Proposal Number:	**PP-2020-05**
Proposal Title:	**Thermal bonding mechanism of polyester spunbond nonwoven and effects of polymer properties and additives**
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1 – Summary and Specific Objectives:

Spunbond process is one of the largest nonwoven processes and also the fastest-growing segment and mostly integrated with thermal calender bonding technology. The majority of spunbond/thermal bond nonwovens consists of polypropylene, followed by polyester. Generally speaking, spunbond polyester production is more complex than that of PP. The most challenging part of the thermally bonded spunbond polyester nonwoven process is the thermal bonding process due to its slow crystallization and inherent brittleness. The most light-weight thermally-bonded spunbond nonwoven such as hygiene applications dominated by PP and polyester spunbond nonwovens used relatively limited applications where PP cannot be used. The rising needs of nonwovens produced from renewable bio-based raw materials may change these market dynamics. Among various bio-polymers, Polylactic acid (PLA) and other aliphatic polyesters have been considered the promising alternative of petroleum based-polymer. As thermal calender bonding is the most common and economic bonding technology for the spunbond process, the difficulty of thermal bonding has been a significant hurdle of expanding polyester spunbond nonwoven and, in particular, emerging bio-based polyesters spunbond nonwovens development. Little research can be found thermal bonding mechanism of polyester and how to enhance it. Therefore, this proposed research aims to explore the thermal bonding process of polyester spunbond nonwovens and how polymer structures and additives influence the thermal bonding process, bond morphology, bond strength, and nonwoven properties.

Specific objectives of this study include, but not limited;

1. Investigate the thermal bonding mechanism of Polyesters- PET and PLA – Effects of polymer properties on bond formation, bond morphology, and failure mechanism.
2. Identify possible methodology/approaches to address challenges in thermal bonding of polyester spunbond nonwoven focused on additive/blend technology
3. Investigate the effects of crystallization kinetics and incorporation of nucleating agents on the bond formation and properties of thermally bonded nonwovens
4. Demonstrate the role toughening agents/plasticizer on bond rigidity and morphology and their influences on failure mechanism and load sharing behavior of thermally bonded polyester nonwovens.

2 – Literature Review (Scientific Literature)

Spunbond process is one of the largest nonwoven processes and also the fastest-growing segment. By INDA, in 2013, 27% of nonwoven production capacity in North America are spunbond or spunbond/meltblown composites, and it also accounts for the majority of the recent growth of nonwoven product capacity (1).

Spunbond process is evolved from the filament melt spinning process, sharing the same principles of fiber formation and the step where microstructure and fiber properties are determined, but there are differences. Fibers extruded through a spin beam, which has multiple rows of spinnerets with the spinneret density of 3000–6000 holes/m and 1–5 m width and fibers are quenched and drawn by air and collected with a web lay down system, such as a belt or a drum collector. As drawing and collection of fibers on the belt are carried out by processing air, so spinning speed and quench are controlled by processing air pressure and the equipment configuration. It is integrated with the bonding technology, so laid down webs directly transfer to the bonding steps. In principle, any bonding technology can be used, but thermal calender bonding is the most used process due to its speed-compatibility and economic advantages. The majority of spunbond/thermal bond nonwovens consists of polypropylene, followed by polyester. Due to its hydrolytic degradation at high temperature, slow crystallization, high chain rigidity, the production of spunbond PET is more complex than that of PP. Crystalline/fine structures and properties of polyester fibers are highly dependent on fiber formation conditions. But the most challenging part of thermally bonded spunbond polyester nonwoven production is the thermal bonding process. The most light-weight thermally-bonded spunbond nonwoven such as hygiene applications is dominated by PP and polyester spunbond nonwovens used relatively limited applications where PP cannot be used. The rising needs of nonwovens produced from renewable bio-based raw materials may change these market dynamics. Among various bio-polymers, Polylactic acid (PLA) and other aliphatic polyesters have been considered the promising alternative of petroleum based-polymer. Many scientific and industrial research was devoted to melt-spinning and spunbond production of PLA polymers(2-10), but little is known how PLA polymer properties and fiber structure formed in the spunbond process influence thermal bonding of PLA webs and nonwoven properties. In that regard, all polyesters are hard to bond, but the little study was conducted regarding the bond formation of polyester.

