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RESEARCH ARTICLE

Cure Kinetic Study of Epoxy Systems for Advanced Composites and Surface Film Applications

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ABSTRACT

In this study, a comprehensive investigation is conducted to improve a surface film resin formulation for advanced composite applications. This surface film is designed to be co-cured with a base substrate made of carbon fiber/epoxy-based prepregs. The curing behavior of an epoxy resin formulation for a prepreg with a high glass transition temperature and a surface film formulation containing a high percentage of glass microspheres were characterized by isothermal and dynamic Differential Scanning Calorimetry, and rheometry; and the cure kinetics profiles were modeled. The effects of the curing system, glass microspheres, and accelerator on cure kinetics and rheological behavior were thoroughly investigated to assess the compatibility of these two resin systems to be used in a composite lay-up. Initial trials resulted in excessive bleeding of the surface film resin, and specific improvements have been made to accelerate the reaction so that the system co-cures without bleeding.

1 | Introduction

The aerospace industry is progressively adopting prepregs and surface films in composite structures due to their high mechanical properties, weight-to-strength ratio, and improved bonding characteristics [1–3]. Prepregs offer significant advantages regarding consistency and quality control during manufacturing. Carbon fiber reinforced polymer (CFRP) prepregs are particularly important due to their consistent properties and high strength-to-weight ratios that are critical for aerospace applications [4, 5]. Epoxy surface films, commonly employed as an outer layer in composite structures, make them more resistant to damage from weather and environmental hazards, such as lightning strikes or electromagnetic interference shielding [6, 7].

Epoxy resins are thermosetting polymers extensively utilized as matrix materials in reinforced composites within the aerospace sector [8]. Their characteristics are influenced by the specific

combination of epoxy resin types and curing agents employed [9–12]. Due to their excellent mechanical strength, as well as their resistance to heat and chemicals, epoxy resins are widely applied across various industries, serving as matrix systems in fiber-reinforced composites [13]. Optimizing the curing kinetics of epoxy resins is crucial to increasing their effectiveness. The curing process involves the transformation of liquid epoxy monomers into a solid thermosetting polymer through a series of chemical reactions, which are highly dependent on several factors, including temperature, type of curing agent, and resin formulation [14–18]. The choice of curing agent impacts the kinetics, as different agents can alter the reaction mechanism and the rate of crosslinking, which is essential for achieving the desired thermal and mechanical properties [14, 19]. Additionally, the incorporation of additives such as accelerators or inhibitors allows for fine-tuning of the curing process, enabling customization of the epoxy's characteristics to meet specific application requirements [20]. Various studies have been carried out

Summary

- Surface film leads to significant resin bleeding and warpage.
- Adding an accelerator boosts resin retention in the surface film.
- The accelerator enhances the curing kinetics, facilitating faster gelation.
- The accelerator syncs the co-curing of surface film and prepreg.

on cure kinetic studies and modeling of cure kinetics of epoxy resins and amine-type cure agents [21–28]. In order to create mathematical cure kinetic models, Differential Scanning Calorimetry (DSC) has been commonly employed to analyze the heat released during the curing reaction [29]. Moreover, the rheological effects of inorganic fillers, such as glass spheres, on epoxy resins have an important effect and have been extensively studied. Research has demonstrated that adding glass spheres can induce changes in the rheological behavior and cure kinetics of epoxy resin systems [30–32]. In terms of the curing behavior of epoxy resins, adding inorganic fillers can induce latent curing behaviors, affecting the overall rheological properties of the resin matrix [33]. Furthermore, the response of fillers in the crosslinking process of epoxy resins is crucial for thermosetting resin composites, guiding the design of new materials with tailored properties [34]. Studies have also shown that the filler content and bead size of glass microspheres influence cure kinetics by affecting the crosslinking process [35]. Studies on epoxy resins with various fillers, including microspheres, have explored their effects on flow and mechanical properties [36, 37].

Glass microspheres are frequently added to epoxy formulas to lower density and weight, enhance thermal insulation, and reduce heat transfer. These hollow and spherical particles create a barrier that delays heat flow and lowers the composite material's thermal conductivity. However, they can also influence the cure kinetics of the epoxy. The microspheres can change the heat distribution within the curing system, which could slow down the exothermic reaction of the epoxy. This can result in a longer cure time or lower peak exotherm, which may require adjustments in curing schedules or formulations to achieve optimal properties. Several studies have demonstrated that incorporating glass microspheres into epoxy resins significantly reduces thermal conductivity in epoxy resins [38–40]. Studies also indicated that the thermal conductivity of the composites decreases with increasing glass microsphere content or decreasing glass microsphere density [41]. Glass microspheres restrict polymer chain movement during curing, creating a physical barrier that influences curing kinetics. Higher filler content and smaller particles lower activation energy, accelerating initial curing, but the process slows later due to diffusion limitations and reduced reaction order [42].

