

A Temperature and Time Dependent Forming Limit Surface for Sheet Metal Forming at Elevated Temperatures

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ABSTRACT

Sheet metal forming at elevated temperatures, or so-called sheet metal warm/hot forming, is a relatively new forming process to make sheet metal parts with low mass. An accurate and convenient description of forming limit is critical for the success of forming process design and improvement. Strain based Forming Limit Diagram has long been used to describe forming limit in cold sheet metal forming. However, at elevated temperatures, the formability of those sheet metals is strongly governed by both temperatures and strain rates. In order to extend the Forming Limit Diagram method into elevated temperature domain, a large number of forming limit curves are intuitively required to cover different temperatures and strain rates. It is not only costly to obtain but also inconvenient to apply those forming limit curves in industrial practice. In this study, Zener-Hollomon parameter, which was used to describe both temperature and strain rate effect on flow stress, is proposed to represent time and temperature effect on forming limit curves. Under a hypothesis, a polynomial relationship between natural logarithm of Zener-Hollomon parameter and major strain exists at each corresponding minor strains, a forming limit surface, which is constructed in a three dimensional Cartesian coordinate system with three axes of major strain ϵ_1 , minor strain ϵ_2 and natural logarithm of Z ($\ln(Z)$), is then proposed. The hypothesized correlation between $\ln(Z)$ and forming limit curves is validated by published test data on Aluminum alloy 5083 at temperatures ranging from 293K to 573K and strain rates ranging from 0.0001 to 0.1 s^{-1} . A forming limit surface is then constructed. Since only one surface is needed, the method could reduce the efforts of laboratory testing and provide a convenient tool in the development of thermal forming processes.

Key words: Forming Limit Surface, Zener-Hollomon, hot forming, warm forming, aluminum alloys, magnesium alloys, boron steel

CITATION: Sheng, Z., "A Temperature and Time Dependent Forming Limit Surface for Sheet Metal Forming at Elevated Temperatures," *SAE Int. J. Mater. Manf.* 5(2):2012, doi:10.4271/2012-01-0016.

INTRODUCTION

Due to the direct impact of vehicle mass on vehicle fuel economy, materials with high specific strengths (strength-to-weight ratios) are used increasingly to make light weighting vehicles. However, those materials, such as aluminum alloys, magnesium alloys and high strength steels, generally have inferior formabilities at room temperature [1, 2, 3]. Sheet forming processes at elevated temperatures, so-called warm/hot forming, on those materials are thus developed to replace commonly used commercial steel sheet materials, such as HSLA or cold-rolled CQ, DQ etc. [4]. At elevated temperatures and moderate forming speeds, the formabilities of those sheet materials are enhanced by activating additional sliding systems. Components with complex geometries, such as B-pillars and A-pillars by hot stamping Boron steel and

liftgate by hot blow forming aluminum alloy SPF-5083, can be made, see Fig.1 [4, 5]. Finite element method based forming simulations are widely used to design and improve sheet metal forming processes at elevated temperatures, see Fig.2 [5, 6, 7, 8]. Because of its convenience of implementation, Forming Limit Diagram (FLD) or Keeler-Goodwin diagram is a widely accepted method to identify fracture failures in sheet forming at room temperature [9]. If strain path effect isn't significant, one Forming Limit Curve is sufficient for most stamping processes due to relative small strain rate effect. However, at elevated temperatures, strain rate effect become prominent with the increase of temperature. It is found that the formability decreases with the increase of strain rates and decrease of temperature [10, 11, 12, 13, 14, 15]. On the other hand, in reality, with the blank/tooling contact during the progress of a forming, there

