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Transaction ID: OCLC:ISM-30904837:DLC was linear dynamic and impact forces were assumed and input into the finite element code. Only a qualitative comparison, between the finite element results and the shape of the failed abrasive grains, was provided. A nonlinear static material model was developed by Hassan and Kosmol [4,5]. The model predicted the plastic deformation occurring at the initial stages of impact. Deformations and stresses were computed and related to the erosion phenomena. The static assumption oversimplified abrasive waterjet impact. A three dimensional non linear finite element model was recently provided by Mohan and Kovacevic [6]. The model considered plastic deformation and failure of the workpiece material. As the model is non-linear static, it did not consider the dynamic behaviour of the high speed abrasive waterjet impact. Pressure loading was assumed and input into the finite element code. Finally, the finite element results were not verified with consistent experimental results. Another simple recent model was developed by both Guo et al. [7] and Guo and Ramulu [8]. This model was far limited in representing the actual abrasive waterjet process, as it was a static model representing a high speed impact process. Additionally, the workpiece material nonlinearity was not considered. The maximum linear strain did not exceed 0.0001 in a process whose strains may exceed unity, especially at the cutting interface where the impact deformation is the largest. Due to the above shortcomings of the previous finite element models, a more comprehensive non-linear dynamic finite element model is required, to fully understand the mechanism of erosion in abrasive waterjet machining.

A new approach of non linear dynamic modelling of abrasive waterjet machining using virtual finite element method has been recently developed by Hassan and Kosmol [9]. This approach consists of tracing the abrasive particle, from its early exit from the mixing tube nozzle until it is reflected from the surface after interaction with the material, at small time intervals, e.g. 0.01 μs. This method has proved to be very rewarding in explaining the mechanism of material removal and the overall behaviour of the process. Using this method, the depth of abrasive waterjet kerf is now obtainable.

All the above models were designed for isotropic materials like steel.

Polymeric composite materials, or fibre reinforced plastics (FRP), are increasingly being to be rapidly developing commercial materials for use in applications which require both high strength and light weight As composite materials become commonplace, the search for efficient machining processes becomes more significant. However, conventional machining of polymeric composite materials is often not effective because the structural characteristics inherent in fibre reinforcement promote excessive tool wear [10]. Also the material is subject to severe damage including inter laminar delamination, fibre pullout and poor surface quality that may adversely affect the part performance under service loading conditions. The real benefit of AWJM lies in the last item of the

PRELIMINARY ATTEMPT TO FEM MODELLING OF AWJM OF POLYMERIC COMPOSITES

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Abstract: *The paper presents a first attempt to Finite Element Method modelling of AWJM of polymeric composites. There is a state of art of FEM simulation of AWJM presented. Assumptions of a FEM model of AWJM of polymeric composite are discussed. Von Mises stresses development of a glass/epoxy (G/Ep) polymer composite as a result of AWJM impact for several different time steps is shown. It helps to explain the mechanism of AWJM erosion of polymer composites.*

1. STATE OF ART OF THE FEM MODELLING OF AWJM

The finite element method has been successfully applied in modelling of many conventional and non-conventional machining processes. Up to date, there has been only few simple attempts for analysing both waterjet and abrasive waterjet machining processes using the powerful tool of the finite element method. A preliminary effort of modelling the pure waterjet using a finite element model was carried out by Hassan and Kosmol [1]. Using this model, it was possible to predict the shape of the abrasive waterjet kerf, workpiece deformations and stresses. The main drawback of the model was that, it could not be used in the prediction of the depth of cut, as it was linear elastic. A linear dynamic finite element study of waterjet was carried out by Adler [2]. Due to the linear analysis, which was assumed, the maximum compressive stress obtained was 480 MPa, when using a 2 mm diameter water drop travelling at a speed of 305 m/s. This level of low compressive stresses explains the inability of waterjet to erode metals. These models failed to accurately represent the actual erosion occurring in abrasive waterjet machining. They either oversimplified modelling, by assuming linear elastic material models, or idealised the physical event, by assuming static analysis.