Building on this understanding of curing kinetics, researchers have studied autocatalytic reaction models to characterize the cure behavior of epoxy resins [43–48]. Additionally, the selection of curing agents has been found to influence the cure kinetics

of epoxy resin systems, with different curing agents leading to changes in the autocatalytic cure reactions. Research investigated an autocatalytic mechanism [49] as well as the influence of various curing agents on the kinetics of the curing reaction in epoxy resin systems, highlighting the significance of identifying kinetic parameters for different curing agents [50–52].

In aerospace composite parts, epoxy surface films serve as a protective outer layer. However, their incorporation causes several problems, such as extensive resin bleeding during curing due to their high resin content, affecting the overall fiber-to-resin ratio, interface bonding, defect formation, and warpage problems due to the cure shrinkage of epoxy in the composite structure. Compatibility of prepreg and surface film is important to control resin bleeding, avoid resin-starved or resin-rich areas, and ensure uniform thickness in the composite structures. Optimizing the cure kinetics of both material and processing conditions, including temperature, pressure, and layup design, ensures that the interaction between the prepreg and surface film leads to high-quality composite components with consistent mechanical and surface properties.

Although the use of accelerators to adjust cure kinetics and the addition of glass microspheres to modify rheology are well-established methods widely investigated in the literature on epoxy resins, their interaction has not been studied extensively so far. Thus, this study aims to bridge this gap by demonstrating a tertiary epoxy resin system that incorporates both a rheology modifier and a cure accelerator.

Nowadays, part manufacturers require advanced resin systems that minimize manufacturing defects such as resin bleeding, warpage, non-homogeneities, and nonuniformities in thickness without much need for modification of process parameters and reduce the dispensable molding materials such as resin dams, release films, and so forth. These are all requirements for net-shape composite part manufacturing with minimum trimming and less scrap.

The main objective of this study is to develop resin systems that can help to mitigate two undesirable effects that are widely encountered in composites laminated with surface films: (1) resin bleeding in the corners of the laminates, especially from resin-rich surface film layers and (2) warpage due to the differential thermal expansion and cure shrinkage of the substrate and surface film layers. Furthermore, this study aims to characterize the cure kinetics and rheology of the prepreg and surface film resins for a Finite Element Analysis-based process simulation to optimize the cure cycles in order to reduce manufacturing-related problems.

To address these challenges, this study explores two resin systems designed to enhance the compatibility problem between prepreps and epoxy surface films, a problem that is commonly encountered in industrial applications but not investigated in detail in academic studies. Both resin systems are based on multifunctional epoxy resins and aromatic diamine as a curing agent. One of the systems (PreP) is designed for prepreps used in advanced aerospace applications, and the other is a high Glass Transition Temperature (T_g) surface film. The surface film formulation contains hollow glass spheres as filler to reduce cure shrinkage and thermal expansion

coefficient, as well as to enable better paint adhesion after grinding. In the preliminary studies, it was observed that the surface film caused extensive resin bleeding when it reached high temperatures under pressure in the autoclave, which caused thickness variations and distortions in the composite plate. In order to solve this problem, surface film formulation was fine-tuned by adding an accelerator, and a new formulation was developed, which aims to make it gel faster than the prepreg resin, thus preventing flow when it reaches high temperatures. Consequently, two different formulations were studied for the surface film system, without an accelerator (SF) and with an accelerator (SFa).

2 | Experimental

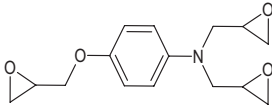
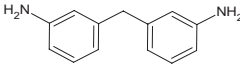

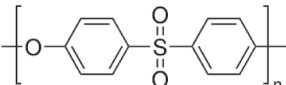
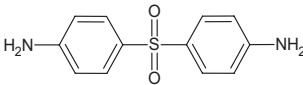
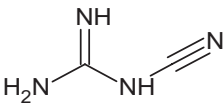
2.1 | Materials

In order to prepare PreP formulation, high-performance thermosetting epoxy pre-polymers, Araldite MY0510, which is based on standard N,N-Diglycidyl-4-glycidyoxyaniline (TGPAP) epoxy resin with an epoxy equivalent weight (EEW) of 98.5 g/eq, a three-functional epoxy resin, Araldite MY 720 resin is based on 4-[(4-aminophenyl)methyl]aniline;2-(chloromethyl)oxirane (TGDDM) with an EEW of 112.5 g/eq and an aromatic diamine curing agent, the Aradur 9664-1 is a 4,4'-Diaminodiphenyl sulfone (DDS) amine type with amine equivalent weight (AHEW) of 62 g/eq, were supplied by Huntsman, Tienen (Belgium). The stoichiometric amounts of the curing agents were calculated through the number of active amino hydrogens in DDS, and the stoichiometric ratio between the resin mixture and curing agent was set at 1:1 to replicate industrial practice for

thick-section carbon fiber-reinforced polymer composites as used in aerospace applications. Polyether sulfone (PES) was supplied by Sumitomo Chemical Europe, Machelen (Belgium), and used as a thermoplastic toughener in the formulation, and 20% was added to the prepreg formulation and 14% to the surface film formulations.

