

Lightweight Stiffening Ribs in Structural Plates

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ABSTRACT

The aim of this analysis was to model the effect of adding stiffening ribs in structural aluminum components by friction stir processing (FSP) Nano material into the aluminum matrix. These stiffening ribs could dampen, redirect, or otherwise alter the transmission of energy waves created from automotive, ballistic, or blast shocks to improve noise, vibration, and harshness (NVH) and structural integrity (reduced joint stress) response. Since the ribs are not created by geometry changes they can be space efficient and deflect blast / ballistic energy better than geometry ribbing, resulting in a lighter weight solution. The blast and ballistic performance of different FSP rib patterns in AL 5182 and AL 7075 were simulated and compared to the performance of an equivalent weight of RHA plate FSP helps to increase localized strength and stiffness of the base metal, while achieving light weighting of the base metal.

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INTRODUCTION

Friction Stir Processing (FSP) has been used to refine grain structure in sheet metals, and is based on friction stir welding (FSW) principles developed and patented by TWI Ltd, Cambridge, UK in 1991 [1, 6, 7]. In Friction Stir Processing (FSP) a tool generates heat from friction and pressure causing a material to become plastic without melting. The tool then mixes the base material in a circular motion as it traverses laterally through the material (Figure 1).

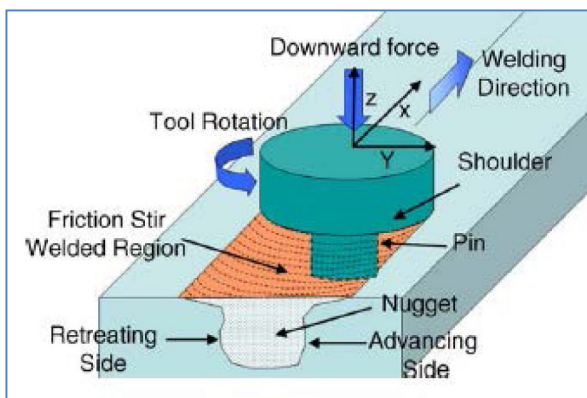


Figure 1. Friction Stir Processing [1].

It is possible to add 2D or 3D Nano particles (Figure 2) to locally alter the material's stiffness (young's modulus). One obtains better material mix when the rotational mixing speed is high relative to the advancement speed. It is possible to process RHA plate up to a depth of 1/4" or 1/2" if processing from both sides.

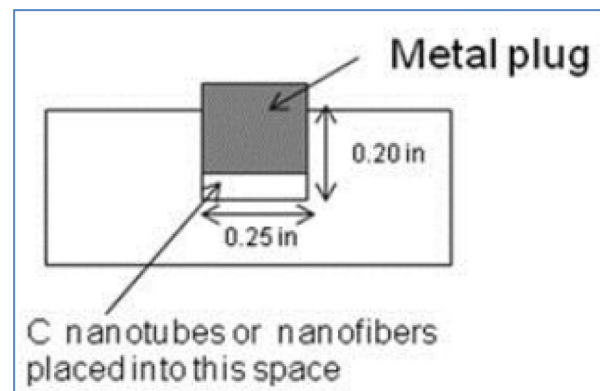


Figure 2. 2D metal plug with Nano tubes.

For example, friction stirred *TiB₂* particles in cast iron resulted in over 2x hardness and wear resistance by ASTM G35 (Figure 3) [2, 3, 8]. Since FSP is not a forming process, the pattern of the ribs can be any 2D pattern (linear, circular, spiral, etc.). The main focus of the Nano-reinforced FSP is to achieve increased localized stiffness with minimal increase in density of the local material to achieve light weighting. The addition of Nano-particles in addition to grain refinement of the localized microstructure results in improved mechanical properties such as higher yield strength (YS) and elastic modulus [4]

