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Static and Dynamic Processing of Intractable ArFRP Laminates

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Abstract; The purpose of the present research is to develop a simple and convenient processing method of aramid composites by static as well as dynamic press workings. Under tightly restrained condition, they are processed by a specially designed hollow punch. The present improved technique named strong restraining shear processings (SRSP) has realized an excellent and convenient processing which has never been achieved by any other high technology such as water jetting.

1. INTRODUCTION

Aramid fiber reinforced plastics (ArFRP) are very excellent in specific tensile strength as well as in energy absorption capacity. Though they are quite expensive under present situation, they have often been used in important parts of such vehicles as automobiles, ships and airplanes [1] [2]. Because aramid/carbon hybrid composites are extremely light, tough and strong, they will be expected to be widely used for main members of aeronautical as well as astronautical structures. However as is well known, aramid composites have been one of representative bullet-proof materials, and therefore they have been believed to be quite intractable. In fact, a lot of labourious works have been paid for achieving good finishing especially for removing many left fluffs after machining. Though aramid composites have been processed by using such high technologies as water jetting or vibration pressing in order to achieve better workability [3], it has been still quite difficult to process aramid composites of over 80% fiber in their volume fraction without any remarkable surface roughness and conspicuous left fluffs even by water jetting. The present technical situation will undoubtedly wait for new, simple and economical processing technique of these materials. In order to answer the demands, one of the present authors has developed a simple processing technique for the composites based on the punching technique of engineering ceramics [4] [5].

The present report aims to introduce the punching and forming technique for aramid laminates newly developed by improving conventional press working techniques, and also aims to present its possibilities and availability in both static and dynamic processing of intractable aramid laminates.

2. TEST MATERIAL

Test material consists of laminated composites of plain weave 0.4mm thick preregged Kevlar sheet (DuPont-Toray, K-29; 3000 denier, average diameter $15\mu\text{m}$) with matrix of polyvinyl-butylal phenol resin (volume fraction of the fibers; 90%). 4, 8 or 15 prepregged sheets was used to make laminated plates, and corresponding thickness is about 1.65, 3.3 and 6.3mm, respectively. Uniaxial tensile strength of the plain weave laminated plate is 500~530MPa, while the average strength of Kevlar fibers of $15\mu\text{m}$ diameter themselves is about 3.2~3.3GPa (the fiber length; 100mm). The maximum elongation of the fiber is 2.5~4%, and they break in perfectly brittle manner [6]. The elastic modulus of 4~8 laminated plate is 32~35GPa in tension, and that in thickness direction is 0.9~1.5GPa in compression tests depending on plate thickness.

3. TESTING METHOD

Newly developed quasi-static processing works were fundamentally carried out under tightly restrained condition. Figure 1 shows the clamping apparatus of an aramid sample, which was originally manufactured for the punching works in engineering ceramic plates [5]. The apparatus consists of steel frames and struts, and a commercial compact jack. After an aramid plate is set between a die and a clamping plate, the aramid plate is tightly clamped by the jack (max. load: 49KN). Punching or forming works were performed by loading the top of a punch in a conventional testing machine (Simazu AG2000), and the working load P -displacement δ relations were directly measured by X-Y plotter of the machine. Punching works of hole diameter $D=10\text{mm}$ were systematically performed by using 3 kinds of punches depicted in Figure 2. Figure 2-(A) and (B) show conventional flat and blunted conical punches, respectively. By using these punches, mechanical behaviours during punching works were carefully investigated. In Figure 2-(C), a hollow punch is illustrated. The punch was specially designed for punching works of aramid laminates based on the punching results by using the conventional flat and conical punches. All of these punches were made of 0.45%C steel and the top of the punches was quenched. In the newly developed punching method by the hollow punch, a back plate was installed to restrain the aramid laminates even at its rear face. The back plate plays a quite important role to chop away fine fibers which always remained as fluffs in the processings of aramid composites. Various kinds of materials were examined whether they are available for the back plate. They are 1mm thick toughened Zr plate, 1mm thick steel plate, 3 and 10mm thick PMMA plate or 1.2mm thick Duralumin plate. In order to investigate the processing possibility of the developed method, punching works of such modified shaped holes as non-circular and hexagon shaped ones were also carried out. Blanking works of 4 laminates were also performed to make disc specimens ($D=18\text{mm}$) for impact punching test by using 3mm thick PMMA back plate.