The iM16K glass microspheres, provided by 3M (France), were incorporated to reduce the final part weight and enhance dimensional stability in the surface film formulation. The glass spheres also provide a pitted surface when ground for better paint adhesion. The iM16K glass microsphere concentration constituted 18wt% of the total surface film formulations. Additionally, the proportion of PES was reduced to 14% in the surface film formulations, as the elevated quantity of toughener was deemed unnecessary for surface film applications, and also to adjust the viscosity of the final formulation. Dicyandiamide (DICY), which is supplied by Evonik (USA), was employed as an accelerator in the surface film formulation to shorten the gel time compared to the prepreg formulation. This adjustment was necessary due to the higher resin content in the surface film, which is ~90%, increasing the likelihood of resin flow. Since resin flow was observed in the composite plate containing SF, a second surface film formulation, SFa, was studied by adding an accelerator to reduce this flow while maintaining a 1:1 stoichiometric balance. The accelerator was included at 2.5% of the total formulation weight, equal to 1 stoichiometric ratio in the total formulation. Table 1 provides a comprehensive overview of the selected raw materials, including their molecular weight, chemical structure, epoxy or amine hydrogen equivalent weight, and nomenclature.

TABLE 1 | Raw materials in detail.

Name	CAS number	Abbrev.	Equivalent weight (g/eq)		Chemical structure
			Epoxy	Amine hydrogen	
Triglycidyl-p-aminophenol	5026-74-4	TGPAP	95–107	—	
N',N'-tetraglycidyl-4,4'-diamine diphenyl methane	28390-91-2	TGDDM	117–134	—	 
Polyethersulfone	25608-63-3	PES	—	—	
4,4'-Diaminodiphenyl sulfone	80-08-0	DDS	62	—	
Dicyandiamide	461-58-5	DICY	21	—	
Soda lime borosilicate glass	65997-17-3	Glass sphere	—	—	SiO ₂

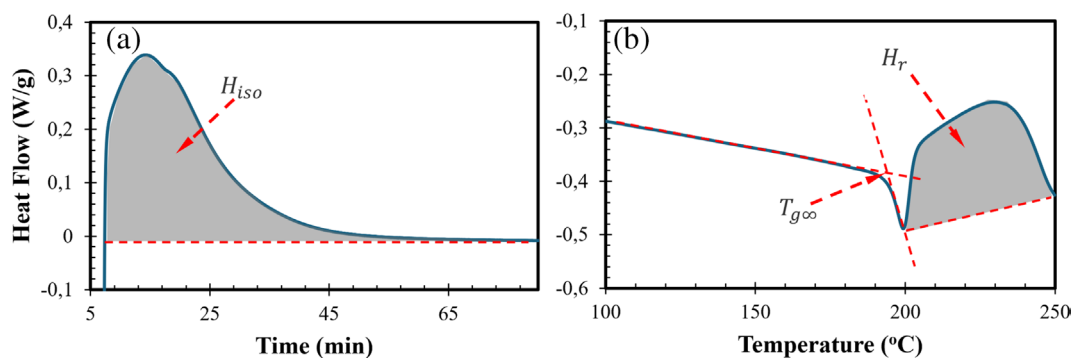


FIGURE 1 | (a) Heat flow during isothermal curing at 180°C and (b) heat flow after cooling the sample and reheating at a rate of 2°C/min.

TABLE 2 | The total heat of reactions and initial and ultimate glass transition temperatures for PreP, SF, and SFa.

	PreP		SF		SFa	
	H_{tot}	T_g	H_{tot}	T_g	H_{tot}	T_g
Unit	(J/g)	(°C)	(J/g)	(°C)	(J/g)	(°C)
Initial		-18.34		-14.50		-0.88
Ultimate	-473.65	223.5	-370.43	213.4	-476.85	213.4

2.2 | Sample Preparation

The resins, TGPAP and TGDDM, preheated to 120°C, were combined with the toughener, PES, in the specified proportions and placed into a plastic container. This mixture was then homogenized using a speedmixer for 5 min. Next, glass spheres were weighed and added to the hot mixture, followed by an additional mixing period of 3–5 min until the mixture was homogeneous. The curing agent, DDS, was weighed, added to the mixture at 80°C, and mixed for 2 min. Finally, the accelerator, DICY, was weighed, added, and mixed in for 2 min to complete the process. The samples were immediately flash-frozen using a freezer to avoid premature curing reactions until the testing.