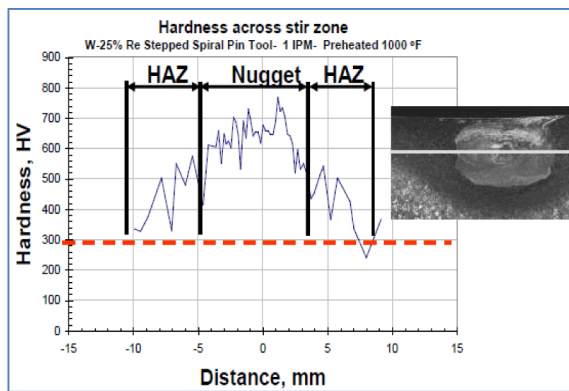


Figure 3. Friction Stirred TiB2 in cast iron [3]

FSP SIMULATION METHOD

Before assessing the effect of FSP stiffening ribs, it was necessary to establish blast and ballistics performances of the base metals: Aluminum 5182 and 7075 alloys and equivalent weighted Rolled Homogeneous Armor (RHA) steel. Figure 4 shows the 4'x4' blast and ballistics plates used in the simulation. The aluminum 5182 & 7075 plates weighed 282 kg and was 31.8 mm thick. The mass equivalent RHA was 10.9mm thick.



Figure 4. Al 5182 and equivalent weighted RHA base metals.

Two FSP stiffening ribs pattern were chosen to analyze the localised stiffness of base metals Al 5182 and 7075. FSP ribs were spaced 4 inch apart with one half inch in thickness. Figure 5 below shows the two FSP ribs pattern chosen in this study

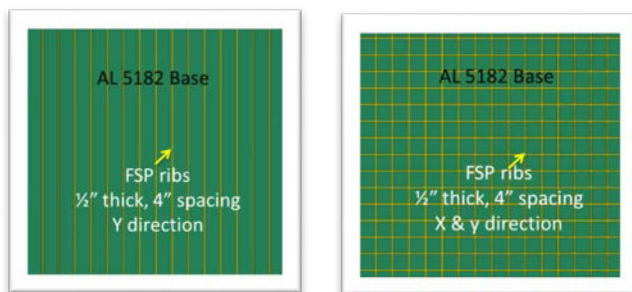


Figure 5. FSP ribs pattern in x, and xy directions.

Simulation matrix & material properties

The material properties for the FSP ribs were estimated as a percent change of the base metal alloy's properties (Table 1). In this particular study, elastic modulus of an FSP ribs was increased by 100%, YS increased by 50% and density by 10% relative to the base material.

Table 1. Material properties.

	Elastic Modulus (Mpa)	Yield Strength (Mpa)	Density (kg/m3)
Base metal AL 5182	7.14E+04	2.46E+02	2661
FSP Insert	100% of AL 5182	50% of AL 5182	10% of AL 5182
	1.43E+05	3.75E+02	2927
RHA	2.10E+05	7.74E+02	7860

Table 2 shows the matrix of simulation studies conducted. Base metal Al 5182 is the baseline. A mass equivalent amount of RHA was also simulated (equivalent RHA). In order to study which aspect of the nano material had the largest effect, the elastic modulus and yield strength were studied separately. Lastly, in order to gain insight into rib patterns, studies were conducted on ribs in Y direction only, X&Y direction, and completely covering the AL 5182 base material.

Table 2. Simulation matrix for AL 5182 & 7075 and RHA.

	Thickness (mm)	Weight (kg)
Base metal (AL 5182)	31.8	282
Base metal Elastic Modulus doubled	31.8	282
Base metal Yield Strength increased 50%	31.8	282
Base metal + FSP insert in Y direction	31.8	284
Base metal + FSP insert in X & Y direction	31.8	286
Base metal replaced by FSP properties	31.8	286
Equivalent RHA	10.9	285

BLAST SIMULATION

Blast simulation was performed by using the well documented Defense Research and Development Canada (DRDC), plate model. The simulation engine was LS-DYNA explicit non-linear solver. Figure 6 shows the simulation set up of the blast model. C4 is used as an explosive material and is buried 2 inches (50 mm) deep inside the soil. Standoff between the plate and the ground surface is at 16 inches as shown. A ballast mass of 10,620 kg is placed on top of the fixture frame to simulate the mass of a light armor vehicle (LAV).

