Mechanical Properties of Al-Cu-Mg Taylor-made functionally graded layers by Friction Stir Additive Manufacturing

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Abstract

In this study, the new solid-state method of joining metal by friction stir additive manufacturing (FSAM) method is used for the fabrication of functionally graded composite. The principle of Friction Stir Welding (FSW) was utilized to fabricate the stacking of Aluminium, Copper and Magnesium layer-by-layer. This technique associates to achieve superior and modified mechanical properties with least defect like internal cavity, shrinkage or high dimensional inaccuracy. The metals are lap welded by the virtue of transition zone (TZ) which are formed near the interstitial area of the joints. The stacked specimen developed and tested for the mechanical behaviour. In the stacked sample, microstructure harness increases enthrallingly.

Keyword: *Friction Stir Additive Manufacturing (FSAM), Friction Stir Welding (FSW), Mechanical Behaviour.*

1. INTRODUCTION

The demand of high strength to low weight is increasing with rapid growing industries. Rapid proto typing with high strength is a challenging factor and rising demand for industry 4.0[1], [2]. Improved materialistic properties like as of Functionally graded materials (FGMs) are in high demand than conventional materials [3], [4].There are severaladditive manufacturing (AM) methods developed for the stacking of materials. The leading technique for solid-state metal additive manufacturing (MAM) is been developed from friction stir welding (FSW)[5] and friction stir processing (FSP)[6] for friction stir additive manufacturing (FSAM). The concept was first investigated by the "The Welding Institute" (TWI)[7]–[11].In the FSW method a tuning tool with pin and shoulder is utilized to stir between the two butt jointed metals [12], with applied pressure and due to friction the stirred zone temperature is reached above the recrystallization but is below the melting point of the metal. Similar phenomenon is utilized in FSP where the sole purpose of processing is grain refinement and improved microstructure and mechanical behaviour [13]. In this a FSW tool is utilized to stir the processing zone. Friction Stir Additive Manufacturing, a multi-layered form is fabricated by embedding a non-consumable apparatus into the covering sheets or plates to be welded and navigated along the joint line. Friction Stir Additive Manufacturing be a change about rubbing mix welding in terms of setting time. In this way, the junction is accomplished in a solid condition. Rubbing exposure in the middle of the device and the work piece in addition with serious fictile disfigurement accomplished by the shear distortion gracefully warmth and add to the conditioning of material. As the instrument turns and advances, union of the fabricate happens by the development of mellowed material from the front to the rear of the pin. In FSAM, heat is created between a third body (apparatus) and the layers that should be solidified. Because of this trademark, more prominent control is practiced over the microstructure prompting better properties. In this strategy, last form stature relies upon the depth of each coating and the quantity of gathering coating. Besides, adjustments of plan calculation can prompt various shape and sizes with various calculations. In FSAM, the general energy of micro-structural advancement relies upon the warm cycle, strain rate which are constrained by the cycle factors that incorporate rotational rate, cross speed, apparatus math and manufacture power [14]. Figure 1 manifest a diagrammatic representation of the cycle alongside the clarity for the device and piece to be machined.

Friction Stir Additive Manufacturing was initially put in and protected by White in 2002[15], and a comparative technique was presented by Thomas et al. in 2005 [16]. The business utilization of Friction Stir Additive Manufacturing was highlighted in 2006 when Airbus exhibited its capacity of manufacturing the construction at a quicker degree by fewer substantial left-over [17]. Friction Stir Additive Manufacturing stays a quickly developing added substance fabricating procedures that remains executed through the way toward linking different constituent coating upon coating in the direction of building up a 3-Dimensional item after advanced information. The aforementioned deals with the standard of contact mix welding. Notwithstanding, FSAM varies from FSW as joining of one layer after the another is joined by warming and re-sintering[13]. The ideal strategy for the FSAM method is like the idea of contact mix lap welding. Additive Friction stir processing(AFSP) is defined as the addition of other materials into base metal using friction stir processing [18, p.], [19]. AFSP is different from FSAM because AFSP is a localized method of grain refinement and also does not create heat affected zone(HAZ).