The production of carbon fiber unidirectional UD prepreg using a hot melt prepreg machine involves impregnating continuous 12K A-49 Dowaksa tows with the PreP resin film under controlled heat and pressure, ensuring uniform resin distribution and fiber alignment. Additionally, surface film productions are achieved by applying a specially formulated SF and SFa resin films onto a 46gsm plain weave glass fabric carrier, resulting in a thin, uniform surface layer used for enhanced surface finish and protection in composite structures. Both the UD prepreg and surface film productions are carried out by Kordsa Teknik Tekstil A.S., ensuring consistent quality and performance for advanced composite applications.

2.3 | DSC Measurements

Mettler Toledo DSC 3+ (Mettler-Toledo, Schwerzenbach, Switzerland) was used to perform dynamic and isothermal experiments to provide data for calculating parameters in the

TABLE 3 | Parameters for n th order, autocatalytic reaction of PreP, SF, and SFa.

Parameter	Unit	PreP	SF	SFa
A	s^{-1}	36,140	231,212	221,778
E	J/mol	61,128	70,137	70,173
n		1.656	1.096	1.420
m		0.468	0.484	0.174

model equations that describe the cure kinetics over a wide range of conditions. Isothermal experiments were performed by heating the uncured resin from 25°C to 150°C, 160°C, 170°C, 180°C, and 190°C with a heating rate of 20°C/min, then holding at the specified temperature for the reaction to complete as indicated by a straight baseline reaching to a horizontal asymptotic value in the heat signal, as shown in Figure 1a, the isothermal specimens are cooled to 25°C and then heated to 250°C to find the ultimate glass transition temperature $T_{g\infty}$ and residual heat, H_r , as shown in Figure 1b, the total heat of reaction H_{tot} for the isothermal runs are found by adding up the heat released during the isothermal hold H_{iso} plus the residual heat, H_r . The ultimate degree of cure attainable at an isothermal hold X_∞ can be found by:

$$X_\infty = H_{iso} / H_{tot} \quad (1)$$

Dynamic experiments were performed by heating from -30°C to 250°C at rates of 1°C, 2°C, 5°C, and 10°C/min. The glass transition temperature of the uncured resin and T_g can be calculated from the step change in the heat flow signal. A sigmoidal baseline is drawn to integrate the heat flow signal to find the ultimate heat of reaction.

2.4 | Rheology Measurements

Rheology measurements are carried out in an Anton Paar MCR 302 (Anton Paar GmbH, Graz, Austria) rheometer using the parallel plate mode. A 1 mm thick liquid resin is poured between the plates, and the upper plate oscillates with a frequency of

10 rad/s. Isothermal and Dynamic runs were performed to provide a versatile data set to calculate rheology model parameters. Isothermal and dynamic temperatures for the isothermal and dynamic runs were the same as those in the DSC experiments. The gel point is measured as the crossing point of the storage modulus and loss modulus during isothermal runs.

