

Joint Shared Frailty Survival Modeling Approach to Reliability Analysis of Rolls Used in Rolling Mills

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ABSTRACT

Reliability of repairable rolls used in Rolling Mills was modeled taking to survival modeling route to address the presence of recurrent failure events, censoring event and terminal event processes observed longitudinally in rolls. All the event processes were influenced by measured and unmeasured covariates. Prior to fitting appropriate model, Archimedean Gumbel and Clayton Copula analyses confirmed that the measured covariates had no significant dependence structure. Since the censoring events were “informative terminations”, joint shared frailty multivariate survival models involving Log-Normal, Gamma and Log Gamma frailty distributions were fitted to recurrent and terminal events data where, the ‘frailty’ parameter represented the effect of unmeasured covariates related to condition of rolling operation. Gaussian quadrature method helped in estimating the model parameters. Statistical significance of the frailty parameter and its variance in all the models confirmed existence of heterogeneity across the recurrent failure events within and between rolls on account of unmeasured covariates. The statistically significant positive association between hazard functions of both the recurrent failure events and the terminal events justified joint modeling approach to the recurrent events and the terminal events processes observed in rolls. The joint lognormal shared frailty multivariate survival models were considered appropriate for analyzing the reliability of rolls.

Keywords: Censored Events, Gaussian Quadrature, Informative Censoring, Joint Multivariate Models, Lognormal Shared Frailty, Measured & Unmeasured Covariates, Roll's Recurrent Failure Events, Terminal Events

1. INTRODUCTION

Reliability analysis of ICDP (Indefinite Chill Double Pour by Centrifugal Casting) Cast Iron Roll, a repairable engineering system, used

in heavy duty steel Rolling Mills for hot/cold rolling of steel billets/ plates/sheets was very important from the point of view of evaluating its design and competitiveness in domestic and international market. Indefinite chill cast iron is

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between chill cast iron and grey cast iron and such rolls possess excellent wear-resistance, thermal cracking resistance, spall resistance and biting properties. The rolls are costly and have price tag of US \$18,700 - \$26,850 in the diameter range: 600-820 mm.

A new roll's operating life starts when (i) it is mounted in a rolling mill and (ii) the mill starts performing rolling jobs. The rolling job performed by a roll between the two successive points of its mounting and dismounting in a rolling mill constitutes a "rolling campaign". The roll may become unfit for rolling several times during its entire operating life mainly because of defects appearing on its surface. Every time a roll becomes unfit, it is dismantled from the mill, reconditioned by means of surface-grinding to make it fit and is mounted again in rolling mill for rolling till it becomes permanently unfit.

Modeling the reliability of rolls required an appropriate approach to address the following features, not so common in most other repairable engineering systems.

- A. The recurrent failure events observed in each roll were essentially multivariate longitudinal data.
- B. A terminal event (i.e.; death) was observed in each roll as a result of repeated reconditioning (i.e.; surface-grinding) that kept on reducing its diameter. The terminal event occurred in a roll when it (a) reached/crossed its scrap diameter that was determined from theory of roll technology for given chemistry and dimension of roll or, (b) became unfit beyond repair before reaching its scrap diameter.
- C. Terminal events, however, were not observed in many rolls due to loss to follow up and they were "right-censored".
- D. The "right-censored" rolls were essentially "informative dropouts" because, their diameters were found very close to their respective scrap diameters. As per the standard operating practice, a 'frail roll' was discarded for having inadequate strength before it reached its scrap diameter. Informative termination caused dependence among the recurrent event, censoring event and terminal event processes of a roll.
- E. The recurrent failure event, censoring event and terminal event processes of a roll were most likely to be influenced by a number of "measured" and "unmeasured" covariates.
- F. Information on few measured covariates was available from the roll history cards.
- G. Information on unmeasured covariates pertaining to the rolling condition was not available.

2. SEARCH FOR APPROPRIATE MODELING APPROACH

Stochastic point process framework with Non homogeneous Poisson Process (NHPP), Homogeneous Poisson Process, Renewal Process, Trend Renewal Process models were predominantly used for modeling reliability of most repairable engineering systems like rolls with maintenance policies of minimal repair, perfect repair, imperfect repair etc. (Majumdar, 1993; Majumdar, 1995; Guo, Ascher and Love, 2000; Pham, 2003; Lindqvist, 2006; Muralidharan, 2008; Moustafa, 2008). Other modeling approach consisted of: Lloyd-Lipow and Aroef differential equations (Ascher and Feingold, 1984; Rigdon and Basu, 2000), stochastic differential equations (Guo and Love, 2003), steady-state probability (Hajeeh, 2010; Hajeeh, 2011), Bayesian-NHPP (El-Damcese, Temraz, 2010; Tian, Tang & Yu, 2011; Ghosh & Majumdar, 2011), Markov process (Lindqvist & Amundrudstad, 1998; Ghosh & Majumdar, 2010), Monte Carlo simulation (Kaminskiy & Krivtsov, 2006), Petri Nets (Knezevic & Odoom, 2001) and Proportional Hazard concept (Sunethra & Sooriyarachchi, 2010).

The approach to modeling reliability of rolls needed to take account of the longitudinally observed recurrent failure events in rolls. The features of longitudinal data are: (i) the number of times (of failures) is a consequence of process development over time and can be treated as stochastic process data (ii) the number of times events occur in a subject is random, (iii) even

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