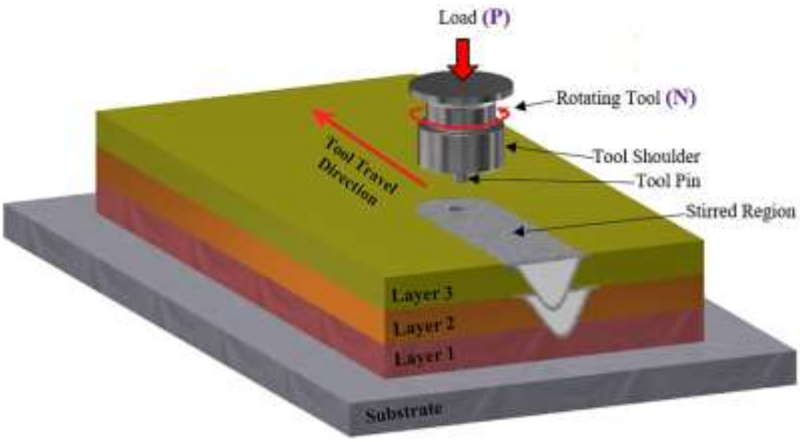

Figure 1.Schematic representation of Friction Stir Additive Manufacturing (FSAM)

Work on FSAM lacks in number i.e. number of papers published or experiments carried out are still less in number. So, manufacturing a component by FSAM and testing it for mechanical and microstructural properties is itself a new task. Collecting evidence that would prove supremacy of FSAM is itself a novel task. The project work not only intend to add another proof of superiority of FSAM process but also it aims to find outoptimum method or condition for production of superior component in terms of mechanical properties. The component manufactured by FSAM will itself be a combination of different material or may be different design and tool parameters in order to produce a superior component with exceptional properties in comparison to its raw material and other advanced mechanical components. We all are familiar with different phases of industry and right now industry is in phase known as Industry 4.0 and Industry 4.0 depends highly on Additive Manufacturing and in that also it depends mostly on 3D printing. It is known that although 3-Dimensional printing is a revolutionary technology but it fails when component with high structural strength is needed to be produced. The project aim is to gives a new process which can produce material with high mechanical properties. The present work will be to attempt to stablish a less known method of Additive Manufacturing called Friction Stir Additive Manufacturing as a superior technique. We also aim to show the materials considered as non-processable or are not machinable or have high melting point can also be used after finding out the ideal way with proper variables and controls after Friction Stir Additive Manufacturing is established as ideal process.

2. EXPERIMENTAL PROCEDURE

In order to perform the process of FSAM, Aluminium, Copper and Magnesium are taken as these are highly demanded material for industrial purpose. Composition and melting point were the important factor to fabricate the material as shown in table 1.Magnesium AZ91 is a widely used magnesium alloy due to its high strength and relatively better corrosion resistance. Copper is commonly used due to high heat conductivity, better electrical conductivity and good machinability. Al-7075 is an Aluminium alloy having Zinc as the primary alloying element. This material is widely used in the aircraft industry due to its high strength and lighter weight.

Table 1. Materials and their Mechanical properties

Material	Density (g/cm3)	Modulus of Elasticity (Gpa)	Tensile Strength (Mpa)	Yield Strength (Mpa)	Thermal Conductivity (W/(m·K))	Melting Temperature (°C)
AZ91	1.81	45	250	160	72	533
Cu	8.95	117	221	138	391	1085
Al-7075	2.81	71.7	572	503	196	556

Thickness of each sheet was 2-3 mm. Substrate was of cast iron,as itdepends on its high ability to absorb energy and also the ability to deform without fracture. It also has ability to regain its original shape after the release of load. 8mm punch was made on the substrate for clamping purpose. The substrate which was placed belo w the axial drill machine as shown in figure 2.The tool is made of high-speed steel (HSS) to complete the FSAM process on the plates by the conventional turning. HSS is used because it can withstand higher temperatures without losing its temper (hardness), it also exhibits high strength and hardness but typically exhibit lower toughness. Figure 3 shows the HSS tool with threaded pin design and physical image of tool during the FSAM operation.

