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Mechanics in frictional penetration with a blind rivet

Junying Min[a,*], Yongqiang Li[b], Jingjing Li[a], Blair E. Carlson[b], Jianping Lin[c,**]

[a] Department of Mechanical Engineering, University of Hawaii at Manoa, 2540 Dole Street, Honolulu, HI 96822, USA
[b] Manufacturing Systems Research Lab, General Motors Global R&D, 30500 Mound Road, Warren, MI 48090, USA
[c] School of Mechanical Engineering, Tongji University, Shanghai 201804, China

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ABSTRACT

The mechanics of frictional penetration driven by a blind rivet to sheet metals is analyzed for a friction stir blind riveting process. Analytic models are deduced to calculate the material removal rate, penetration force and torque during the frictional penetration process. Frictional penetration tests with modified rivets and an Al alloy sheet were carried out at various rotation speed–feed rate combinations, where the penetration force and torque were recorded with a data acquisition system. An analysis of the contact condition between the rivet tip and the work material based upon the assumption of pure sliding contact in the initial penetration to partial sticking contact beyond a critical penetration depth of the rivet is completed, and the results are discussed based on the comparison of the analytically calculated and experimentally measured torque–force ratios.

1. Introduction

Friction stir blind riveting (FSBR) as reported by Gao et al. (2009) and Lathabai et al. (2011) is a novel mechanical joining method and is being developed, which combines the advantages of FSW and the blind riveting. In FSBR (Fig. 1), a blind rivet is driven toward the work materials with a high-speed rotating tool (e.g. 3000 rpm or above). The rotating rivet generates frictional heat when engaging the work materials. The elevated temperature can significantly reduce the yield strength of the work materials. This allows the blind rivet to penetrate through the workpieces with reduced forces as compared to self-piercing riveting which occurs at room temperature. Herein lies the advantage of FSBR to achieve single sided joining. Once the blind rivet is fully seated, the internal mandrel is pulled upward to mechanically fasten the work materials, and the mandrel is broken to create a friction stir blind riveted joint. FSBR is capable of joining a variety of materials, e.g. dissimilar metals such as Mg alloy to Al alloy by Min et al. (2014a) and Al alloy to composites by Min et al. (2014b).

Most existing studies on FSBR or FSR are experimental investigations aimed at demonstrating its feasibility for joining dissimilar sheet metals. For example, Gao et al. (2009) joined AA5052 sheets by FSBR and found that the FSBR joints carried higher tensile loads and exhibited greater fatigue resistance than joints produced by resistance spot welding. Lathabai et al. (2011) investigated the effect of blind rivet design for FSBR of Al alloys to Mg AZ31. Min et al. (2014) joined cast Mg alloy AM60 to Al alloy sheets by FSBR and concluded that the FSBR joints carried greater tensile loads than joints fabricated using the conventional blind riveting method. Analytical and numerical modeling studies have focused on the FSW process, and in particular included thermal, thermo-mechanical, and friction models. Schmidt and Hattel (2008) reported basic thermal equations for friction stir welding and clarified several uncertainties regarding the different mechanisms of heat generation. Kuykendall et al. (2013) modeled the FSW process and found that the selection of constitutive law has a significant effect on the prediction of the temperature profile, the peak strain as well as the peak strain rate. Schmidt et al. (2004) developed an analytic model for the heat generation in FSW with several assumptions of contact conditions between the friction tool and the workpiece. Mishra and Ma (2005) showed that the frictional condition between the tool and the workpiece (2024Al-T3 alloy) changed from "stick" at lower rotation speeds (<400 rpm) to "stick/slip" at higher rotation speeds of the tool. Chen and Kovacevic (2003) established a 3-D finite element model incorporating the frictional heat source between work materials and the tool to study the thermal history and thermo-mechanical process in FSW of AA6061 alloys.

To the best of the authors' knowledge, there has been no published research on the mechanical modeling of the relatively new joining process, FSBR. The mechanical analysis will not only provide understanding of the FSBR process, but also other friction stir processes, such as friction stir drilling. The objective of this work is to analyze the mechanics of frictional penetration with a blind rivet. The upsetting step is not analyzed here and will be covered

* Corresponding author at: Lehrstuhl für Productions systeme, Ruhr-Universität Bochum, Bochum 44780, Germany. Tel.: +49 15738011709.
** Corresponding author. Tel.: +86 13901719457.
E-mail addresses: junying.min@gmail.com (J. Min), jplin58@tongji.edu.cn (J. Lin).