With respect to abrasive waterjet machining, there has also been a few preliminary finite element models developed so far. A two dimensional plane strain simple finite element model was developed by Hlavac and Sochor [3]. The model whole depth of cut. It is recommended to use pressures in excess of 250 MPa for machining of thick laminates. Large abrasives increase the initial damage zone which results in a wider entrance kerf and in turn, a larger taper ratio. Increasing the traverse rate results in a lower kerf taper. Generally when higher jet pressures are used, the kerf taper increases with an increase in the stand off distance.

The surface texture that may be associated with WJM include: surface waviness, burr formation, surface finish and lay. König and Wulf [23] found that increasing the pressure from 300 MPa to 400 MPa in WJM of CFRP would improve the surface finish of the machined surfaces. Yet the values of surface roughness were comparatively high (up to R_t = 100 μm). As the jet penetrates into the workpiece material, the loss of the WJ velocity causes a decrease in the surface quality towards the exit side. König et al [12] carried out a comparison between WJM and AWJM, for two FRP materials i.e. carbon fibre/epoxy and. It is apparent that the surface roughness decreases significantly in case of AWJM than in WJM due to the high cutting ability of the entrained abrasives.

Delamination is usually observed when machining FRP using AWJM. It only occurs if the deformation wear mode of erosion exists. The impact of the jet on a step formed at a certain depth will result in water deflection which, if with sufficient pressure, will laterally penetrate between layers to cause delamination. This mechanism of delamination occurs if the abrasive flow rate is interrupted during cutting [15]. Ramulu and Arola [10] found out that fibre pullout and fibre/matrix delamination are limited due to high interfacial bond strength coupled with the localised cutting forces associated with AWJ. The mechanism of delamination in WJM was studied in detail by Ho-Cheng [14] using fracture mechanics. Hashish [15] found that the pressure plays an important role in the delamination process while drilling Gr/Ep. When reducing pressure from 345 MPa to 240 MPa, hole delamination at the bottom was significantly reduced.

As it was shown above there are no attempts for applying the Finite Element Method for modelling AWJM of polymeric composites. In other hand success of application of the FEM for modelling AWJM of ductile materials made by Hassa and Kosmol [4],[5],[9] encourage us to try to do the same for polymeric composites. The paper presents the first attempt to modelling AWJM of polymeric composites by means of FEM made in the Department of Machine Technology of The Silesian University of Technology of Gliwice.

2. MODEL OF AWJM OF POLYMERIC COMPOSITE

In the present study, the following assumptions are relevant:

- The hydrostatic loading plays a secondary role in the cutting process, i.e. the effect of the carrying fluid is only to accelerate the abrasive particle.

advantages i.e. the non thermal machining of high cost heat sensitive materials such as polymeric composite materials to justify the slower traverse rates than plasma arc machining whose principal limitation is the thermal damage of the workpiece surface [11].

Up till now only a limited number of research studies have been conducted in this field. After switching to AWJM in the early eighties, several studies concerning the erosion process had been evolved. In an early study of sand blasting of polymeric composite materials, Tilly and Sage [19] found that composite materials generally behave in an ideally brittle fashion i.e. maximum erosion rate occurs at normal impact, i.e. at 90°. Fibre reinforcement may improve or worsen the resistance to erosion, depending on the type of fibres used. In addition, the erosion rate in composites increases with the particle size. It was found that the erosion rate of fibre reinforced plastics is greater than that of steel. Zahavi and Schmitt [17] found out that three polymeric composite materials, quartz-polyimide, glass-epoxy and quartz-polybutadiene, showed maximum erosion at normal impact i.e. 75° -90°. This is consistent with their properties as thermosetting resins and inorganic fibres.