It is known that the bond formation dominates strength and other properties of nonwoven fabrics, and there has been extensive literature reported on these topics. Still, most research is focused on polypropylene nonwovens (11-17). It has been recognized polyesters included PLA is harder to bond than PP due to their thermal, morphological, crystallization properties as the bond formation and the properties of thermally bonded nonwovens is determined by heat transfer during the bonding process and response of polymer chain to the heat energy. Bond formation during the thermal bond processes can be described in three steps; 1) Release of the polymer chain segment by partial melting of the crystalline during heating, 2) Diffusion of newly release polymer chain segment across the fiber-fiber interface by chain reptations, and 3) Locking the entangled polymer segment that diffuse across the fiber-fiber interface by solidification and crystallization during cooling (18).
The properties of the thermally-bonded fabrics are often dominated by bond formation. Interestingly, it is found that increasing fiber strength in thermally bonded nonwoven does not always lead to higher fabric strength, and often, it yields the opposite effects (18). The strong bond is formed when the temperature of the web raises enough to melt a sufficient number of

chain segments (11) and enough time for the chains to diffuse to fiber-fiber interfaces, and proper cooling rate to allow crystallization. However, too high temperature and too long time would result in excessive morphological changes in bond points, and create rapid morphology gradient at the bond edges. Even though the strength of the bond itself is high, but the bond site edges becomes stress concentration points and mechanical mismatch between bonds and bridge fibers results in premature failure (12). Time and temperature ranges for bond formation (often called a bonding window) depends on polymer properties. Heat capacity, thermal conductivity, melting behavior (both melting point and shape of the DSC melting peak determined by crystalline structure), chain diffusivity or reptation time, glass transition temperature, crystallization kinetics will influence in these three steps of bond formation and influence bond strength and bond morphology. But little is known how this bond formation and failure mechanism of thermally bonded nonwoven established based on PP nonwoven apply to other types of polymer, in particular, polyesters including PLA.

One speculates one of the possible reasons for the unsatisfactory bonding of PET is its higher melting temperature, which requires a longer time for the whole web to reach melting temperature and results in higher temperature difference between the surface and middle of the web (18). But this logic does not apply to PLA as optimum bonding temperature reported from some research is not higher than PP (19) (20). Zhang at el studied cohesion energy of thermally bonded PET nonwovens at different temperatures but did not elaborate on how this will impact the bond formation and properties of thermally bonded nonwovens (21). A few studied the effect of calendar temperature on PLA nonwovens. They found the same general trend that tensile strength and strain increased with bonding temperature to maximum and then decreased (19) (20). But when and how this happens relative to the melting curve and failure mechanism does not clary followed what is known for PP. Bhat et al found maximum tensile strength of carded thermal bonded PLA nonwoven is obtained at 145^{o}C, which is slightly higher on-set melting points. But he reported bond point damages – holes on bond points – were started developed at this temperature and become sever at 150^{o}C (19). They also observed the reduction of the crystallinity of the web after the bonding due to slow re-crystallization. Puchalski et al (20) studied the effect of bonding temperature at the range of 70-130^{o}C, which is far below PLA melting temperature. They reported increases in fabric crystallinity when bonding temperature is higher than Tg, but the change of crystallinity is highly dependent on initial fiber structure and filament spinning speed during the spunbond process. These studies demonstrate challenges in the thermal bonding of polyester nonwovens but do not provide understandings of how polyester polymer properties related to this poor and different bonding behavior.

There is extensive research about the effects of PLA structures and additives in PLA crystallization and properties, but these results may not directly translate to fiber and spunbond process and thermal bonding process. Additives such as nucleating agents to improve the crystallization behavior (22) and other additives to reduce brittleness and enhance the toughness of PLA polymer (23, 24) have been studied, but how these changes influence thermal bonding process of PLA nonwoven is still not known. Changing crystallization behavior, brittleness, heat capacity, other polymer properties arise from additive addition may impact the bonding process where these polymers are melt and re-solidify forming bond morphology. But, no research can be found on how additive influences properties of polyester thermally bonded nonwoven.