Figure 2. (a) Drilling on the base material, (b) Drilled base

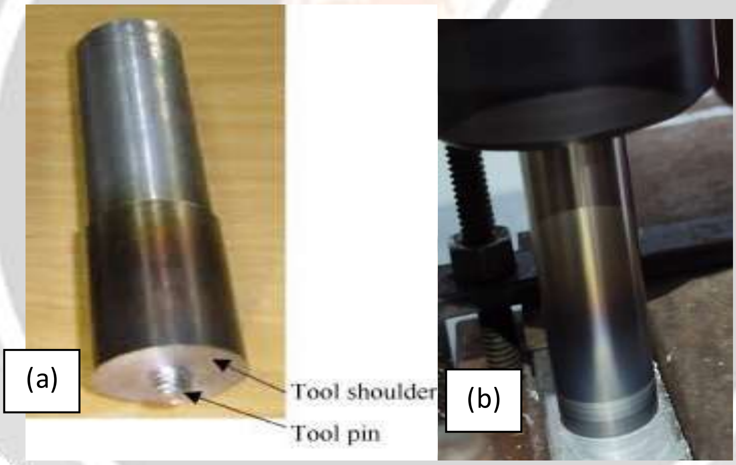

Figure 3. (a) HSS tool used for the process (b) Tool during the stirring process

Design parameters play a crucial role in attaining the desired result for the project. After the review of previous work various parameters affecting the properties of the manufactured component were identified e.g. rotational speed of tool, tilt angle, transverse speed, shoulder diameter of the tool, tool pin shape and tool diameter. After understanding their relationship with the properties of the manufactured component a suitable range of parameters was selected. Table 2 shows the combination of process and tool parameters used in this study. These values are selected on the basis of pilot experiments. This combination will be used in order to achieve the satisfactory result by trying and applying them until it gives a satisfactory result.

Table 2. Process and tool parameters

Rotational Speed (rps)	Transverse speed (mm/min)	Tilt angle (degree)	Shoulder Diameter(mm)	Tool pin shape	Tool pin diameter (mm)
2000	40	0	11.8	cylindrical threaded	4

Step by step plates are joined together with the mechanism shown in Figure 1. Figure 4 shows the VMC used in this study. The friction which has been generated between the plates due to the rotation of the tool on the milling machine the plates joined properly. When the friction stir additive manufacturing process is done we got our final composite, after that, we used the cutting tool attached to the milling machine to cut the final component for the various testing of the component. When the small specimen is cut out from the final component we start our testing on these specimens with the use of testing machines depend upon the test be performed, like for the tensile testing we have used the Tensiometer to check the tensile strength of the component. Vickers hardness testing machine is used to check the microhardness hardness of the component and finally, we have performed the microstructure test on the electron microscopy to find the microstructure and grain size of the final component which we have produced with the help of friction stir additive manufacturing.The testing was performed to get the Mechanical properties of the component which is produced by the method of FSAM. For the purpose of mechanical and the microstructural testing of our designed component, we have to extract test specimens from the component in desired shape to find the result as shown in Figure 5 (a-c). We have used a vertical milling machine to cut the specimen in various dimensions for testing of various properties of the component which is manufactured by friction stir additive manufacturing.

