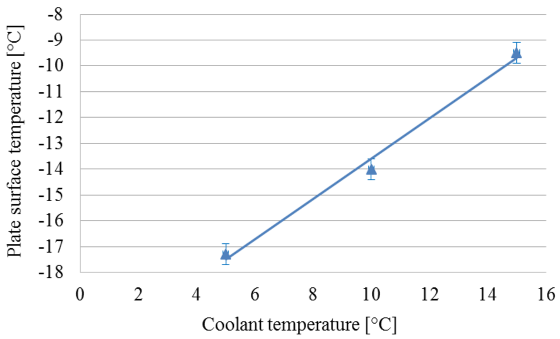


Figure 7: Cryo fixture surface temperature vs coolant temperature, after 180 seconds at 6 V

Power was supplied to the four Peltier modules and the time required for the surface temperature of the cryo fixture to reach a steady value was recorded. The test was repeated multiple times and for several input power levels and the results are shown in Figure 8. Four features are evident:

1. the time required for the cryo fixture surface temperature to stabilise increases with increasing supply power.
2. increasing the supply power to the TEC array lowers the surface temperature but by successively smaller amounts.
3. at 6V supply, the fixture temperature experiences fluctuations during the cooling, indicating a threshold for the system.
4. at 12V supply, the fixture temperature has increased dramatically as the chiller is no longer able to sufficiently cool the hot face of the four Peltier modules.

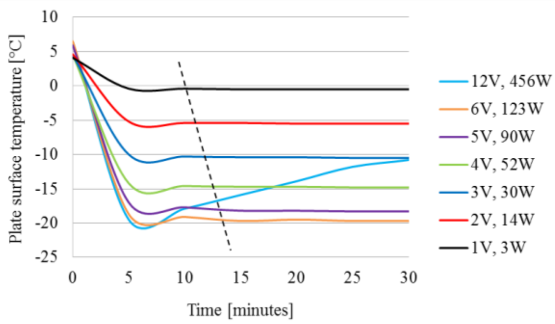


Figure 8: Cryo fixture surface temperature against time for various supply powers

For the purpose of the experimental work, the chiller was set to circulate water at 5 °C and the supply voltage, current and power to the Peltier modules was 6 V, 20.5 A and 123 W respectively. As an example, Figure 9 shows the ability of the cryo fixture to secure a workpiece in position, in this case fixing a standard laboratory glass beaker at an arbitrary angle.

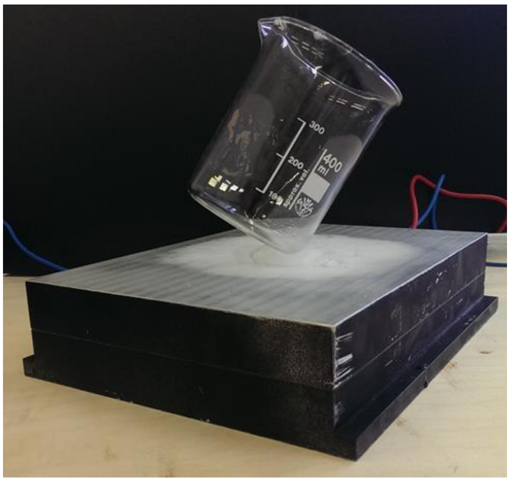


Figure 9: Example of workpiece holding using ice adhesion on the cryo fixture, showing a glass beaker frozen into position

5. Force loading experiments

To assess the suitability of the cryo fixture for use in manufacturing applications, several workpiece specimens were fixed to the fixture surface plate using ice adhesion. The assembly was subjected to both tensile and shear loading using an Instron 8874 axial torsion system. This Instron model has an axial force capacity of ±25 kN and the force readings are accurate to ±0.5 % of the indicated load. The machine is configurable to allow for the attachment of a range of hooks, bolts, and clamps to the load cell, and for almost any shaped object to be fixed underneath the load cell.