3 – Prior Art Search (Patent literature)

(* Note:Exceeded page limit as a response of pre-proposal feedback asking more detailed/expended list of patents)

The scope of the proposed work is fundamental in nature, little background IP that directly related to it. Even the vest number of patents exist for applications PET and some bicomponent fiber production; there are a minimal number of patents directly addressing the spunbond process and thermal bonding process of PET nonwovens. There is extensive patent literature about PLA composition containing additives and other polymers for the various molding process. Most of the patents utilize nucleating agents, plasticizers, other polymers (with or without compatibilizer), fillers to achieve high impact strength, heat deflection temperature, and heat stability. Other group patent documents also claim PLA stereo complex polymer to improve the crystalline structure and PLA based copolymer. But those on PLA spunbond and melt-spun fibers relatively are limited. Most relevant patents and patent applications that are related to PET and PLA spunbond and melt-spun fibers are listed below. These are not a comprehensive list (Due to page limit), and in-depth review will be provided during the proposed study.

Patent

	Title	Assignee	Year	Scope/Summary
US 5698322	Multicomponent Fiber	KC	1997	Multicomponent fiber useful in making nonwoven structures - comprising two polylactic acid polymers (different L:D ratio) which are easily prepared, readily processable, biodegradable and thermally bondable
US 5833787	Process for making a nonwoven web derived from lactic acid, web produced thereby and apparatus therefor	Fiberweb	1998	Nonwoven fabric (Spunbond/thermal bond) produced from spun biodegradable poly lactide filaments-by fixing and adjusting deg. of crystallinity and internal stress of fibers in web by fiber tension, for disposable diaper, sanitary towel and surgical gown
US 5753736	Dimensionally Stable Fibers and Nonwoven webs	The University of Tennessee	1998	Dispersion of a nucleating agent into a polyester through melt mixing, extruding the resulting melt, passing it into a cooling bath to solidify it and produce pellets; Melt blowing or spunbonding the pellets into fibers.
US 6211294	Multicompoent fiber prepared from a thermoplastic composition	KC	2001	Biodegradable thermoplastic composition comprising an unreacted mixture of a PLA, PBS, polybutylene succinate adipate polymer, wetting agents.
US 6475418	Methods for making thermoplastic composition and fiber including same	KC	2002	Biodegradable nonwoven material with improved fluid management properties comprises poly(lactic acid) polymer, polybutylene succinate and/or polybutene succinate adipate polymer, and wetting agent
US6491777	Method of making nonwoven composite transfer layer	PGI	2002	Manufacture of nonwoven composite web comprises depositing a first polyester spunbond layer and a second polyester layer on the first layer, the second layer having a melting point different than the first layer; thermally bonding the first and second layers to form a micro-bulked web, and mechanically bulking the micro-bulked web. High Bulk, Low cost production.
US6506873	Degradable polymer fibers: Preparation product: and method of use,	Cargil	2003	Degradable polymer fibrous materials comprising several polylactide fiber which are high shrinkage or low shrinkage. Extrusion process to provide low and high shrinkage fibers
US 6548431	Melt spun polyester nonwoven sheet	Dupont	2003	A nonwoven sheet is made by extruding melt spinnable polymer containing at least 30 wt.% poly(ethylene terephthalate), drawing the extruded fiber filaments, laying the fiber filaments down on a collection surface, and bonding the fiber filaments together to form a nonwoven sheet. High air permeability, liquid barrier properties, strength, low linting characteristics.
US 6787493	Biodegradable formable filament nonwoven fabric and method of produce the same	Unitika	2004	Biodegradable filament nonwoven fabrics - comprises filaments of poly:lactic acid-based polymer. It is quenched drafted at drafting speed of 1000-2500m/min. The filament supercool index (Tm-Tc)/(Tm-Tg) ranges 0.3-0.5. Good thermoforming processibility