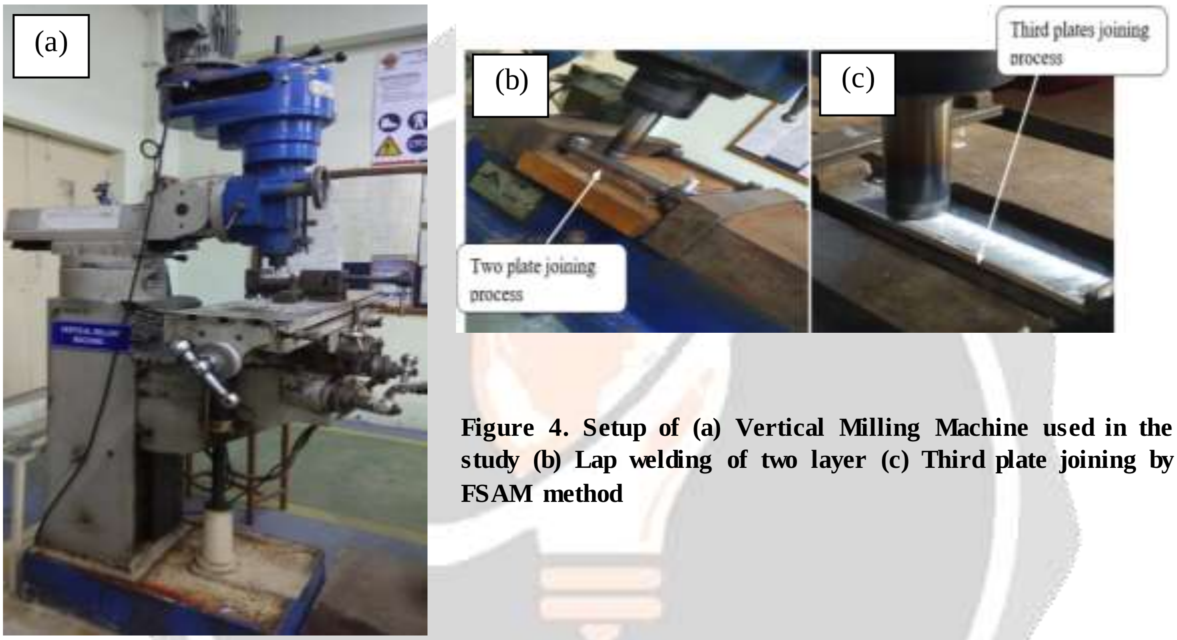

Figure 4. Setup of (a) Vertical Milling Machine used in the study (b) Lap welding of two layer (c) Third plate joining by FSAM method

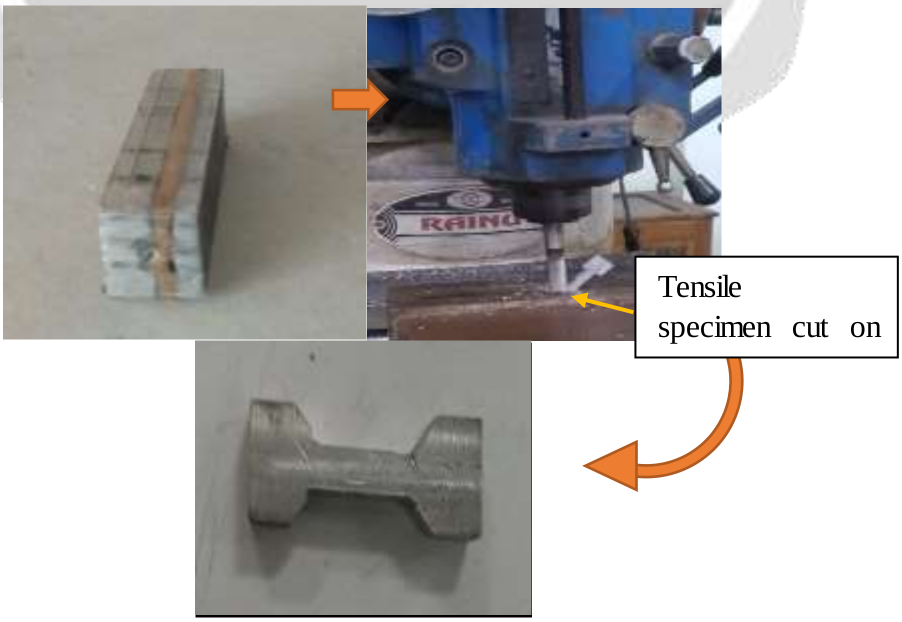

Figure 5. Extracted parts from the component for testing of mechanical and microstructural properties (a) Sample for making Tensile specimen (b) Development of Tensile specimen (c) Developed specimen for Tensile test

3. RESULTS AND DISCUSSION

The microhardness test has been conducted on the transverse section of the specimen at three points, one at each layer. The test was conducted at 300 gm load indented for 10 seconds at normal room temperature of 23^0C. Figure 4.8 shows the indentation points on the joint plates. Table 3 shows the testing report of Micro Vickers hardness test. The results show the hardness of 64.8HV, 67.5HV and 65.2HV of three respective plates of Aluminium, Copper and Magnesium. It can be stated here that FSAM process have induced the hardness of all three plates compared to unprocessed values of 56HV, 59HV and 58HV, respectively.