Several workpiece specimens were designed and manufactured in Trinity College Dublin. Figure 10 displays the different geometries for the tensile and shear test specimens considered. An M6 tapped hole in each design was used to attach the specimen to the Instron 8874. To investigate the effect of workpiece contact surface area on adhesion strength, both the tensile and shear test pieces were manufactured with base diameters of 20mm, 30mm, 40mm and 50mm. A minimum of one workpiece of each diameter was manufactured using three different materials: 304L stainless steel, 6000 series aluminium and PTFE.

To create the ice, a small amount of distilled water is sprayed onto the surface in the centre of the cooling zone. The power to the TECs is initiated and freezing commences rapidly. Experiments were carried out to investigate the effects of the following parameters: fixture surface temperature, workpiece contact area, and workpiece surface roughness.

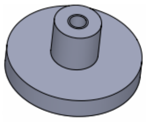
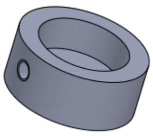
Diameter [mm]	Material	Orientation
20	Steel	Tensile Unit 
30	Aluminium	
40		Shear Unit 
50	PTFE	

Figure 10: Experimental design showing workpiece in different materials, for shear and tensile tests

A Mitutoyo SJ-400 surface roughness tester was used to measure the R_a (arithmetic average of absolute values) and R_z values of the workpieces. The surface roughness of the aluminium fixture was also measured periodically and determined to have an average surface roughness of $R_a = 2.32\mu m$.

5.1 Tensile loading setup

The cryo fixture was clamped securely to the base of the Instron and positioned so that the line of action was directly above the centre point of the cooling zone established by the thermal characterisation work presented in Section 4. A steel hook was secured in the load cell jaws, from which a short chain was held above the fixture and grasped by another hook. The test units were placed on the very centre of the fixture, with their centre axis lying above the centre of the modules. The experimental setup is shown in Figure 11.

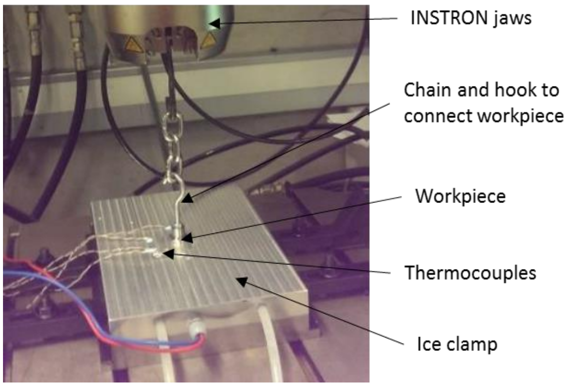


Figure 11: Test setup for tensile loading

Four calibrated thermocouples were secured onto the fixture surface, using thermally conductive adhesive. Using an IR camera the location of the thermocouples was selected to be within the cooling zone previously identified, and to leave sufficient space for the range of workpieces under test. IR images prior to the load application showed a negligible temperature gradient within the cool zone once the fixture and workpiece were allowed sufficient time to reach thermal equilibrium.

5.2 Shear loading setup

In order to test in a shearing orientation, the cryo fixture was rotated 90°, and secured in place using two long bolts which applied pressure to the upwards-facing edge, as shown in Figure 12. The thermocouples were positioned as in the tensile tests, so that they would not be affected by the chain or the specimen's movement. The fixture was carefully located to let the freely-hanging chain rest directly above the M6 hole in the specimens where the force would be applied. To apply ideal shear, the point of application of the force should be as close as possible to the workpiece/ice plate contact line [38], to avoid the introduction of tensile forces. Due to the nature of the experimental setup where the connection between the Instron and the workpiece was made using the chain, and the fact that the workpiece specimens were place at the centre of surface of much greater area, applying the shear force immediately at the ice plate surface was not possible. Therefore, the reality of the current shear loading setup is a more complex application of both shear and tensile forces. Nevertheless, the results presented herein are representative of manufacturing scenarios where it would be expected that shear loads would be applied at varying distances from the cryo fixture surface during machining operations.