US6780357	Splittable multicomponent polyester fibers	FIT	2004	Mechanically splittable multicomponent fiber comprises at least one poly (lactic acid)polymer and at least one aromatic polyester polymer
US6953622	Biodegradable bicomponent fibers with improved thermal-dimensional stability	KC	2005	Bicomponent binder fiber useful in disposable absorbent product comprises aliphatic polyester material in a side-by-side configuration with polylactide polymer. Reduced shrinkage
US7192499	Nonwoven fabric with characteristics similar to woven and knitted fabric	Hills, Inc.	2007	The method involves extruding a set of component fibers, where the extruded fiber has two polymer components such as polyester. The nonwoven web of fibers is calender bonded to form bond points between the fibers, then heated to a selected temperature to shrink one polymer component in the web to decrease bond point size and a spatial dimension between the bond points. Enhanced strength and reducing the porosity
US 8003719	Nucleating agents	Metaboli x, Inc.	2011	A thermoplastic composition comprises a thermoplastic polyester or polyolefin; and a nucleant. The nucleant comprises a compound comprising a nitrogen-containing heteroaromatic core. The composition has improved or increased crystallization rate and/or improved physical properties e.g. increased mechanical strength.
US7604859	Heat Adhesive Biodegradable Bicomponent Fibers	Far Eastern Textile	2009	PLA/PLA sheath/Core binder fiber. Sheath comprises with low melt PLA or low melt PLA blend
US 7994078	High Strength Nonwoven Web From a Biodegradable Aliphatic Polyester	KC	2011	Biodegradable nonwoven web (spunbond/thermal bonded) useful in a personal care product is prepared from a polymer blend comprising biodegradable aliphatic polyester polymer (PLA, etc) and second polymer (a polymer with lower melting point or lower molecular weight, generally amorphous). Improve tear strength
US7989061	Polylactic acid resin, textile products obtained therefrom and processes for producing textile products	Toray	2011	Polylactic acid resin used for multifilaments, monofilaments, and long-fiber nonwoven fabric, has excellent processability with a relative viscosity ranges of 2.7-4.5
US8182725	Methods for making polylactic acid streocomplex fibers	Naturew orks	2012	Manufacture of streocomplex polylactic acid fiber, e.g. for nonwoven fabric, comprises mixing high-D and high-L polylactic acid starting resin melts, melt spinning, cooling below crystalline melting temperature of starting resins, and heat treating. Excellent thermal resistance
US 8461262	Polylactic acid fibers	KC	2013	Bidodegrdae fiber comprising PLA, plasticizer and compatibilizer.
US8936740	Modified Polylactic acid fibers	KC	2015	Forming multi-component fiber, used in nonwoven web e.g. airlaid web, comprises blending polylactic acid, polymeric toughening additive and polyepoxide modifier, and extruding resultant through a die. Improve mechanical properties, melt strength.
US9163336	Fibers formed from aromatic polyester and polyether copolymer	KC	2015	A fiber is obtained formed from a thermoplastic composition comprising 75-99 wt.% aromatic polyester(s) and 1-25 wt.% polyether copolymer(s). Fiber is used for nonwoven web e.g. meltblown web, coform web and/or spunbond web for absorbent article. Good softness and mechanical properties
US10011929	Nonwoven substrate comprising fibers comprising an engineering thermoplastic polymer	PG	2018	Nonwoven substratehas layer of fibers comprising polyolefin and engineering thermoplastic polymer (PLA, etc.) in certain amount by weight of nonwoven substrate and free of compatibilizer

Patent Applications

	Title	Assignee	Year	Scope/Summary
US2003/0013371 A1	Process for forming soft, drapeable nonwoven fabric	PGI	2003	A method of making a spunbond, involves extruding a molten aliphatic-aromatic polyester resin from a spinneret assembly to form filaments and collecting the filaments to form a nonwoven fabric. The spinneret assembly is operated at spinning speed of no more than about 3000 m/minute. The spunbond nonwoven fabric has extensibility, recovery (claimed), desirable softness, drapeability, excellent gamma radiation stability and elasticity.
WO2009/024837 A1	Method for forming polylactic acid fibers	KC	2009	Forming PLA Fiber – the use of a macrocyclic ester oligomer to improve the crystallization properties of PLA.
WO2009/151439 A1	Methods for forming biodegradable polylactic acids for use in forming fibers	KC	2009	Formation of biodegradable polymer for fiber formation for nonwoven web by melt processing polylactic acid in single screw extruder for hydrolysis reaction to obtain hydrolytically degraded polylactic acid