Table 3.Testing report of microhardness of the component

Indent 1	64.8	HV
Indent 2	67.5	HV
Indent 3	65.2	HV
Average: 65.83 HV0.3		

Tensile test has been conducted to get the tensile strength of the fabricated FSAM component. The test has been performed on Tensometer**.** Firstly, we have cut the Tensile specimen of 50 mm length from our final component which has been designed by FSAM. The cross-section of the specimen was rectangular. After that, we have gripped the specimen at the Tensometer. Figure 6 (a) shows the Tensile specimen placed in the Tensometer for tensile testing.The test has been conducted on Tensometer. The complete data of the specimen during the testing is shown on the screen attached to Tensometer. During the testing of the specimen, the screen which is connected to the Tensometer shows the load vs Displacement graph which provide the maximum bearing capacity of the component which we were developed on milling machine by the process of friction stir additive manufacturing. Figure 4.12 shows the fractured specimen on Tensometer and Figure 6 (b) shows the two fractured part of the tensile specimen breaking from gauge length portion. It is observed from the fractured specimen that the mixed nature of ductile and brittle failure occurs at the fracture point. In the result, we have shown that our specimen has a bear peak load of 2334.1 N before fracture. The peak displacement value is 2.10 mm. The stress was 64.8 N/m^2 at strain 0.1. The graph of load vs displacement plotted during the testing of the component is shown in Figure8. Peak Load was observed to be 2334.1 N where as break load was observed to be 480.5 N. Test speed was kept at 3 mm/min with proof stress of 1%. Engineering UTS was 64.8 N/sq mm.

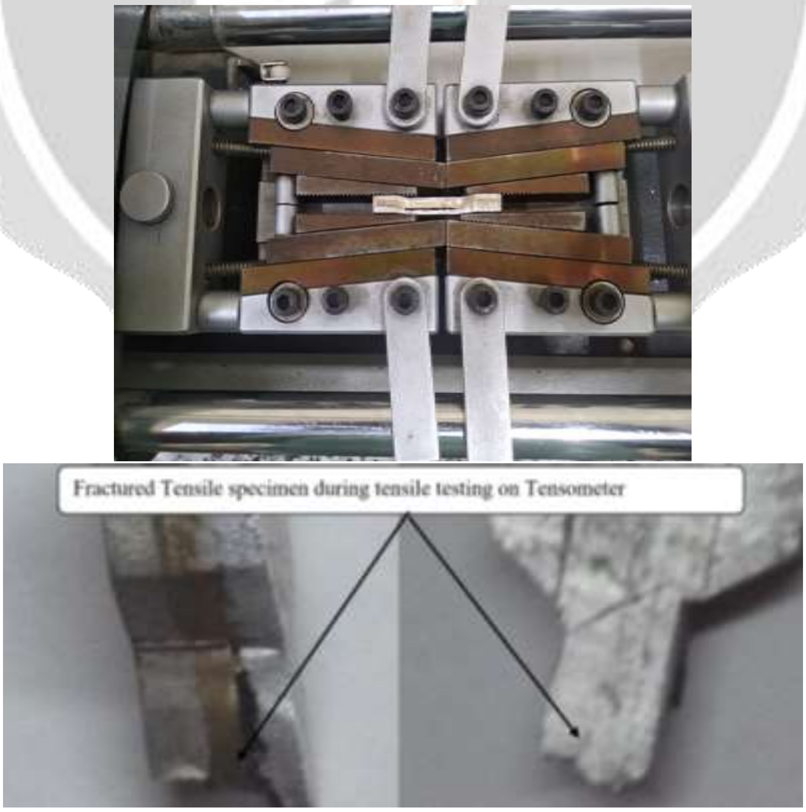

Figure 6. Tensile specimen (a) placed in the Tensometer for tensile testing (b) Fractured specimen after completion of the process of tensile testing

Figure 7 shows the fracture analysis of the broken specimen after Tensile test. The images are taken from the optical microscopy at a scale of 10X. It is observed from the images that the mixed nature of ductile and brittle fracture is observed.