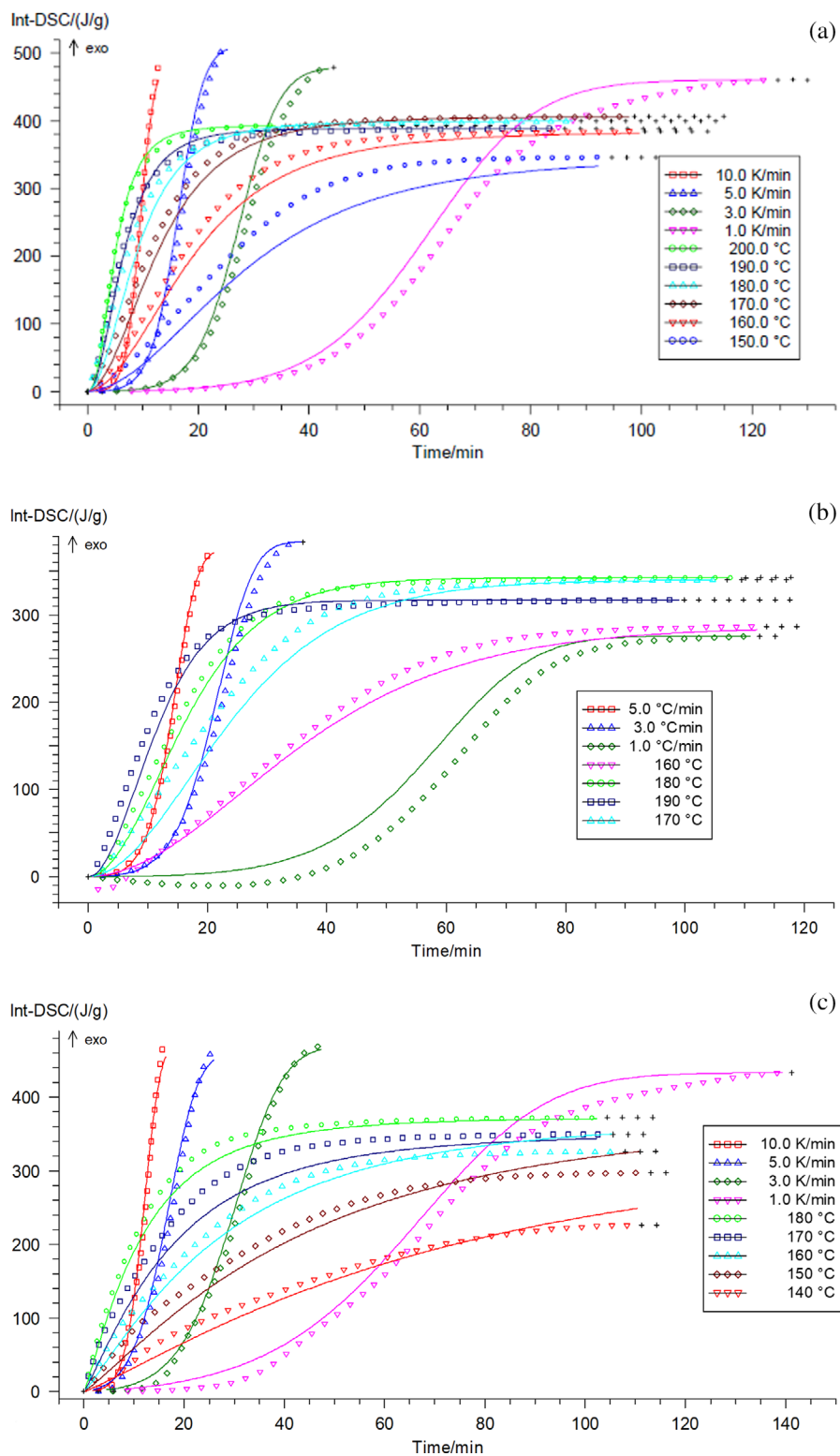


FIGURE 2 | Model fit for using both isothermal and dynamic runs for (a) PreP, (b) SF, and (c) SFa.

3 | Results and Discussion

3.1 | Cure Kinetics Model

The total heat of reactions (H_{tot}) and T_g obtained are listed in Table 2 for the prepreg, PreP, and surface film systems, SF and SFa. It should be noted that the total heat of reaction of the surface film resin is 22% less than the prepreg resin, close to the weight percent of the glass microspheres in its formulation.

In order to fit the degree of cure evolution with temperature, a simple model that includes one single-step reaction is used.

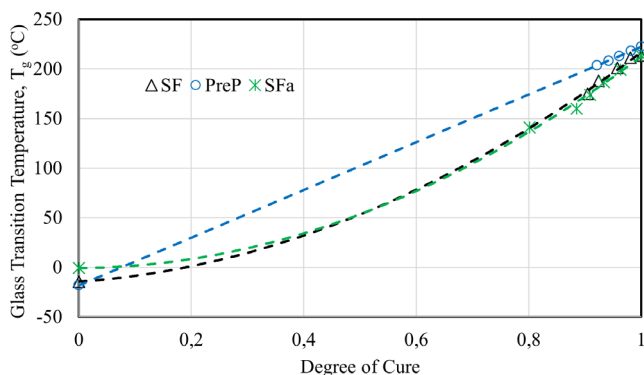


FIGURE 3 | The ultimate degree of cure attainable for isothermal cure temperature.

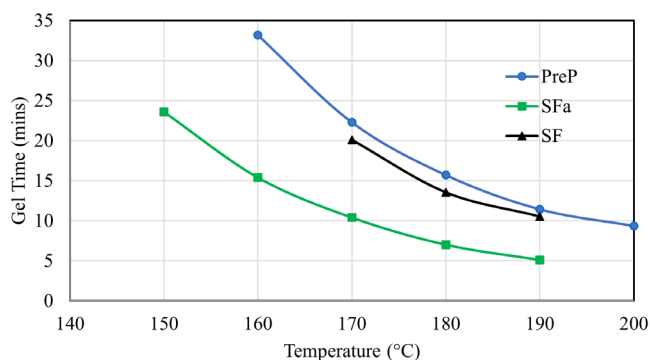


FIGURE 4 | Comparison of gel times at various isothermal temperatures for the PreP, SF, and SFa.

TABLE 4 | Gel time t_{gel} and degree of cure (DoC) at gelation of PreP, SF, and SFa systems.