The Arbitrary Lagrange in Euler (ALE) method was used to simulate the blast event. In ALE, a background solid mesh is created and fixed, and material advects through each cell as volume fractions. MAT_HIGH_EXPLOSIVE_BURN and EOS_JWL were used to characterize high explosive. High explosive (HE) geometry was defined by using INITIAL_VOLUME_FRACTION_GEOMETRY. HE dimensions used in this study was 254 mm in diameter and 76.2 mm height with density of 1630 kg/m³ and detonation velocity of 6930 m/s. Air was represented as MAT_NULL with EOS_IDEAL GAS. There are many different soil models available in LS_DYNA, and this study used the MAT_ELASTIC_PLSTIC_HYDRO_SPALL (EPH) with dry density of 1852 kg/m³ and bulk modulus (K) of 50.00 GPa.

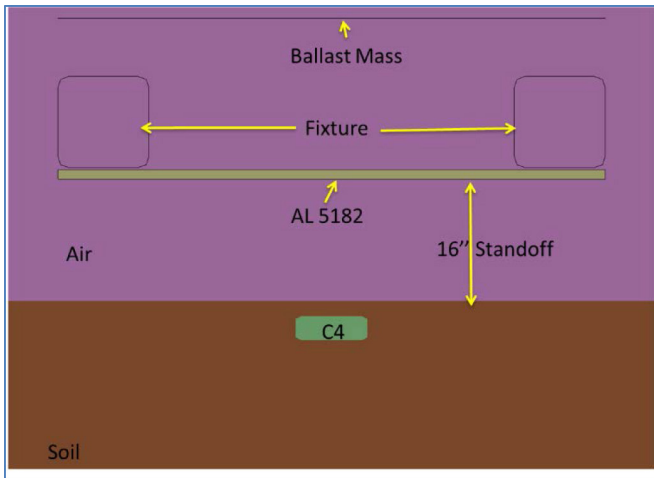


Figure 6. Blast simulation model.

Base metal plates and FSP ribs were modeled as solid elements with Johnson-Cook strength and failure models and Mie Gruneisen equation of state models (EOS). The LS-DYNA material card with strength and failure parameters for AL 5182 is shown in Figure 7.

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*MAT_JOHNSON_COOK_TITLE
Aluminum 5182
$ mid rho g e pr dtf vp rateop
1 2661.0000 2.630E+10 7.060E+10 0.340000 0.000 1.00 0.000
$ a b n c m tm tr epso
2.5000E+8 2.3600E+8 0.340000 1.0000E-3 1.250000 893.00000 293.00000 1.000000
$ cp pc spall it d1 d2 d3 d4
910.00000 -4.281E+9 2.000000 1.000 0.080 0.620000 1.150000 0.016
$ d5 c2/p erod efmin
1.160 0.000 0 1.0000E-6
$
*EOS_GRUNEISEN_TITLE
Aluminum 5182
$ eosid c s1 s2 s3 gama0 a e0
1 5200.000 1.400 0.0 0.0 1.97000 0.48 0.0
$ v0
1.000

```

Figure 7. LS-DYNA material card for AL 5182.

Material properties for FSP ribs were derived from the AL5182 model (Figure 8). FSP rib material properties are scaled up from the AL5182 base metal per table 1. Due to limited availability of strain rate effects and damage parameters for FSP ribs, it was decided to use all the strain rate effects, damage parameter of AL5182. Sound speed for FSP ribs were derived from the following relationship.

$$c = \sqrt{E/\rho} = 6940 \text{ m/s}$$

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*MAT_JOHNSON_COOK_TITLE
FSP insert
$ mid rho g e pr dtf vp rateop
2 2927.0000 2.630E+10 14.120E+10 0.340000 0.000 1.000 0.000
$ a b n c m tm tr epso
3.7500E+8 3.4800E+8 0.340000 1.0000E-3 1.250000 893.00000 293.00000 1.000000
$ cp pc spall it d1 d2 d3 d4
910.00000 -4.281E+9 2.000000 1.000 0.080 0.620000 1.150000 0.016
$ d5 c2/p erod efmin
1.160 0.000 0 1.0000E-6
$
*EOS_GRUNEISEN_TITLE
FSP insert
$ eosid c s1 s2 s3 gama0 a e0
2 6940.000 1.400 0.0 0.0 1.97000 0.48 0.0
$ v0
1.000