US2010/0304066 A1	Polylactic acid filament nonwoven fabric and production method there of	Unitika	2010	Polylactic acid type filament nonwoven fabric comprises sheath/core bicomponent fiber, polylactic acid type polymer and aliphatic polyester polymer which uses butanediol and succinic acid as structural component
US2010/0318050 A1	Fibers and Nonwovens Fabrics with Improved Properties	KC	2010	Article, useful e.g. as personal care article, comprises many fibers, where fibers are formed from thermoplastic polymer material (including PLA) having specific crystallization half-time value and is subjected to anneal-quenching without increasing draw ratio.
US 2012/0034838 A1	Polymeric Blends for fiber applications and methods of making the same,	Fina	2011	Formation of continuous filament, involves contacting propylene polymer with polylactic acid in presence of epoxy-functionalized polyolefin or non-reactive modifier comprising elastomer, and forming blend into product
US2012/0040185 A1	Toughened Polylactic Acid Fibers	KC	2012	Polylactic acid fiber for nonwoens comprises thermoplastic composition containing discrete domains (polymeric toughening additives) dispersed within PLA continuous phase
US2015/0126091 A1	Process for making nonwoven fabrics using polylactide resin blends	Naturework s	2015	Nonwoven fabric through spun-melt process. PLA resin blends containing 1-25% aliphatic or aliphatic-aromatic polyetsers with number average molecular weight 4000-7000 melt spun into filament. Reduced shrinkage
WO 2015/046637	Polylactic acid blended nonwoven fabric having improved flexibility and method for preparing same	Toray advanced materials	2015	PLA blend nonwoven (PLA + PP +dispersing agent + softening agents) for improved flexibility.
US 2017/0145597 A1	Fibers comprising an aliphatic polyester bends and yarns, tows and fabrics formed therefrom	FIT	2017	Fiber used for manufacturing nonwoven fabrics, has homogeneous blend of polylactic acid polymers having specified isomeric purity for D- or L-isomer, in specified weight ratio, and is multicomponent fiber or continuous filament. Reduced shrinkage, increased productivity.
US2017/0241054 A1	Spunbond Web Comprising Polylactic acid fibers	3M	2017	Spunbonded electret web used in filters for air filtration, comprises polylactic acid fibers having its portion melt spun, drawn and charged and comprising preset amount of charging additive (0.1-5%), and is through-air bonded web
US2018/0038026	System and process for preparing polylactic acid nonwoven fabric, US2018/0038026 A1	Fitesa	2018	A system for preparing PLA spunbond nonwoven. Use of ionization source to control static between spin beam and forming belt.
US2018/0051404 A1	Nonwoven Fabrics Comprising Polylactic acid having improved strength and toughness	Fitesa	2018	Spunbond nonwoven fabric comprises several fibers, which are bonded to each other to form coherent web and comprise blend of polylactic acid and secondary alkane sulfonate(s). Increase tensile strength, elongation and toughness
EP 5827706 A1	Biodegradable Nonwoven Fabric,	Ashai Kasei	2018	Biodegradable nonwoven fabric used for forming thermoformed molded article for producing e.g. beverage-extraction container, comprises fibers of polylactic acid polymer blends. High elongation, heat stability and excellent formability.
US2019/0071802 A1	Nonwoven Fabric and process for forming the same	Fitesa	2019	Bond pattern for higher drapability – PLA Nonwoven fabric for use in absorbent article, has alternating pattern of individualized bonded areas for defining non-bonded area and surface of bonded areas and surface of non-bonded area is at specific range of total surface of side.

4 – Proposed Study

Spunbond process is one of the largest nonwoven processes and also the fastest-growing segment and mostly integrated with thermal calender bonding technology. The majority of spunbond/thermal bond nonwovens consists of polypropylene, followed by polyester. Generally speaking, spunbond polyester production is more complex than that of PP. The most challenging part of the thermally bonded spunbond polyester nonwoven process is the thermal bonding process due to its slow crystallization and inherent brittleness. The most light-weight thermally-bonded spunbond nonwoven such as hygiene applications dominated by PP and polyester spunbond nonwovens used relatively limited applications where PP cannot be used. The rising needs of nonwovens produced from renewable bio-based raw materials may change these market dynamics. Among various bio-polymers, Polylactic acid (PLA) and other aliphatic polyesters have been considered the promising alternative of petroleum based-polymer. As thermal calender bonding is the most common and economic bonding technology for the spunbond process, the difficulty of thermal bonding has been a significant hurdle of expanding polyester spunbond nonwoven and, in particular, emerging bio-based polyesters spunbond nonwovens.