A limited experimental as well as analytical work on productivity has been reported. Early attempts for WJM of polymeric composites started two decades ago and included boron/epoxy, boron/polyester, aramid/epoxy (up to 12.5 mm), glass/epoxy, glass/phenolic (12 mm thickness), glass/polyimide and graphite/epoxy (up to 16 mm) [20]. A study on WJM of polymeric composite materials was conducted by Engemann [21] who found out that a stand off distance of 10-20 mm, which is the range for the core zone of the free jet, is optimum for obtaining the maximum depth of cut. Increases in jet pressure and nozzle diameter led to an increased depth of cut. Oweinah [22] showed that the maximum WJ erosion in glass fibre composite occurs at a stand off distance around 20 mm.

Surface quality of AWJ machined composites has drawn greater attention from most of the researchers although they are few. Hashish [15] conducted a comprehensive pioneering research work on the surface quality and productivity of some composite materials including fibre reinforced plastics, such as carbon epoxy and fibre reinforced thermoplastic composites. It was found that the matrix material is more influential on the surface quality than the reinforcement material to the contrary of machining using conventional processes. Removal rates were found to be larger than many of the other machining processes, but the dimensional accuracy was still low. A characteristic feature associated with AWJM of composite materials is the taper of the kerf from jet entrance to the jet exit. Kerf geometry may not only limit the ability to meet component tolerances, affecting lay-up and fastening of joints, but may also adversely influence the strength and service life of component parts [13]. The effect of AWJM conditions on the kerf taper shown that higher pressures significantly reduce the kerf taper over the particle was 250 m/s and the stand off 0,05 mm. The properties of the abrasive material are shown in Tabel 2.

Tabel 1. Data of workpiece material

Properties	**Matrix**	**Fiber**
	Epoxy	**Glass**
Density, g/cm^3	1,15	2,49
Young's modulus E, GPa	3,35	85,5
Poisson's ratio, ν	0,38	0,2
Yield strength, Mpa	60	2510

Tabel 2. Data of abrasive material

Properties	
Abrasive materia	Garnet
Young's modulus E, GPa	248
Poisson's ratio	0,27
Modulus G, Gpa	97,634
Density, g/cm^3	4,325

Thirty-two 3D contact elements were added between the abrasive particle and the workpiece that allow for complete interaction including transfer of momentum between the abrasive particle and the workpiece.

The abrasive waterjet is allowed to move downward perpendicular to the workpiece surface.

3. FEM SIMULATION – AN EXAMPLE OF STRESSES DEVELOPMENT OF A GLASS/EPOXY (G/Ep) POLYMER COMPOSITE

Fig. 2 shows Von Mises stresses development of a glass/epoxy (G/Ep) polymer composite as a result of AWJM impact for several different time steps.

Beginning of stresses development in the workpiece materials was at t= 0,1975 μs (Fig. 2a) as an effect of high speed of the abrasive waterjet i.e. 250 m/s. Such high momentum of the particle is interchanged for workpiece deformation. The deformation of the workpiece rises sharply in a very short time. While the first contact with the surface at t= 0,1975 μs (Fig. 2a) stresses rapidly increases up to the yield point of the matrix (epoxy), i.e. 60 MPa. It is very important that the maximum stresses is localised in the area of impact. At t= 0,2025 μs (Fig. 2b) the strength of the matrix was exceeded and the flow begun. Stresses moved very fast to the centre of the impact.

- For the FE code to remain stable, the time step must subdivide the shortest natural period in the mesh. In order to get more accurate results, the time step is chosen as 0.0025 μs.
- In this study, particles' disintegration in the mixing chamber is neglected.