Impact punching and forming (blanking) tests were performed in a split Hopkinson pressure bar (the bars are steel made and the diameter is 20mm, Figure 3-(A)(B)). In the tests, disc specimens were tightly clamped at the end surface of the output bar by a screwed cup with a 3mm thick PMMA or 1.2mm thick Duralumin back plate. In these tests, metal tools shown in Fig.2 (D) and (E) were used and the die was installed at the end of the output bar in punching works, while in blanking works a flat anvil was used. In the impact tests, it was very sensitive to protect the edge of the tools, because surplus impact energy often injured them. Therefore such thin and soft materials mentioned above were chosen for the back plate, and a cylindrical Duralumin chock is also installed between punch and die (anvil).

Figure 2 Top shapes of used punches, (A)(B)(C); Flat, blunted conical and hollow punches, (D)(E); for impact tests ((D);punching, (E); blanking)

Figure 3 Experimental setup of punching (A) and blanking (B) processing in SHPB

4. EXPERIMENTAL RESULTS

4.1 Static and dynamic conventional punching tests.

In order to clarify mechanical behaviours during punching and also to investigate difficulties in the processings, some preliminary quasi-static and dynamic punching works were performed by using conventional punches (Figure 1-(A)(B)). Because aramid laminates are very flexible, they were deformed remarkably showing a bowl-like shape by the punching load. By the deformation, serious flange wrinkles were generated around punched region, and the wrinkles consequently brought interlaminar delaminations and serious damages. Continuous loading produced crunches between die and punch, and they were often injured. In order to avoid such serious punching situation, aramid plates were clamped tightly by the apparatus shown in Figure 1. Figure 4-(A) shows typical $P-\delta$ relation of the punching test by flat punch with clamping stress $\sigma_c \approx 150\text{MPa}$. Rear view of punched plate (4 laminates) is shown in Figure 5-(A). This punching method is quite similar to the conventional precision shear punching technique in metals, and so that a good performance will be expected. However it became clear that not only incompletely chopped strong fine fibers can easily escape to the gap between die and punch, but also serious damages appear around punched region. Fig.4-(B) shows $P-\delta$ relation for the conical punch, and the corresponding rear-view of the punched plate is shown in Figure 5-(B). No remarkable improvement was achieved either in the eradication of incompletely chopped fibers or in the repression of damages. These results indicate that drastic improvement has not been expected by these conventional punching technique even under tightly restrained condition. Figure 4-(C) shows $P-\delta$ relation by the newly developed hollow punch. Although this punch achieved conspicuous decrease in the working load, incompletely chopped fine fibers still remained around punched region (Figure 5-(C)).

Figure 6 shows impactly punched aramid disc-samples by the conical and hollow punches, respectively. Punching results show the same trend as the one in quasi-static, and they are also unsatisfactory for engineering use. Especially in the punching works by the conical punch, the die and the punch seriously crunch with each other and the aramid is heavily torn off. This miserable remains will make us imagine the bullet-proof ability of aramid composites.

Figure 4 Quasi-static working load P -displacement δ curves in conventional punching works under $\sigma_c \approx 150\text{MPa}$

Figure 5 Punched aramid laminates (each corresponds to Figure 4)

Figure 6 Punched aramid discs by conical punch (A) and hollow punch (B) ($V \approx 10\text{m/s}$)