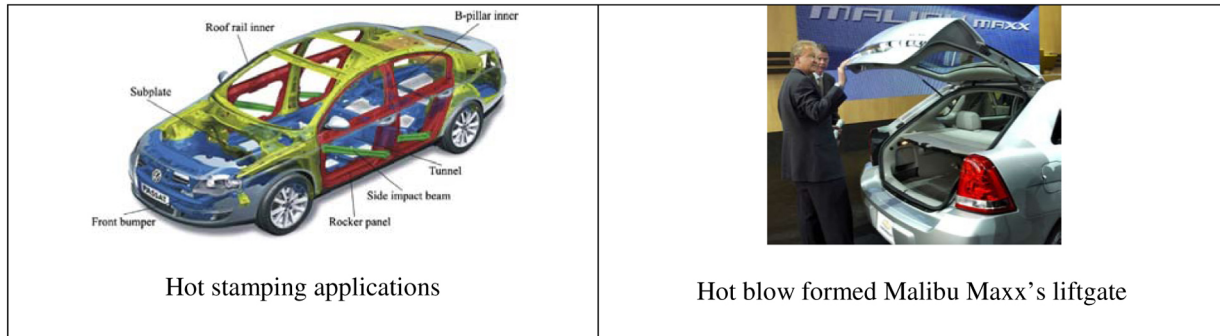


Fig.1. applications of hot forming

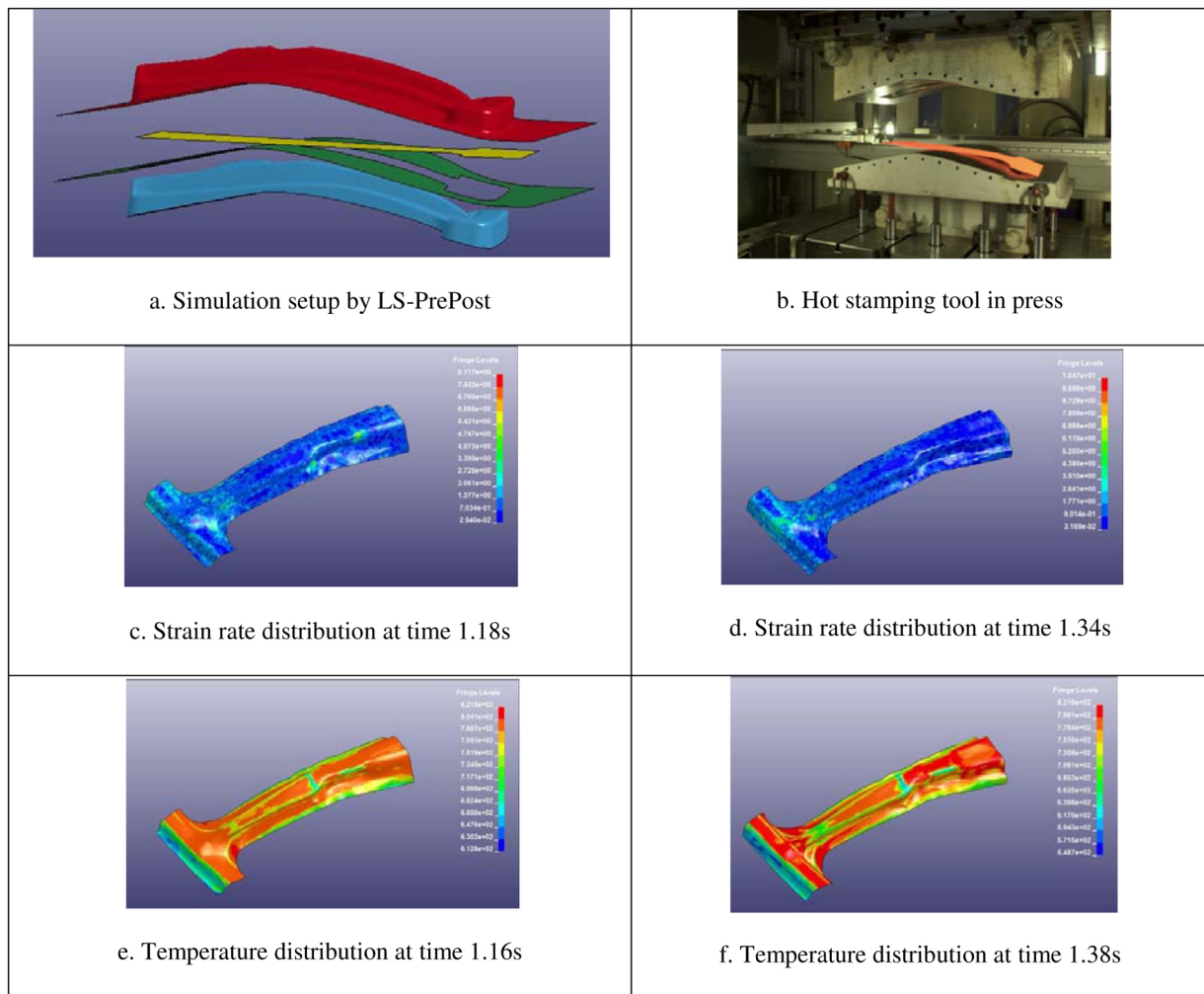


Fig.2. NUMISHEET Benchmark3 - Continuous press hardening BM3 [6]

is a spatially and temporally different distribution of strain rates and temperature on a workpiece, see Fig.2 c-f. In order to describe these situations, the strain based forming limit needs to be extended into a four dimensional manner, e.g. a large number of forming limit curves, which cover concerned temperature and strain rates, or a group of three dimensional forming limit surfaces at different strain rates, each surface is

represented by major strain ε_1 , minor strain ε_2 and temperature T .