Therefore, this proposed research aims to explore the thermal bonding process of polyester spunbond nonwovens, including PLA and how polymer structures and additives influence the thermal bonding process, bond morphology, and bond strength. Even a large volume of work can be found in the thermal bonding mechanism and effects of the thermal bonding process on nonwoven fabrics in polypropylene nonwovens, how this translates to polyester nonwoven has not to be explored.

In this proposed research, first, we will focus on the thermal bonding mechanism of polyester nonwovens (Task 1). We aim to build knowledge of the behavior of different polyesters in the thermal bonding process and identify the possible causes of poor bond formation related to polymer properties that lead to properties deterioration. Then we will target to modify identified properties through additives or polymer structure modifications (Task 2). The approaches and additives used in Task 2 will be further defined based on Task 1 results, but according to initial literature and patent review, we plan to tackle two possible problems (1) slow crystallization kinetics (Task 2-1) and (2) bond rigidity (Task 2-2). Various factors impact the thermal bonding process, and the research approach are schematically shown in Figure 1.

Task 1: Thermal bonding mechanism of polyester nonwovens and the effects of molecular structures and fiber structures on bonding formation

Generally speaking, achieving good bonding in polyester is more difficult than polypropylene. In this task, we will try to answer the question of why it is hard to achieve good thermal bonding in polyester nonwoven? More precisely, how polyester polymer properties influence the physics of bond formation and, in turn, bond morphology and failure mechanism? How polymer properties may affect the thermal bond formation and nonwoven properties are schematically shown in Figure 1. Heat capacity and thermal conductivity of the fiber will determine changes in temperature at the given thermal bonding conditions (Calender temperature and line speed). Melting behavior which is determined by crystalline structure created during the fiber formation (both spinning conditions and polymer resin type will affect) will determine how much crystalline will melt and how many changes are released to form bonds. The higher melting temperature of PET would have an impact on the length of time in the nip or calender temperature. Chain

diffusivity or reptation time of these chains both affected by polyester type, molecular weight, and the temperature is another important factor in proper bond formation. Finally, recrystallization during the cooling would lock these chains to form bonds, so crystallization kinetics of polymers are very important. Morphology of the bond formed, and properties of the bond (strength and strain) and its relationship to morphology and properties of adjacent fibers would determine the properties of thermally bonded nonwovens.

