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Calendering of metal/polymer composites: An analytical formulation

B.O. Calcagno[a,d,*], K.R. Hart[b], W.C. Crone[a,b,c]

[a] Materials Science Program, University of Wisconsin-Madison, United States
[b] Engineering Mechanics Program, University of Wisconsin-Madison, United States
[c] Department of Engineering Physics, University of Wisconsin-Madison, 1500 Engineering Drive, Madison, WI 53706, United States
[d] Department of General Engineering, University of Puerto Rico-Mayagüez, Call Box 9000, Mayagüez, PR 00681, United States

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ABSTRACT

The process of calendering, or cold rolling, is relevant to geologic processes and industrial applications, ranging from food processing to thin film transistor manufacturing. When dissimilar materials are sandwich stacked and then subjected to extrusion-like deformation between rollers, several factors influence the outcome of the product composite. In this work, Newtonian and Power Law models are developed to predict the pressure and stresses experienced by the materials during calendering. Experiments with polymer/metal sandwiched layers inform the parameters used in the models and allow for validation. A parametric analysis is conducted to further explore the influence of material and processing parameters. The pressure profiles predicted by the models are compared to experimental results of the pressure sensor data and the parameters leading to inclusion fracture in the six composite material combinations explored. The Newtonian model is found to have the best correlation with experimental findings.

1. Introduction

Cold rolling is a process that reduces the thickness of sheets of materials by extruding them through hard rotating rollers. Cold rolling can also be combined with folding to induce deformation and structural transformations of metallic multilayers, induce grain refinement (Crone et al., 2004; Crone et al., 2002; Perepezko et al., 2004), and to produce particle disperse composite from multilayer material (Antoun, 2003; Calcagno, 2008). Cold rolling is also known as calendering when the material processed is paper, plastic or rubber (Gaskell, 1950).

A variety of industries use calendering to process materials and components. In food processing, sheeting/rolling is used for forming pastas, bread, and biscuit dough. Cereal grains go through the flaking process to produce cereal flakes. Work has also been conducted to find the process conditions to shape cheese without fracturing by use of rolling (Levine, 1996; Levine and Levine, 1997; Mitsoulis and Hatzikiriakos, 2009; Peck et al., 2006). Calendering is also extensively used to improve paper and fabric's surface smoothness (Forseth and Helle, 1998; Hardman, 1994; Retulainen et al., 1997). For electronic applications, rolling processes are used to control grain orientation of materials to produce thin film transistors on steel and plastic foil (Shen, 2008; Suo et al., 1999).

Gaskel developed a model that uses the momentum and continuity equations to analyze the process of calendering of Newtonian and Non-Newtonian viscous liquids (Gaskell, 1950). This model assumes unidirectional, incompressible, isothermal and steady state flow through a very small nip gap. These assumptions together with

* Correspondence author at: University of Puerto Rico-Mayagüez, Department of General Engineering, Call Box 9000, Mayagüez, PR 00681-9000, United States. Tel.: +1787 832 4040x3069; fax: +787 265 3816.
E-mail addresses: barbara.calcagno@upr.edu (B.O. Calcagno), crone@engr.wisc.edu (W.C. Crone).

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neglecting of the inertial effects are known as the lubrication approximation (Deen, 1998). McKelvey, and Chong worked on a more complete analysis of Newtonian and power law fluids which used three constitutive equations to analyze the calendering of thermoplastics: a power law, a three-constant Oldroyd, and modified second-order Rivlin–Ericksen fluid equations (Chong, 1968; McKelvey, 1962). An isothermal model accounting for slip at the calender surface was developed by Vlachopoulus and Hrymak and compared to experimental values obtained for PVC resins with good agreement (Vlachopoulos and Hrymak, 1980). A two dimensional, isothermal, and non-isothermal analysis of calendering without the lubrication approximation was performed using a finite element program for Newtonian, power law, and viscoelastic fluids (Mitsoulis et al., 1985). In their work, the results were compared with those obtained with the lubrication approximation, showing that the latter underestimates the temperature profiles in the nip gap but gives similar pressure, and moment distributions.