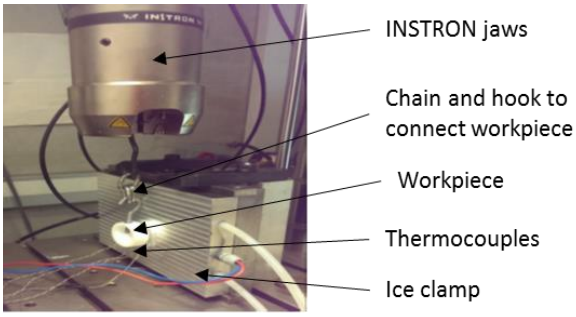


Figure 12: Test setup for shear loading

6. Results and discussion

Using the experimental setups shown previously, and with due care not to exceed loads that may cause excessive deflection of the cryo fixture surface plate, a number of tensile and shear tests loading tests were carried out. Due to the somewhat stochastic nature of water freezing on a surface, no two experiments produce the same results. In the following figures, error bars are included to represent the standard deviation for each data point calculated from the average of multiple experiments using the same test configuration and settings.

6.1 Effect of fixture surface temperature

The steel, aluminium, and PTFE 20mm diameter workpieces were tested at ice plate setpoint temperatures of -3°C, -7°C, -10°C, and -14°C. Approximately 1ml of distilled water was sprayed onto the fixture surface in the centre of the cooling zone. Sufficient time was allowed for freezing to occur before the application of any mechanical load. A displacement rate of 0.4mm/min was applied. It can be seen from the results in Figure 13 that the adhesive strength varies according to the workpiece material types. When the tensile load is applied, the steel specimens display the highest adhesive strength, followed by the aluminium, and then the PTFE. This is consistent across all ice plate temperatures.

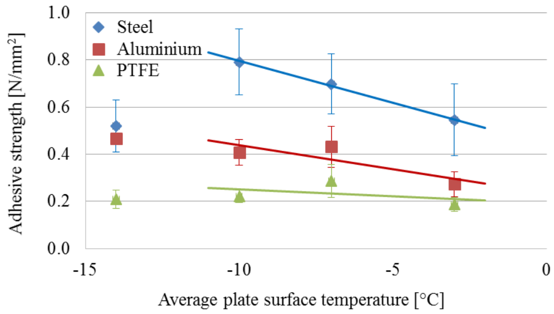


Figure 13: Effect of fixture surface temperature on the strength of the ice adhesion during tensile loading

When a linear fit is applied to the initial data points, it can be seen that the adhesive strength increases initially with decreasing temperatures, with different rates of increase noted depending on the material type. Below -10°C the trend is inconsistent and this is noteworthy as these findings are broadly in agreement with the work of Jellinek [10, 11, 20] who noted a transition to more random fractures below -10°C. It is noted that the plate surface temperatures in Figure 13 are determined by averaging the signals of the thermocouples which are located around the cooling zone. Therefore, it is possible that the temperature of the ice interface directly under the workpiece may be higher. In the case of the steel specimens at -14°C, the largest adhesive strength might be expected. Detailed analysis of the results suggest that when the largest forces are applied to the workpiece, the local thermal contact resistance between the Peltier coolers and the underside of the central section of the ice plate increases. This results in less effective cooling of a small section of the surface, which may result in locally weaker adhesion. This behaviour was noted only for the steel specimen at the lowest plate setpoint temperature and was consistent across a number of tests. In future experiments, PID control of the plate surface temperature will be employed to mitigate this effect.

The 20mm diameter steel and aluminium samples were then tested in shear. The 40mm PTFE samples were used for shear tests, since the 20mm pieces adhered poorly to the fixture for useful measurements. The pieces were tested at the same setpoint temperatures. A displacement rate of 0.5mm/min was applied.

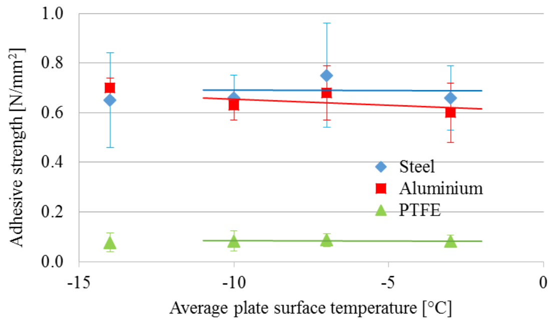


Figure 14: Effect of fixture surface temperature on the strength of the ice adhesion during shear loading