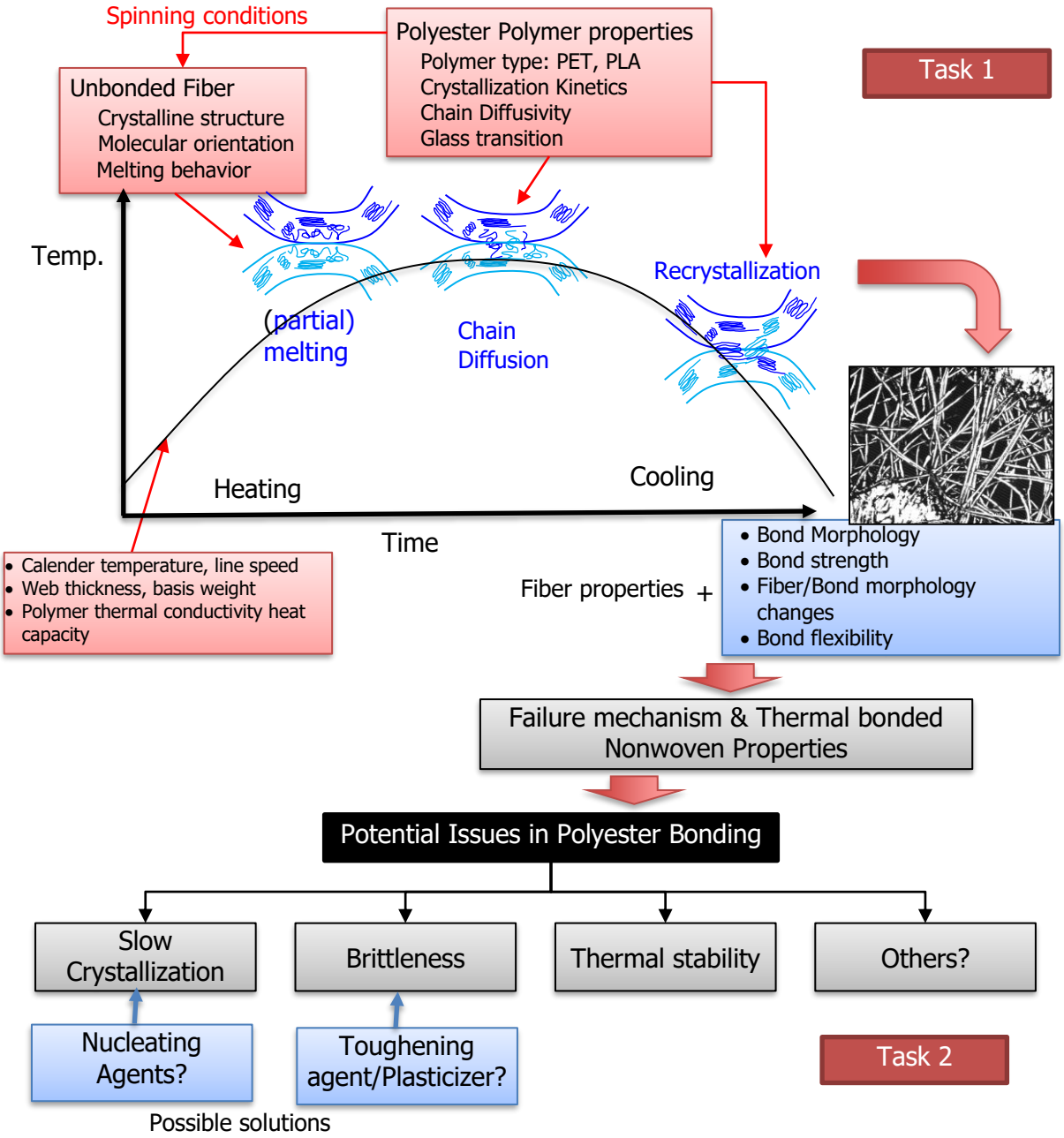

Figure 1: Bond formation in thermal bonding process related to the material properties and research approach

The goal of this task is to understand the effects of polymer properties of polyesters on the bond formation and failure mechanism. We will evaluate effects of crystallization kinetics and polymer thermal properties (glass transition, melting curve shape) as well as unbonded fiber structure & properties (crystalline structure, molecular orientation, single fiber tensile properties) on bond morphology, failure mechanism, the strength of thermally bonded nonwovens under the various thermal bonding conditions, in particular bonding temperature and time. A series of PET and/or PLA fiber will be produced from different grade resin under various spinning conditions to created ranges of crystallization rate and fiber structures. These fibers are thermal calendar bonded under various temperature and time and properties and structure of thermally bonded nonwoven (including bond morphology, tensile properties) will be fully analyzed. The knowledge created in this task will be used to guide how to modify polyester properties to improve its bonding properties and to determine optimum bonding conditions.

Task 2: Modification of polymer properties via additive incorporation to improve the bond formation

In task 2, our focus will be shifted to how to address the properties and behavior of polyester that negatively impact the thermal bonding process identified in Task 1 through the understanding of the thermal bonding mechanism of the polyester nonwoven. The use of additive or blend would be the most feasible and economical ways to modify the bonding properties of the polymer. Incorporation of additives can modify crystallization, thermal properties, chain diffusivity, brittleness, heat capacity, and it will lead to significant changes in bonding mechanism and may enhance properties of PLA nonwoven. We will also consider changes of fiber microstructure formed during the fiber formation by additives or polyester molecular structure changes as crystallinity and molecular orientation in fibers would influence the bonding process.

The approaches and additives used in Task 2 will be further defined and modified based on Task 1 results, but we are proposing two potential strategies based on literature and patent review.
We believe two main problems in thermal bonding in polyester are (1) Slow crystallization and (2) Rigidity/Brittleness of bond and fibers. Therefore we are proposing the use of nucleating agents to facilitate crystallization rate (Task 2-1) and toughness agent or plasticizer to reduce bond/fiber rigidity (Task 2-2). We may also explore other possible approaches to address other probable causes of bonding problems, such as thermal stability, if necessary.