T (°C)	Prep		SF		SFa	
	t_{gel} (min)	DoC	t_{gel} (min)	DoC	t_{gel} (min)	DoC
140					37.0	0.397
150					23.6	0.406
160	33.20	0.464			15.4	0.410
170	22.31	0.454	20.10	0.456	10.4	0.420
180	15.72	0.468	13.55	0.448	7.01	0.431
190	11.44	0.476	5.10	0.410	5.10	0.410
200	9.37	0.574				
Average		0.487		0.452		0.407

The reaction is assumed to be of n th order, autocatalytic type reaction:

$$\frac{\partial \alpha}{\partial t} = k \alpha^m (1 - \alpha)^n \quad (2)$$

where k is the temperature-dependent rate constant, and m and n are freely selectable temperature-independent exponents.

The chemical rate constant is described in the form of the Arrhenius equation:

$$k = A \exp \{ -E / RT \} \quad (3)$$

where A is the pre-exponential factor, E is the activation energy, R is the universal gas constant, and T is the absolute temperature in degrees Kelvin.

Table 3 lists the parameters optimized using non-linear regression for PreP, SF, and SFa.

The model fit using the n th order, Prout-Tompkins type reaction for prepreg, and unaccelerated and accelerated surface film formulation are shown in Figure 2, respectively. Figures indicate that the model accurately predicts the DSC signals. The model fit plot for the surface film without an accelerator is very similar to the Prepreg model, so it is not presented here. In these plots, the y-axis shows the evolution of the integrated DSC signal in terms of energy per unit mass (J/g) as a function of time for both isothermal and dynamic runs, showing the progress of the exothermic curing reaction. The model effectively fits the experimental data across various conditions with $R^2 > 0.90$ in all cases, providing insight into the kinetics of the curing process.

3.2 | Glass Transition Temperature

Figure 3 shows glass transition temperatures (T_g) of the three resin systems as a function of the degree of cure that was obtained from the dynamic DSC rescans of partially cured resins at specified isothermal temperatures. Also shown are curve fits according to the Di Benedetto equation:

$$\frac{T_g - T_{go}}{T_{g\infty} - T_{go}} = \frac{\lambda\alpha}{1 - (1 - \lambda)\alpha} \quad (4)$$

The parameters T_{go} and $T_{g\infty}$ were determined with glass transition temperature measurements of uncured and fully cured DSC samples. λ is the fitting parameter and was found to be 0.5 for the prepreg resin and 1.0 for the surface film resin. Although there are not sufficient data points at lower degrees of cure, it can be seen that surface film resins have lower T_g for the partial degree of cure as compared to the prepreg resin, although both resins reach the same T_g when fully cured.

3.3 | Gelpoint

The comparison of gel times for the three resin systems for various temperatures is shown in Figure 4. It can be seen that the prepreg and the unaccelerated surface film resin gel at approximately the same time for all temperatures, while the accelerated surface film gels faster than the other two due to the presence of the accelerator. Table 4 shows the gel time and degree of cure at the gel time for the prepreg and surface film resin systems, respectively.

3.4 | Viscosity Model

The selected model to represent the viscosity evolution of the presented resin systems, first proposed by Kim and Macosko [53], is shown in Equation (2).

$$\eta(T, \alpha) = \eta(T) \left(\frac{\alpha_g}{\alpha_g - \alpha} \right)^{(\alpha + b\alpha)} \quad (5)$$

TABLE 5 | Parameters for the viscosity model of Prep, SF, and SFa.

Parameter	Unit	PreP	SF	SFa
η_0	Pas	4.36E-05	2.23E-09	6.65E-09
$E_{a,M}$	J/mol	4.16E+04	8.38E+04	7.10E+04
a		4.48	7.18	7.08
b		-3.32E	-8.59	-10.1
α_g		0.50	0.55	0.45

where α_g is the degree of cure at the gelation point. The fitted cure kinetics model (Equation 4), together with the temperature history in each test, was used to estimate the degree of cure at the gelation point. The parameters a and b are constant parameters, and $\eta(T)$ is the temperature-dependent viscosity function, defined as Equation (3).

$$\eta(T) = \eta_0 \exp\left(\frac{E_{a,M}}{RT}\right) \quad (6)$$

where η_0 is the pre-exponential factor, $E_{a,M}$ is the activation energy, R is the gas constant, and T is the absolute temperature.

The viscosity model parameters found by using non-linear regression are listed in Table 5 for prepreg and two surface film systems within the range. All model parameters are calculated empirically using the cure kinetics and viscosity equations for the conversion range between zero up to the gelation degree of cure.

The viscosity model fits for prepreg, and the two surface film systems are shown in Figure 5, respectively, which indicates that the model predicts the experimentally measured viscosity profiles quite accurately, except at the start of the test for surface film formulation. The reason for the exception is the fact that the SF resin is quite viscous at room temperature and retains so until a certain temperature, a behavior that the model cannot capture.