Levine and coworkers used the lubrication approximation to develop a model for a two dimensional flow of power-law fluids for the calendering of finite width sheets (Levine et al., 2002). Results obtained with finite element method were compared with experimental data showing that the model predicted reasonably well the flow and pressure fields of the material in the z direction. Sofou and Mitsoulis used the lubrication approximation theory to produce numerical results for the calendering of pseudoplastic and viscoplastic sheets of finite thickness for a specified exit thickness (Sofou and Mitsoulis, 2004). The same authors reported later work that included a slip coefficient to account for slip over the roller surfaces for the calendering of a sheet from an infinite reservoir (Mitsoulis and Sofou, 2006). The results reported by most of the prior works published include the pressure gradient and distribution of the pressure inside the roller's gap, the maximum pressure reached, the forces exerted on the rollers, and the power input to the rollers.

In a previous work, which explored the calendering of a sandwich composite incorporating metallic inclusion, we reported fracture and deformation behavior similar to those exhibited in geological formations seen in nature (Calcagno et al., 2012). Effects such as boudinage and folding are observed in both systems (Lloyd et al., 1982; Masuda and Kuriyama, 1988; Zhao and Ji, 1997). The potential for an analog system with closer materials property match which is testable in a laboratory setting would hold significant value for geophysicist. Moreover, the development of a mathematical description that could model behavior for a range of scientific and industrial applications has significant value.

In this work we develop an approximate analytical formulation to determine the pressure and tensile stresses profiles in the inclusion during calendering, and the role that material properties, and processing parameters play in the fracture event. In particular, we extend the equations developed for a traditional calendering process for a composite compressed between two rotating cylinders to model the load transferred by a polymeric matrix to a metal strip inclusion embedded within the composite.

This model is based on the lubrication approximation, and at this stage the metal inclusion is modeled as a fluid with a much larger viscosity than the polymer matrix. We are not considering strains in the metal inclusion but the model permit us to find a first estimate of the pressure and stresses on the inclusion, which may cause deformation and ultimately its fracture. Both, a Newtonian and a Power law approaches are used to find the pressure profiles, which are compared against experimental values measured with a pressure sensor. Some of the experimental data used for comparison was taken from controlled rolling experiments which aimed to obtain fracture of the metal strip with the minimum rolling passes (Calcagno et al., 2012). In addition a parametric analysis is performed to analyze the effect of some processing parameters on the pressure profile.

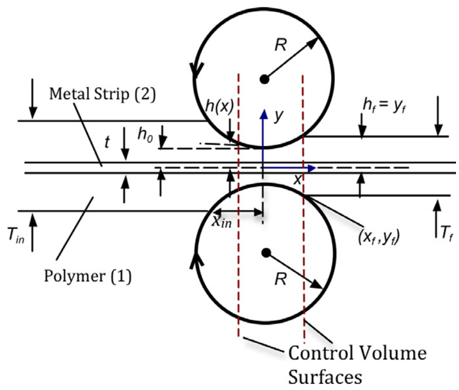

Fig. 1. Schematic diagram of the cold rolling system.

2. Analytical model

An analytical solution using dimensionless variables was derived using the continuity and momentum equations to determine the velocity profiles in a sandwich composite sample in the zone between the rollers during a calendering process. The sample modeled consists of two layers of a material with properties identified by subscript (1), and a thin layer of a second material sandwiched between those layers with properties identified by subscript (2). Following the shear lag or load transfer theory (Lloyd et al., 1982), a strong interfacial adhesion was assumed to exist throughout the process. The flow of the sample through the rollers was assumed unidirectional, isothermal, steady state, and incompressible. Following the work of Gaskell (1950) and Sofou and Mitsoulis (2004), friction between the polymer and the roller is neglected in this analysis. Because the highest stress regions within the nip occur at the roller/polymer interface, prior work has shown that the polymer behaves much more like a liquid than a solid locally. This is consistent with the lubrication approximation and is relevant to calendering of polymeric materials like those at the interface of the roller in the experiments reported here, as in contrast to cold rolling of metallic materials (Karabin and Smelser, 1990). Further, following prior assumptions of the lubrication approximation (Deen, 1998), the momentum equations were simplified under the assumption of having a very small nip gap between the rollers compared to the radius of the calenders, $2h_0 << R$ (see Fig. 1). Additional assumptions similar to those used in the lubrication approximation are: a) the pressure gradient inside the nip gap is a function of x only, thus $\frac{\partial P}{\partial y} << \frac{\partial P}{\partial x}$, b)