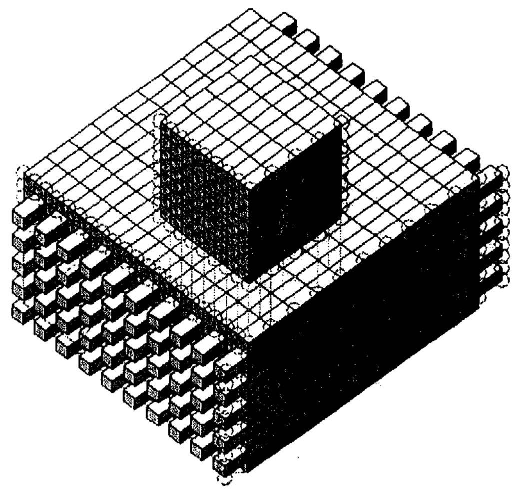

Fig. 1. FEM model of AWJM of polymer composite

The model was then analysed on a Pentium II PC workstation and stresses in the workpiece material were obtained using ALGOR Accupak/VE non-linear dynamic stress analysis and event simulation, Version 12 WIN, which models the non-linear behaviour by incrementing the load and updating the geometric stiffness matrix. Figure 1 shows the geometrical model of the AWJM, i.e. model of the workpiece and model of the abrasive particle.

The workpiece consists of two groups of material: matrix and fibre. In the present study uniaxially oriented fibres was analysed only, with 25% volume fraction. The polymer composite was modelled as 3D 20 nodded , non-linear solid elements. A total number of 2200 elements were used to model the matrix and 600 elements to model the fibres. The size of each element was 0,01*0,01*0,025 mm. Number of nodal points was 3577. The overall workpiece dimensions were: 0,2*0,11*0,2 mm. The properties of the workpiece material are shown in Tabel 1.

The constitutive model used for the workpiece is chosen as Von Mises elastoplastic isotropic hardening with linear strain hardening but due to polymer composites the modulus of hardening was 0 MPa. In the present study a composite material such as glass/epoxy (G/Ep) was analysed. The workpiece is fixed supported from the bottom as it is fixed on the table of the AWJ machine

The abrasive particle was modelled using 256 twenty nodded solid elements. The size of each element was 0,01*0,01*0,025 mm. The initially speed of a

Because after t= 0,2025 μs the matrix of the composite was damaged the upper layer of the matrix (thickness 0,01 mm) was removed and than we analysed stresses only in the layer where fibres were localised. At t= 0,2025 μs (Fig. 2c) while the matrix is flowing compressive stresses are taken by the fibres. Non-homogeneous of the composite causes nonsymetrical development of stresses. We observe that stresses develops more down the fibres that crosswise (Fig.2d at t= 0,225 μs). At t= 0,25 μs (Fig. 2e) stresses first increases than decreases very sharply at t= 0,3 μs (Fig. 2e). It may be a result of free space between fibres, which was formed instead of removed matrix. Than probably decreasing of compressive stresses may occur. At t= 0,35 μs (Fig. 2g) we observe increasing of stresses again but the zone of stresses decreases while the particle penetrates into the workpiece and the front of stresses moves to the jet impact region. It is very characteristic that the zone of stresses is larger into axial direction. At t = 0,3875 μs (Fig. 2h) fibres are broken because the strength of the material (glass) was exceeded. It means stresses reached 2510 MPa. After that the zone of stresses sharply decreased. The time between the first contact of the particle and the workpiece and fibres breaking is a period when delamination may occur. The front of stresses spreads along fibres far away from the impact region as it was shown on Fig. 2d. It may causes separation of fibres from matrix far away from the point of AWJ cutting and finally delamination.

3. CONCLUSION

Presented simulation was only a first attempt to recognise the mechanism of AWJ erosion of polymer composites. Several simplification were made building AWJ model as follow:

- Dimensions of the model are very small, so we are able to observe effects of AWJM on very small area only. The power of computers and abilities of FEM software decide on possibilities of increasing the size of the model.
- We omitted the zone of the contact between matrix and fibres. Contact properties have a great influence on the properties of polymeric composites.
- The first results of simulation show that FEM is a powerfull tool for AWJM modelling.