3.5 | Simulation of Cure Cycle

The curing processes of the composite materials have been optimized by cure kinetic study using the cure kinetics and rheology models. Figure 6a demonstrates the evolution of the degree of cure, glass transition temperatures, and viscosity for PreP, SF, and SFa during a typical cure cycle with a heat-up ramp of 3°C/min and a hold at 180°C.

Figure 6b shows that properties of PreP and SF formulations evolve more or less in the same way except for viscosity, which is an order of magnitude higher in SF due to the presence of glass microspheres. The gel point of PreP and SF formulations takes place around 60 min, as indicated by a sharp rise in the viscosity. In contrast, the SFa formulation gels about 10 min earlier due to the presence of an accelerator. However, as the

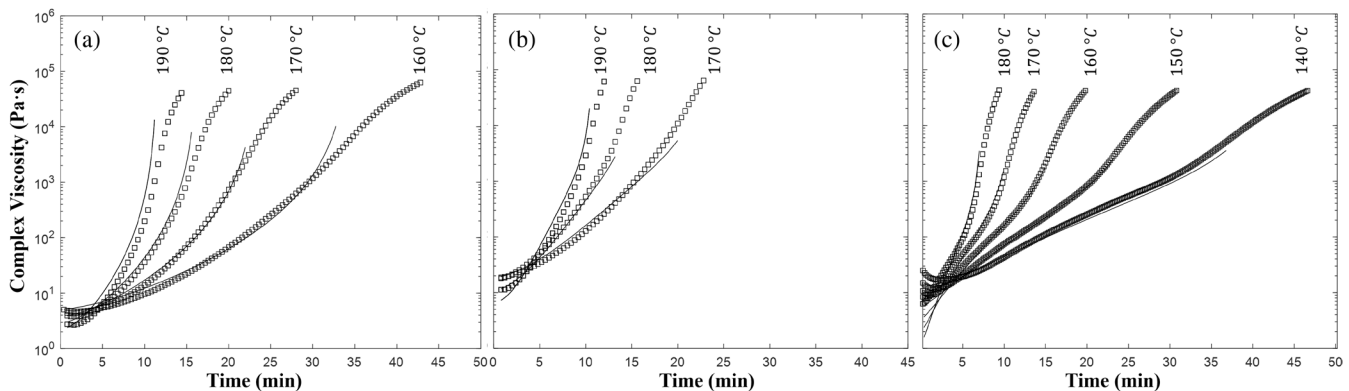


FIGURE 5 | Viscosity model predictions (solid lines) compared to experimental data (dot lines) for (a) PreP, (b) SF, and (c) SFa.

cure advances, a polymer network is formed, the curing reaction becomes more diffusion-dominated, and the reaction rate of SFa becomes slower than that of the PreP and SF formulations. Vitrification of PreP and SF formulations takes place around 65 min, which is indicated by the glass transition temperature curves reaching the process temperature. However, the SFa formulation vitrifies much later, around 90 min. While the SF formulation reaches maximum T_g in approximately at 100th minutes, whereas the SF formulation needs another 20 min to reach the maximum T_g . It can be said that 2 h at 180°C is the optimum cure cycle for a system that utilizes both PreP and SFa formulations.

This combination will allow compatible curing without much resin bleeding from the surface film, and there is a minimal amount of resin bleeding when this combination is used. Figure 7 shows two composite panels that demonstrate the

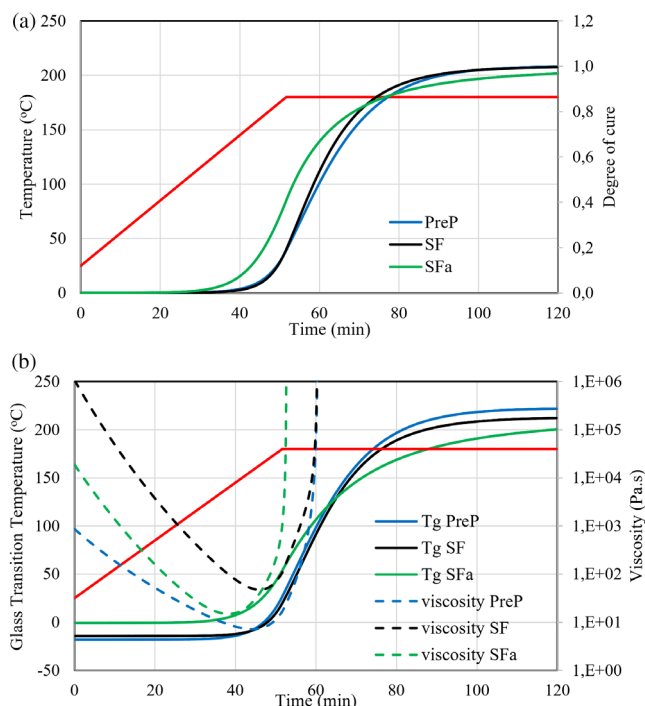


FIGURE 6 | (a) The degree of cure and (b) viscosity, and glass transitions of PreP, SF, and SFa as a function of the cure cycle.

effects of resin control and incorporating an accelerator during the curing process. The composite plates are manufactured by stacking eight layers of CFRP prepreg impregnated with PreP resin and one layer of glass veil impregnated with surface film resins SF and SFa. Standard procedures for vacuum bagging are applied with nonperforated release film and without resin dams. The recommended cure cycle, which can be seen in Figure 6, is carried out.