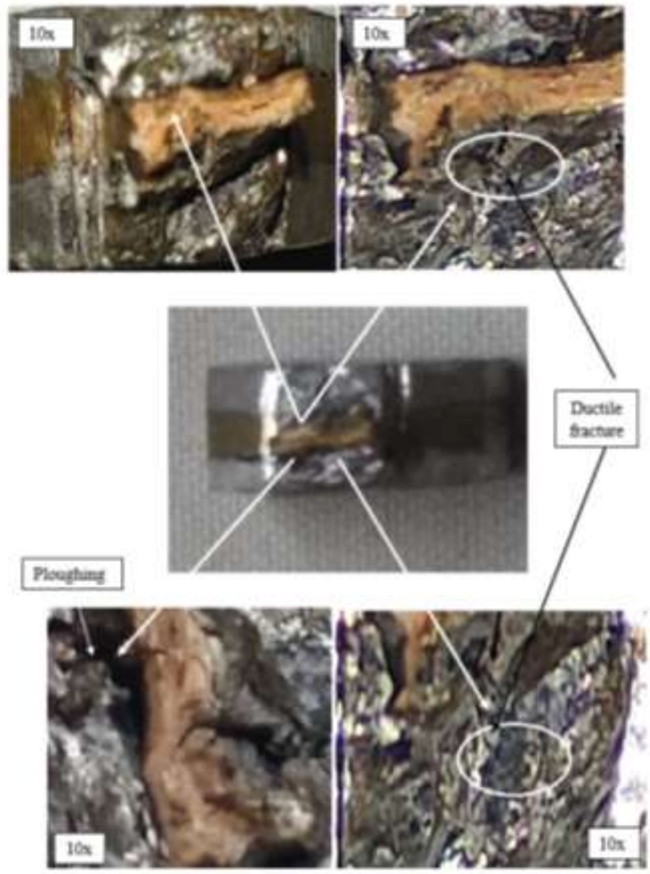

Figure 7. Microstructural images of fractured component of the Mg-Cu-Al

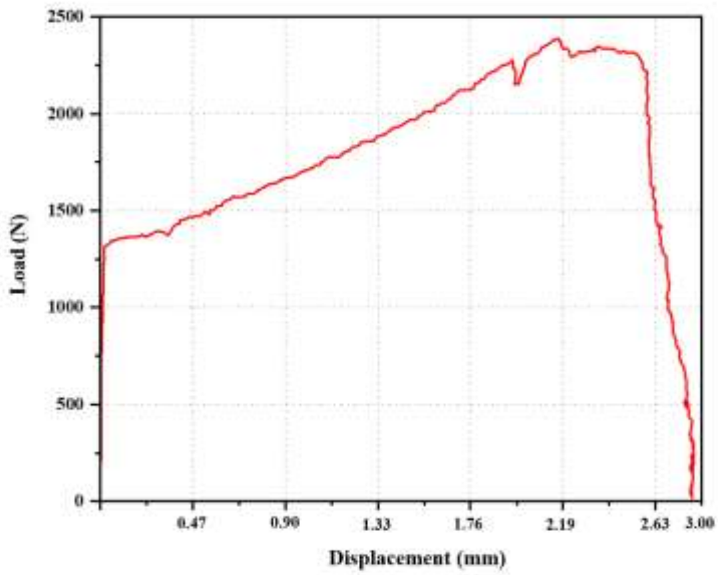

Figure 8. Load vs Displacement graph of the component during testing on Tensometer

4. CONCLUSION

In FSAM, the component is designed to consist of 3 layers of Aluminium, copper and magnesium. After joining of plates, we have performed various tests to know the various properties of the designed component. Mechanical and microstructural tests have been performed to know the newer property that has been developed in the component after the friction stir additive manufacturing process. In mechanical properties, we have conducted the tensile test on a Tensometer, in this test we have got that we have to eliminate the defects like porosity and surface roughness to get a better result in terms of tensile test.Vickers Micro hardness test has also been performed on the components specimen to understand the hardness number.The indents have been made on the specimen to get the hardness number. Microstructural tests like grain size and microstructure have been performed using optical microscopy to understand the microstructure changes in the component after friction stir additive manufacturing. .In the tensile test, the result has shown that our specimen has bear a peak load of 2334.1 N before fracture. The peak displacement value is 2.10 mm. The stress was 64.8 N/m^2 at strain 0.1. In microhardness Vickers test three indents have been made at 300 grams load and the hardness number are 64.8, 67.5 and 65.2 respectively. The average hardness number is 65.83 HV.When we are working on friction stir additive manufacturing we encountered no such problem related to environmental impact. In comparison to another solid-state manufacturing process like welding, FSAM emits no such harmful gases which damage our environment. As we know that in welding or any solid-state technique carbon dioxide and carbon monoxide from the decomposition of fluxes are emitted which is harmful to our environment. This problem can be eliminated by the FSAM technique.

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