From Figure 14 it can be seen that the steel workpiece demonstrated the highest adhesive strength, with aluminium also relatively high and the PTFE showing the lowest adhesive strength. In contrast to the results from the tensile tests, there was no discernible trend between adhesive strength and temperature. Furthermore it is notable that the aluminium adhesive strength is higher for the shear loading than the tensile loading, as is the case for steel at setpoint temperatures closer to 0°C. One hypothesis is that the build-up of ice on the periphery of the workpiece is a more significant issue in shear loading than in tensile loading. The results for the steel workpiece shown in Figure 14 would appear to contrast results obtained by Makkonen [17], who observed an increase in adhesion strength in shear between 0°C and -15°C, before a decrease between -20°C and -60°C. A more likely cause for the behaviour in Figure 14 is the current experimental setup which means that the load/force is not applied at the surface, but at a distance from the surface. As detailed by Maitra et al. [38], this results in the simultaneous action of tensile and shear stresses, which can yield different results to those obtained when applying shear forces alone.

6.2 Effect of workpiece contact area

The steel, aluminium, and PTFE workpieces were tested with the 20mm, 30mm and 40mm diameter specimens used. A minimum of 7 experiments were performed for each data point. A displacement rate of 0.4mm/min was applied. The ice plate setpoint temperature was set to -7°C. Figure 15 plots the results obtained from these experiments where it can be seen that the detach load increases with increasing apparent contact area as expected. The rate of increase varies for each material. However, the adhesive strength (detach load/workpiece contact area) does not increase proportionally with the area. Indeed, the adhesive strength is seen to decrease with increasing area for each material. Jellinek [16] proposed that as the area of an ice-solid interface increased, so did the likelihood of a crack existing in the interface, which propagates under an applied load. This ‘chain as strong as the weakest link’ analogy may explain the inverse relationship between interface area and strength, but it requires further investigation.

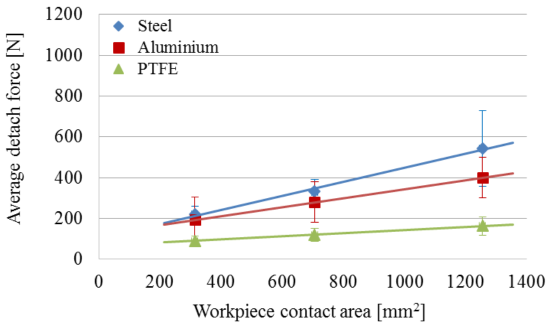


Figure 15: Effect of workpiece contact area on adhesive strength under tensile loading setup

The 20, 30, and 40mm diameter steel, aluminium, and PTFE pieces were tested with the shear loading setup at the same temperature of -7°C and the same displacement rate. Figure 16 displays the results obtained from these experiments and demonstrates the detach load increasing with increasing area, which was also evident for the tensile loading case. However the linear fit is not as strong in the shear case, further corroborating the hypothesis that the shear loading arrangement is not directly comparable with the tensile loading arrangement due to peripheral ice bonding.

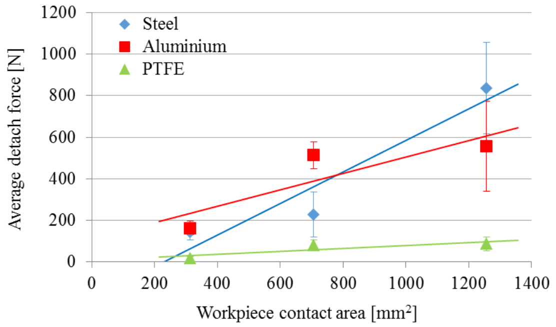


Figure 16: Effect of workpiece contact area on detach load under shear loading setup

Observations during testing showed consistent evidence of an adhesive ice breakage which resulted in the ice remaining on the fixture surface rather on the workpiece surface. While the wettability of the materials is different, again indicating the potential to form a suitably homogenous bond, the results are not consistent with the wettability where steel, aluminium and PTFE have contact angles of 80°, 120° and 100° respectively [34,35]. However this could partly contribute to the difference between the steel and aluminium data.