Panel (a) features a single layer of SF on a carbon fiber-reinforced substrate with significant resin bleeding after curing, reflecting inadequate resin containment. The excessive resin flow compromises the structural integrity and may diminish the visual appeal. Conversely, panel (b) depicts the same composite system with an accelerator incorporated into the surface film matrix, SFa, resulting in minimal resin bleeding and less warpage. The accelerator enhances the curing kinetics, facilitating faster gelation and improved resin retention. This comparison underscores the critical role of resin control and accelerators in achieving near-net-shape manufacturing in composite surface film manufacturing.

4 | Conclusions

This examination of surface film formulations and their cure kinetics and rheology offers a valuable contribution to the field of composite manufacturing. Composite surface films demonstrate significant flow under high temperatures during the curing process due to their high resin content (~85%), particularly when compared to prepregs. Initial trials with a surface film formulation lacking an accelerator, SF, revealed significant resin bleeding during the autoclave curing process when laminated with a prepreg substrate, PreP. This resin flow caused notable thickness variations and warpings in the composite plate, highlighting a critical need for optimization. Therefore, a surface film formulation that gives faster gelation than the prepreg formulation was developed by adding an accelerator to provide a more compatible curing profile with the prepreg lay-ups.

When the evolution of the cure parameters for prepreg and surface film formulations were compared, it was observed that the SF formulation exhibited a similar cure evolution to that of PreP despite containing a high amount of glass spheres. However,

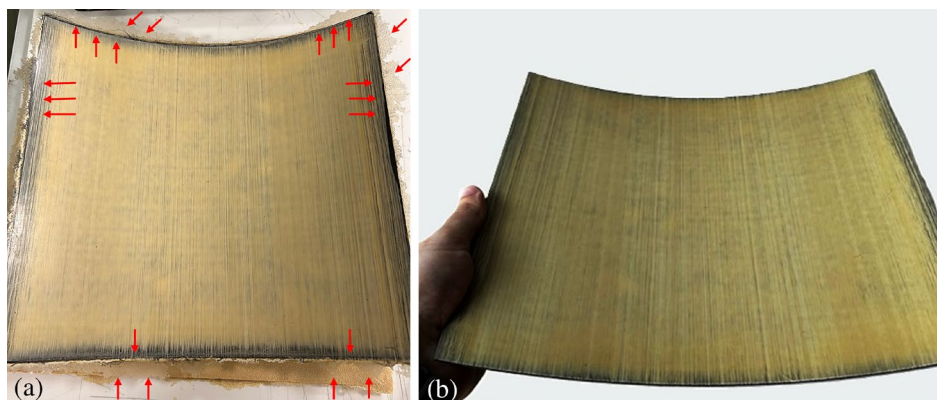


FIGURE 7 | (a) Composite plate with one layer of SF showing excessive resin bleeding and warpage; (b) composite plate with one layer of SFa showing no resin bleeding and less warpage.

when an accelerator is added, the SFa resin gels more rapidly and vitrifies more slowly than in unaccelerated systems. This delayed vitrification can be attributed to differences in the resin composition and curing dynamics. Although the prepreg lamination itself requires less curing time, the need for an extended dwell at 180°C for composite plates with surface film increases the overall processing duration.

To achieve a shorter curing cycle and to ensure that the surface film formulation has a matching cure cycle with the prepreg formulation, it may be necessary to adjust the amount of accelerator in the SFa formulation. By increasing the accelerator content, the curing process can be expedited, allowing the surface film to reach vitrification and full cure in a timeframe similar to that of the prepreg. This adjustment helps synchronize the curing cycles of both materials, ensuring optimal performance and compatibility in composite manufacturing processes. However, the fine-tuning required for the accelerator would need to be determined through careful formulation testing to balance the curing speed without compromising the material properties.

Author Contributions

Koray T. Ilhan contributed to conceptualization, methodology, investigation, analysis, visualization, and writing. Nuri Ersoy was responsible for the original draft, writing, review, and editing. Onur Yuksel contributed to the investigation and analysis. I. Ersin Serhatli was involved in conceptualization, supervision, writing, review, and editing. All authors provided critical feedback and revisions to the manuscript and approved the final version.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.