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Nomenclature

A the slope of F_{Z1}–MRR_1 curve
B the slope of M_{Z1}–MRR_1 curve
f the feed rate
F_Z, F_{Z1} and F_{Z2} the penetration forces on the rivet mandrel tip
F_{Z1_max} the peak penetration force
F_d the driving force applied on the rivet mandrel by the spindle fixture
F_s the force on the shank head applied by the spindle fixture
h the height difference between the surfaces of the penetrated and non-penetrated areas of the workpiece
H the heat generation rate
M_z, M_{z1} and M_{z2} the torques on the rivet mandrel tip
M_{Z1_max} the peak torque
M_d the driving torque applied on the rivet mandrel by the spindle fixture
M_s the torque on the shank head applied by the spindle fixture
MRR_1 and MRR_2 the material removal rates
P_1 and P_2 the pressures acting normal to the rivet shear plane
Q the frictional heat
R the ratio of the penetration force to torque
S_1 and S_2 the shear stresses between the rivet shear planes and the work material
S_{t1} and S_{t2} the shear stresses tangential to the rotational motion
S_{p1} and S_{p2} the shear stresses along the shear planes
t_1 and t_2 the wall thicknesses of the rivet tip
t_{work} the thickness of the workpiece
T the time
v_1 and v_2 the motions of the rivet shear planes relative to the work material
v_{t1} and v_{t2} the motions tangential to the rotational motion
v_{p1} and v_{p2} the motions along the shear planes
v_{t_work} the speed of work material tangential to the rotational motion
V_1 and V_2 the volumes of work material removed by the rivet tip
Z the penetration depth of the rivet tip
$Z_{F=max}$ the rivet travel distance corresponding to F_{Z1_max}
$Z_{M=max}$ the rivet travel distance corresponding to M_{Z1_max}
$Z_{F=0}$ the rivet travel distance corresponding to $F_{Z1} = 0$
$Z_{M=0}$ the rivet travel distance corresponding to $M_{Z1} = 0$
$Z_{H=max}$ the rivet travel distance corresponding to the peak heat generation rate
Z_{R-c} the rivet travel distance corresponding to the critical R
α_1 and α_2 the rivet tip angles
δ the ratio of τ_{work} to P_1
λ a state parameter
μ the friction coefficient between the rivet shear plane and the work material
ρ the distance between the point on the rivet tip and the rotational axis
σ_{work} the yield tensile stress of the work material
τ_{work} the yield shear stress of the work material
ω the rotational speed.

Subscripts
1, 2 indicate the inner and outer shear plane with respect to the axis of rotation, respectively.

in a separate paper. Frictional penetration tests in single AA6022-T4 sheets were conducted. Analytic models for material removal rate, penetration force and torque were established. Particularly, a torque–force ratio is proposed to evaluate the contact conditions between the rivet tip and the Al alloy sheet.

2. Mechanical analysis

Through analyses of a large number of FSBR experiments incorporating several designs of blind rivets, Lathabai et al. (2011) concluded that blind rivets with hollow mandrel heads require significantly lower penetration force than those with solid mandrel heads.

Illustrated in Fig. 2a is a blind rivet including a mandrel body, a hollow mandrel head, shank body, shank head, and break notch. In FSBR, the mandrel body is held with a spindle fixture rotating around the Z-axis at a rotational speed (ω) and fed along the Z-axis at a feed rate (f), as shown in Fig. 2b. The mandrel head is first brought into contact with the upper workpiece of a lap joint, and as it penetrates through the workpieces, the shank head eventually comes into contact with the top workpiece. Assuming that there is no slippage between the spindle fixture and the mandrel body, according to the force and torque equilibrium conditions, Eqs. (1) and (2) can be obtained

$$F_Z = F_d + F_s \tag{1}$$

$$M_Z = M_d + M_s \tag{2}$$

where F_Z and M_Z are the penetration force and torque acting on the rivet tip due to its interaction with the workpiece during frictional penetration; F_d and M_d are the holding force and torque on the mandrel body applied by the spindle fixture; and F_s and M_s are the force and torque on the shank head applied by the spindle fixture, which are subtle and difficult to measure since they are due to static friction between the spindle fixture and the shank head and are also dependent on F_d and M_d. The analysis of overall force and torque equilibrium is beneficial for avoiding quality issues of friction stir blind riveting joints, e.g. intrusion of the mandrel head into the shank during frictional penetration (refer to Min et al. (2015) for details).

The following focuses on the interaction between the rivet tip and the workpiece. Fig. 3a illustrates the axial symmetrical force analysis between the mandrel tip and the workpiece when the penetration depth is Z. For simplicity, only one layer of workpiece is considered in the detailed mechanical analysis. Further, the mandrel tip has a simple sharp shape with two shear planes. With respect to the Z-axis as shown in Fig. 3a, the inner and outer shear planes have angles of α_1 and α_2 respectively. Hereinafter "1" and "2" indicate the inner and outer shear plane with respect to the axis of rotation and the radius of curvature where the two shear planes intersect is considered to be 0. During the feeding of the mandrel tip, there are pressures (P_1 and P_2) acting perpendicular to the shear planes. The rotation of the mandrel tip results in two tangential shear stresses (S_{t1} and S_{t2}), and the feeding motion of the mandrel tip leads to two shear stresses (S_{p1} and S_{p2}) along the shear planes. The mandrel tip in Fig. 3a can be separated into two simpler cases: a mandrel tip with only an inner shear plane as shown in Fig. 3b and a mandrel tip with only an outer shear plane in Fig. 3c. Based upon this breakdown, the effects of the inner and outer shear planes will be discussed and compared, while the experimental validation in this work will focus solely on the case described in Fig. 3b.

2.1. Calculations of material removal rates

The rotating rivet during the frictional penetration portion of the FSBR process displaces the workpiece material which is very