```

Figure 8. LS-DYNA material card for FSP ribs.

Blast simulation results

Peak vertical displacement of the plate at the center was measured and compared to different FSP ribs patterns from the blast simulation. Figure 9 shows the peak vertical displacement for AL5182 of 287 mm.

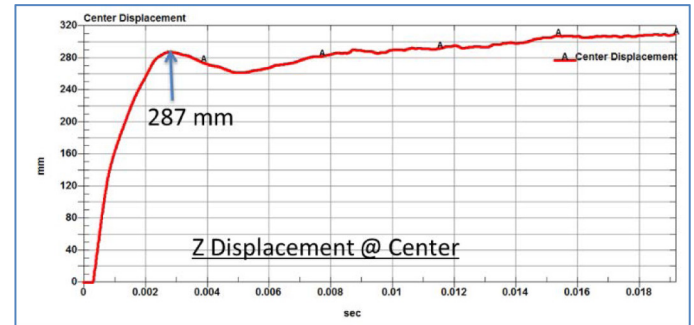


Figure 9. Peak vertical displacement of AL5182

Figure 10 shows the pressure distribution of the plate at the center and at 8 inch away from the center. Pressure waves are mostly tensile in and reflective especially away from the center. For the first two milliseconds tensile pressure is dominant and disperses quickly after 2 milliseconds. This can be attributed to the decay of explosive gases immediately after detonation. In general the detonating products of explosives exhibits peak pressures at about 0.5 milliseconds (Figure 11).

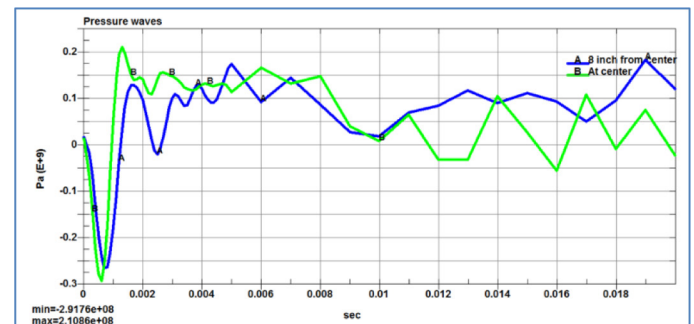


Figure 10. Pressure distributions on the plate

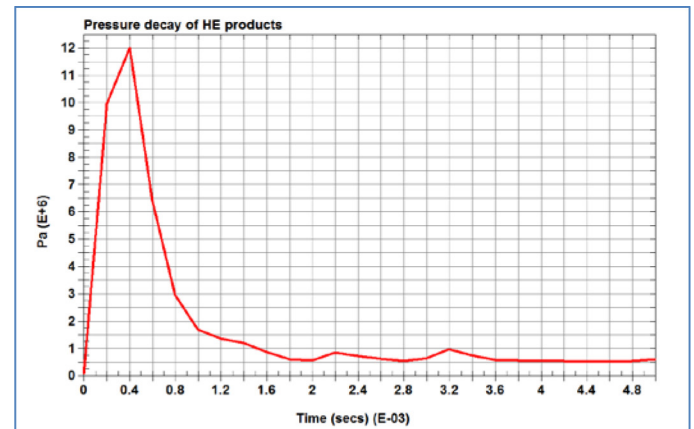


Figure 11. Pressure decay of HE products.