<u>Task 2-1: Effect of nucleating agents on the bond formation and properties of polyester thermal bonded nonwoven</u>

Polyesters, both PET and PLA, are known for their slow crystallization rate, and it may negatively affect the thermal bonding process. Our previous work on a nucleating agent on thermal bonded PP nonwoven, we found additives that modifying crystallization kinetics have a more profound effect on the thermal bonding process than fiber property itself (25, 26). We will incorporate a nucleating agent during fiber formation and investigate its impact on bond strength, bond morphology, nonwoven properties, optimum bonding conditions. We will analyze the effects of nucleating agents on crystallization kinetics and related that to the bond formation. However, we also have to consider, additives, in particular, nucleating agents, can affect crystalline structure and fiber tensile properties (27)., which in turn also affect bond formation. Therefore we will also evaluate the effects of the nucleating agent on fiber structure and properties.

<u>Task 2-2: Control fiber and bond brittleness via additive to improve tensile properties of thermally bonded polyester nonwoven</u>

The rigidity of bond points would reduce the structure to redistribute the stress during the deformation process and create stress concentration and premature fabric failures. Kim et al. (28) observed fiber reorientation and bond deformation during the tensile deformation process in thermally bonded PP nonwoven, and this is an essential mechanism of stress redistribution of point bonded nonwoven. With its relatively high glass transition temperature, polyester tends to create a brittle bond, and it may impact the tensile deformation process. This problem can be more severe in the case of PLA nonwovens. We plan to improve the flexibility of fiber and bonds by incorporating plasticizer or toughening agents and relate bond brittleness to tensile deformation mechanism (reorientation, bond strain), failure mechanism, and properties of thermal bonded PLA nonwoven. We also expect a reduction of glass transition temperature may also facilitate chain diffusion during the bonding process and improve bond strength itself.

5 – Milestones & Deliverables

1st Year: Investigate the thermal bonding mechanism of polyester polymer (Task 1)

- Analysis of polymer properties (Thermal and crystallization properties)
- Evaluate the bonding mechanism and bond morphology of polyester fibers (PLA and PET) under varying bonding conditions

2nd Year: Effect of polyester polymer and fiber properties on the bond formation and evaluate nucleating agents on crystallization kinetics (Task 1 & Task 2-1)

- Investigate polymer and fiber structure produced by fiber spinning conditions on bond formation
- Identify possible methodology/additives to improve bond formation in polyester nonwoven
- Analysis of crystallization kinetics of polyesters with nucleating agents and evaluate its potential impacts on the thermal bonding process.

3rd Year: Effect of additives on thermal bonding process and nonwoven properties (Task 2).

- Fully evaluate the effects of crystallization kinetics of Polyester/nucleating agent on the thermal bonding process and nonwoven properties.
- Investigate bond and fiber brittleness on thermal bonded polyester nonwoven properties and effects of toughening agents/plasticizer.

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Budget for Core Projects
Project Duration: 3 Years Max

Annual budget

SENIOR PERSONNEL	Year 1
Eunkyoung Shim (0.3 month summer + 0.15 month release)	$3,000
Total Senior Personnel	$3,000
Graduate Student	$20,000
Total Other Personnel	$20,000
TOTAL PERSONNEL	**$23,000**
FRINGE BENEFITS	
Eunkyoung Shim	$990
Graduate Student	$3,200
TOTAL FRINGE BENEFITS	**$4,190**
TRAVEL	
Domestic Travel	$1,000
International Travel	$0
TOTAL TRAVEL	**$1,000**
OTHER DIRECT COSTS	
Materials and Supplies	$2,000
Publications/Documentation/Dissemination	$0
Postage & Shipping of Samples	$0
Tuition^	$14,769
Other (Details)	$0
Internal Lab Fees	$1,840
TOTAL OTHER DIRECT COSTS	**$18,609**
TOTAL DIRECT COSTS	**$46,799**
MODIFIED TOTAL DIRECT COSTS	**$32,030**
INDIRECT COSTS*	**$3,203**
TOTAL COSTS	**$50,002**

*NWI will cover work performed in NWI labs not to exceed $25k per year, for 3 years.