Zener-Hollomon parameter (Z), or temperature-compensated strain rate, was proposed to represent strain rate and temperature effect on yield stress [9, 16, 17]. It is recently used to describe effective strain represented fracture limit in a polynomial fashion in forming aluminum and

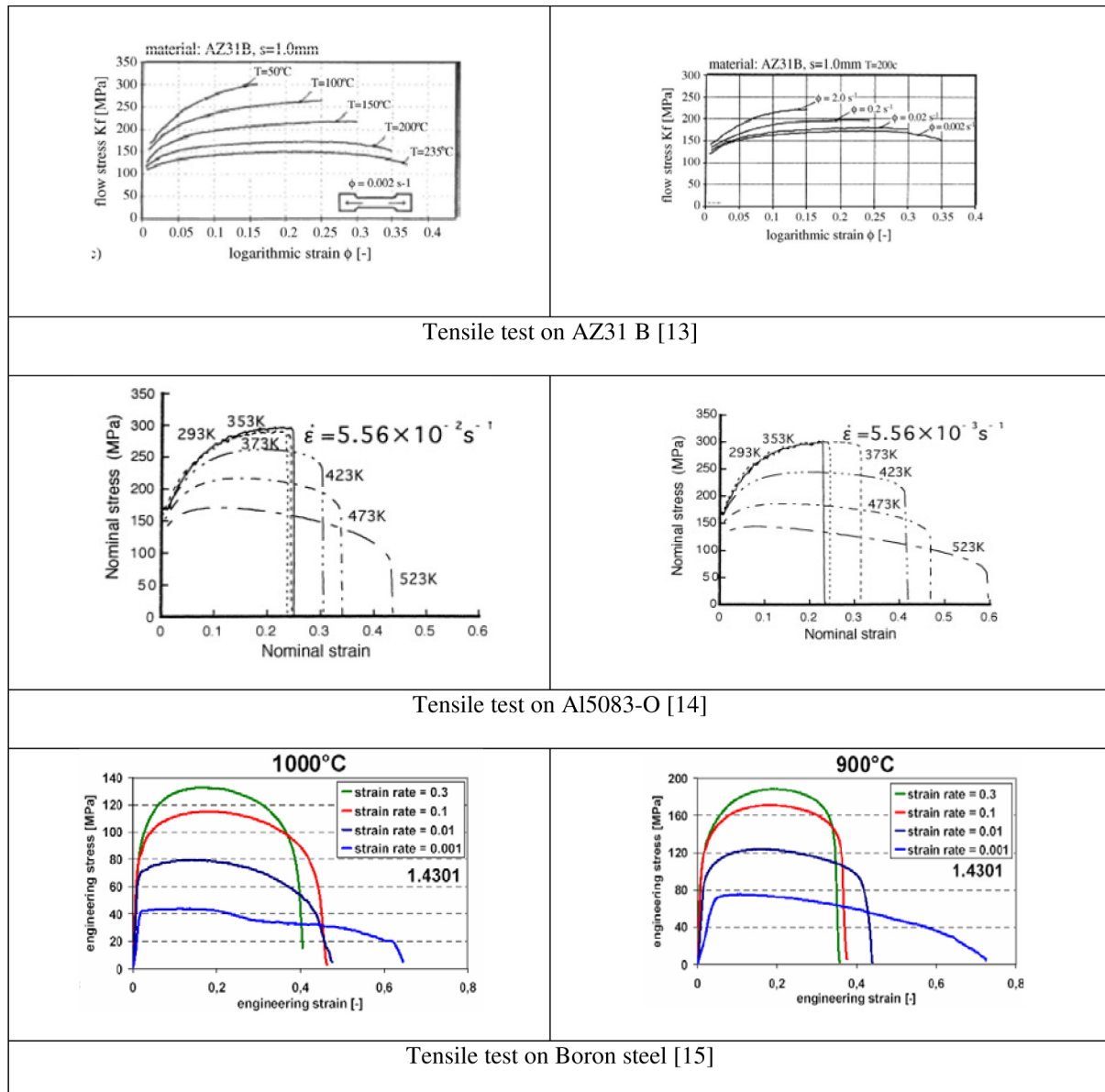


Fig.3. Tensile tests at elevated temperatures and different strain rates

magnesium alloys at elevated temperatures [2, 18]. In this study, a hypothesis that such polynomial relationship could exist among major strains of each corresponding minor strain of the forming limit curves of certain sheet materials is proposed. Based on the hypothesis, a forming limit surface can be constructed with three axis of major strain (ϵ_1), minor strain (ϵ_2) and natural logarithm of Z ($\ln(Z)$). The hypothesis is validated by published experimental result on aluminum alloy 5083. A forming limit surface is constructed by a method proposed in this study.

DEFORMATION MECHANISM AT ELEVATED TEMPERATURES AND DIFFERENT STRAIN RATES

Although a complete explanation of deformation mechanism of sheet metal materials at elevated temperatures is still being developed, it is generally accepted that slip, twin, dislocation mobility and grain boundary sliding are major deformation mechanism while the increase of dislocation and void (volume defect) nucleation, growth and coalescence are primary cause for the fracture [19, 20]. At elevated temperatures, the annealing, which includes dynamic recovery and dynamic recrystallization, reduces dislocation density and void volume. Consequently, the drop of their flow stress levels and the delay of fracture can be