The ability of the steel workpiece to withstand relatively higher tensile loads can be partly explained by the increased stiffness of the combined steel and fixture assembly when bonded, in contrast to the aluminium. The fixture was shown to deflect with high loads than for the less stiff combination of aluminium workpiece on the aluminium surface plate on the fixture. This deflection could lead to crack propagation at the ice-fixture interface. These observations of the ice remaining on the workpiece sample in the cases of steel and aluminium support this hypothesis.

6.3 Effect of workpiece surface roughness

The 20mm diameter aluminium shear and tensile workpieces were each tested at a range of surface roughnesses. The fixture was set to -7°C, and the displacement rate was 0.5mm/min, for each set of tests. The workpiece surface roughnesses were generated by finished turning and by the use of abrasive paper and their surface roughness values recorded, before being tested under tensile and shear loading conditions.

Figure 17 shows that the adhesive strength was observed to decrease with increasing surface roughness during tensile loading, while no clear trend is visible for the shear strength. This tensile result contradicts some theory of ice adhesion which predicts that increasing (microscopic) surface roughness should also increase ice adhesion strength [11, 17, 21]. In this case it might be hypothesised that the surface tension existing in the liquid may prevent the liquid from penetrating the rougher surfaces and therefore, contrary to expectation, lead to a weaker, less homogeneous ice bond (i.e. the interface is in the Cassie state rather than the Wenzel state, as discussed in the introduction). However, it must be pointed out that the mechanism used to roughen the workpiece can not guarantee that the roughness of both workpiece and ice plate is uniform for the entire contacting area. In future work it is hoped that spectral microscopy could be employed to elucidate the true effects of surface morphology.

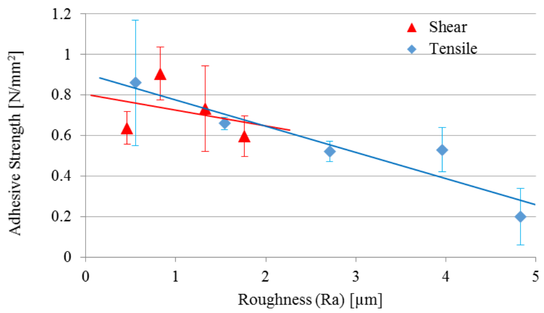


Figure 17: Effect of roughness on a 20mm diameter aluminium workpiece adhesive strength under shear and tensile forces

In the context of manufacturing, the designed cryo fixture demonstrated that it is feasible to bond various workpiece materials and quantify the adhesive loads. Loads under 100N in the case of PTFE and in excess of 600N in the case of steel are shown to be possible to withstand using ice. Machining loads of 500N have been reported for difficult to cut materials such as titanium [36], however workpieces that need to be secured in cryo fixturing systems are typically bespoke and fragile and therefore it is likely that they will not have high machining loads applied. This research presents the novel cryo fixture design based on the Peltier effect and the first results showing the impact of different materials, surface temperatures, load type, geometries and considerations of the surface roughness, targeted at manufacturing process type applications of ice adhesion.

7. Conclusions

Nature inspired design provides opportunities for novel approaches to address engineering challenges. The adhesive potential of ice is known but has not been formally analysed from a manufacturing applications perspective up to now. This research reports on the design and experimental characterisation of a novel Peltier-cooler-driven cryo fixture, suitable for manufacturing operations. It was shown that:

- The aforementioned design with four Peltier modules provides the necessary cooling potential to generate suitable ice bonding for manufacturing applications.
- Application oriented characterisation agreed with the literature that adhesion strength initially increases (up to 45% for steel) with decreasing sub-zero temperatures.
- The adhesive strength under tensile forces appears to be linked to the material's stiffness, but under the combined application of shear and tensile forces no clear relationship was observed.
- The detach load was observed to increase with apparent workpiece contact area for all materials in both tensile and shearing loading conditions.
- Future work should consider the role of surface energies in the adhesion process.

A final conclusion is that nature inspired ice based adhesion has been shown to be quite robust for manufacturing operations where workpieces will have variations in area, variations in surface finish and be subjected to loads in different orientations.

Acknowledgments

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