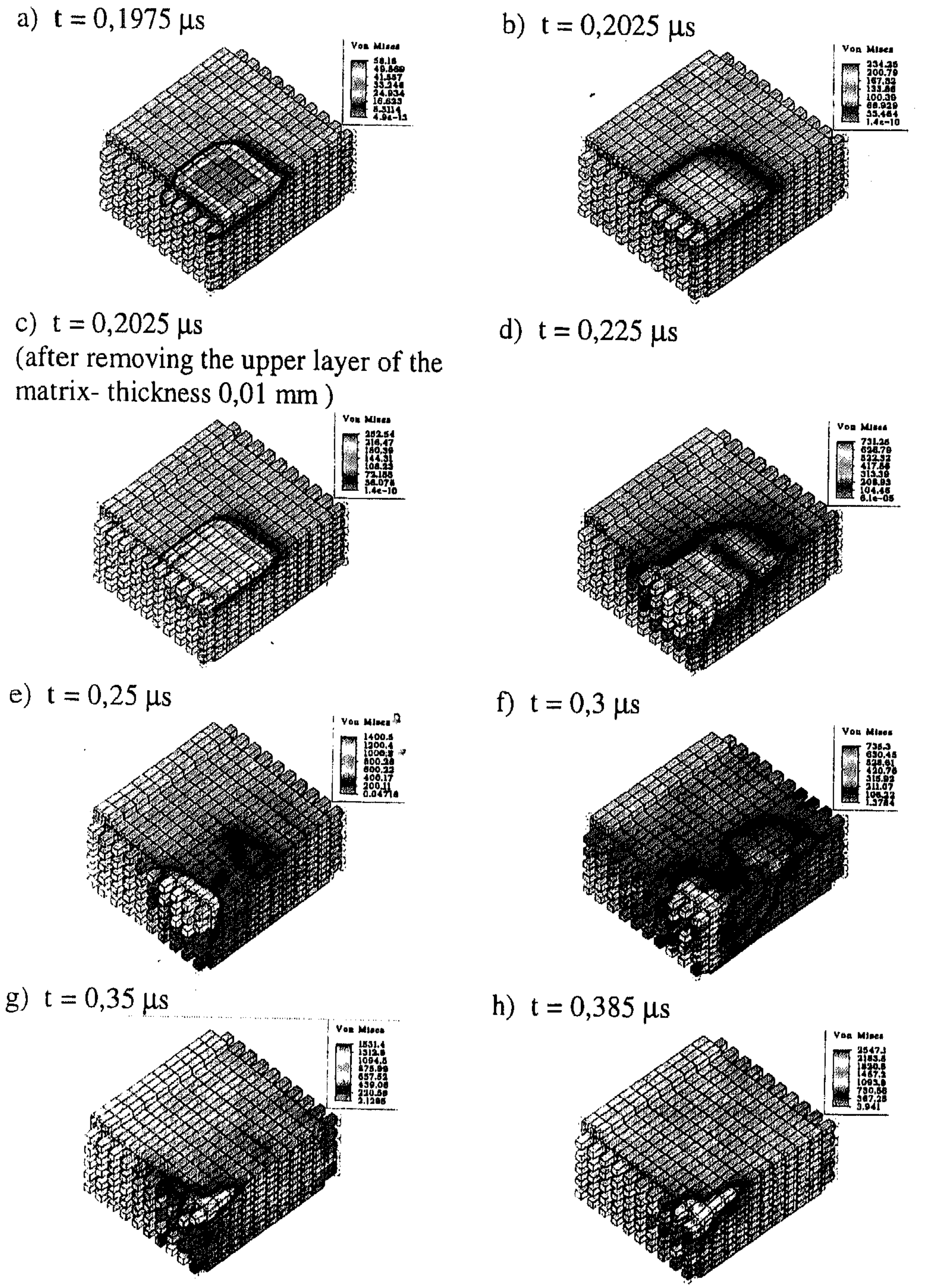

Fig. 2. Development of Von Mises stresses in the workpiece material (G/Ep) as a result of AWJM impact for several different time steps

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