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Relating mold adhesion problems to heat transfer properties

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Interfacial temperature instantaneously approaches a certain level depending on thermal effusivities when two bodies are brought into contact, and this level is decisive for adhesion formation.

A substantial portion of production losses in the plastics industry can be attributed to sticking problems. In injection molding, for example, the sprue or entire parts may stick to the mold, necessitating manual intervention, which in turn decreases productivity.[1–4] Sticking is also undesirable in pelletizing processes because it can impair pellet quality and lead to production failure.[5] In film stretching, the material may adhere to the stretching rolls. When that happens, it leaves small particles on the surface that build up and adversely affect the optical quality of the stretched film.[6] Sticking is a complex phenomenon, with many contributing factors that are not yet fully understood. One crucial parameter, however, is temperature, since most material properties relevant for adhesion and wetting are strongly temperature dependent.

Most published studies dealing with stickiness (tack) report experiments carried out under isothermal conditions.[7,8] But production processes typically involve phase changes (melting/solidification) at highly non-isothermal conditions (e.g., a cold mold into which hot polymer melt is injected). Consequently, the knowledge gained in conventional (i.e., isothermal) tack experiments is not transferable to the conditions found in practice. When sticking issues are encountered, temperatures are often decreased heuristically (i.e., by trial and error). Yet, to the best of our knowledge, no studies describing the fundamentals of non-isothermal tack behavior have been published. Understanding this phenomenon in a more mechanistic way could lead to the solution of many practical problems.

Our recent research provides deeper insight into non-isothermal sticking behavior and establishes a connection between the fundamentals of heat transfer and adhesion.[9] We propose a hypothesis for the occurrence of sticking between polymer melts and solids under nonisothermal conditions that is experimentally supported by our work. This hypothesis is based on the fact that adhesion requires close contact between the materials on a microscopic scale, which can only be obtained through wetting of the solid surface by the polymer melt, creating a large effective contact area. Basic laws of heat transfer state that when two bodies of different temperatures come into contact, the

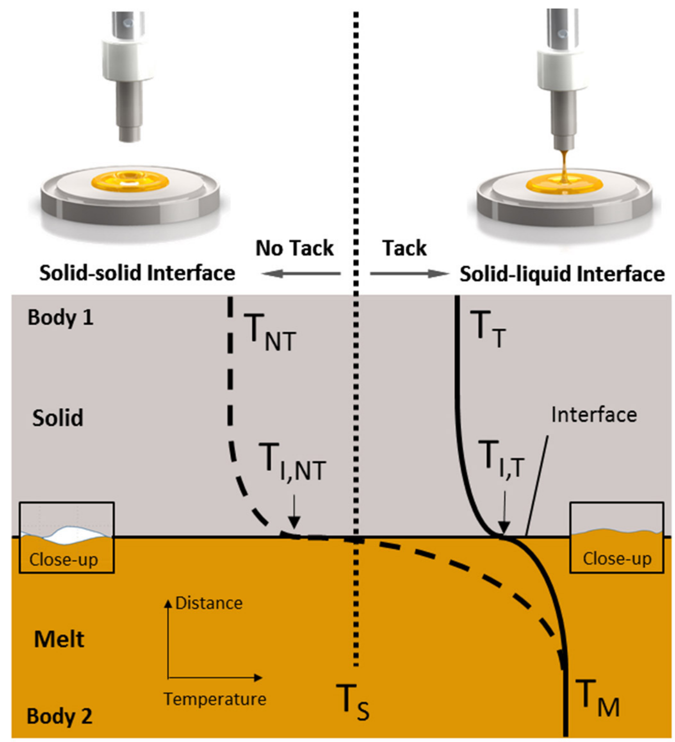

Figure 1. Temperature curves of the contact temperature tack (stickiness) hypothesis. No tack (NT) case: Solid temperature, T_{NT}, and melt temperature, T_M (dashed curve), and interfacial temperature, $T_{I,NT}$. Tack (T) case: Solid temperature, T_T, and melt temperature, T_M (solid line), and interfacial temperature, $T_{I,T}$. T_S denotes the solidification temperature of the melt (dotted line).

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temperature at the interface instantaneously approaches a value that remains steady and does not change over time. Because this concept is applicable when the bodies are sufficiently large, it can be well approximated by two semi-infinite bodies. We describe elsewhere a method for testing the applicability of this simplification.[9] When one body is solid and the other is liquid, applying this fundamental adhesion concept together with the law of constant contact temperature gives rise to two different cases (see Figure 1).

In the 'no tack' case, the bulk temperature of the solid, T_{NT}, and the interfacial temperature, $T_{I,NT}$, are below the so-called solidification point (S) of the melt, T_S. This solidification point is related to a specific temperature, below which a certain mobility of the molecules prevents wetting of the surface for a characteristic time-scale of the experiment. Thus, close contact is prevented when a melt comes into contact with a cold surface: a solid-to-solid interface is formed instantaneously on contact, which is itself not capable of wetting the interface closely. In the 'tack' case, the interfacial temperature, $T_{I,T}$, is above the solidification point, T_S, and a liquid-to-solid interface is formed on contact. The molecules of the melt retain a certain mobility and are therefore capable of wetting the solid surface sufficiently, forming a large contact area that promotes strong adhesion.

Obviously, the interfacial temperature must lie between the bulk temperatures of both materials. The development of the temperature curves depends on the thermal effusivities (a measure of the ability of materials to exchange heat on contact) of the phases as well as the contact time. The thermal effusivity of each material in turn depends on its thermal conductivity, heat capacity, and density. When semi-infinite bodies are assumed, the interfacial temperature depends on the ratio of the thermal effusivities of both phases. Highly effusive metals, in combination with poorly effusive polymer melts, result in interfacial temperatures that are close to the metal temperature and vice versa. For this reason, our findings could contribute to understanding why some material combinations are favored for hot melt gluing, and why materials such as leather, rubber, or paper (which have similar thermal effusivities) are more likely to stick well to a hot melt glue than, say, metals (which have pronounced differences in thermal effusivities). Another example of where our findings could aid understanding is fused deposition modeling (3D printing), where printing on the ground metal plate results in relatively low adhesion (pronounced differences in thermal effusivities and temperature difference), whereas it results in good adhesion between the printed layers with identical thermal effusivities on both sides.

Our hypothesis is experimentally supported by probe-tack experiments investigating the practical adhesion under nonisothermal conditions at various temperatures between a metal probe and a polymer melt. Releasing the probe required significantly higher energy supply at interfacial temperatures above the solidification temperature, whereas little energy was needed when the interfacial temperatures were close to the solidification temperature. If the interfacial temperatures were below the solidification temperature, no energy was needed to release the probe.

The complexity of soft materials that stick to other solids has many far-reaching implications for wetting, adhesion, rheology, and heat transfer. Consequently, our study does not claim to fully resolve non-isothermal tack behavior for all substances. However, from a practical perspective, our findings may be useful to professionals (e.g., in designing new processing equipment or process troubleshooting) as well as consumers (for instance, for hot-melt gluing or 3D printing). Our future work will focus on better understanding the relationship between adhesion and heat transfer.

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