4.2 Punching and Blanking Works by Strong Restraining Shear Processing

In the punching works by conventional flat or conical punch, punching loads became quite large, and consequently such serious damages as pull-out of fibers and delaminations were generated in the wide region around punched hole. On the other hand, in the shear-type punching works with the hollow punch, although incompletely chopped fine fibers were remarkably left, the punching load was improved to be 30~40% of the conventional punching. In shear type punching works, it has been analytically proved that the radial stress σ_r at the die edge ($r=D/2$) is very small [5]. This suggests that serious damages will not be generated at the circumferences of the hole. By using the shear type loading and also by introducing a new chopping-off mechanism of left fine fibers, new processing system has been developed to overcome many difficulties in conventional punchings. The processing technique is schematically shown in Figure 7-(A); the newly developed punching method is based on the following idea; ① in order to reduce the working load and to avoid pull-out of fibers, shear-type loading is selected, ② to chop away fine fibers left around punched hole, a back plate is newly installed (the back plate works as a chopping board of left fine fibers), ③ in order to repress delaminations around punched hole, the circumference of processed region is tightly clamped, and let punched refuse escape upwards inside of hollow punch. Consequently, extremely low working load is achieved, and this technique makes it possible to eradicate left fine fibers around punched hole. Because in the present processing method, the aramid composite is tightly clamped both at punched region as well as at its back, this punching technique has been named '*strong restraining shear punching (processing); SRSP*' method. In the punching works, the hollow punch is machined to have a sharp edge and the outside of the punch is finished straightly. On the other hand, in blanking works the inside of the punch is machined straightly (Figure 7-(B)). By using these punches, swellings of laminates due to delamination are generated in the inside or the outside of the punches in punching and blanking works, respectively.

Figure 7 Punching and blanking models by *SRSP* method

By the *SRSP* method, a series of quasi-static punching and blanking works of 4 and 8 laminates were performed. A toughened Zr ceramic, a carbon steel, PMMA or Duralmin plate was used as the back plate. In the punching works of thin laminate plates (1.65~3.3mm), no clear difference in their processed products is found in these back plates; any back plate works well as a chopping board of the left fine fibers. Examples of processed laminates are shown in Fig.8. Figure 8-(A) shows an example of punched plate of 8 laminates by steel back plate with the clamping stress $\sigma_c \approx 150\text{MP}$ ($D=10\text{mm}$). As can be seen in the figure, the laminates were successfully punched out. By systematic punching works, load necessary for this punching work is roughly proportional to the diameter of the hole (i.e., shear-length) and also depends upon edge sharpness [6]. In order to prepare disc-shaped samples for impact punching tests in a split Hopkinson bar, blanking tests of 18mm diameter discs were performed in 1.65mm and 3.3mm thick plates. The works were performed by using 3mm thick PMMA back plate without restraining. In these thin plates, the work was successful. The sample of blanked discs and the corresponding punched plate is shown in Figure 8-(B).

Figure 8 Examples of punched and blanked aramid laminates by *SRSP* (quasi-static), (A); punched 8 laminates with and without punched steel back plate and swelled punched refuse (a), (B); blanked 4 laminates and formed discs (enlarged) (for impact punching tests, $D=18\text{mm}$)

4.3 Quasi-static and impact punching tests and rate effect on working load

Impact punching and blanking tests were performed by the SHPB apparatus in Figure 2. In order to evaluate the rate effect on working load in the same restraining conditions, quasi-static works were also performed with the same tools used in the impact tests (Figure 9). The test samples were restrained by the screwed cap. Figure 10 shows typical $P-\delta$ relations obtained by the tests. In these quasi-static works, pulsatory motions are clearly seen, and the repetitions correspond to the number of laminates. Hollow circles in Figure 10 show necessary load to make rough finishing. All of the fine fibers are not chopped completely at these loads, but some of them still remains. In order to finish the processings completely without any left fibers, slightly higher loads are necessary (solid circles). Impact punching works were performed by using thin Duralumin ($t=1.2\text{mm}$) and PMMA ($t=3\text{mm}$) back plate. The punched disc specimens are shown in Figure 11. The figure shows that formability in impact works does not differ so much from static ones. However in PMMA, incompletely chopped fibers sometimes remains (arrowed in Figure 11-(B)). Typical input and output traces by SHPB tests are shown in Figure 12. Obtained working load P_{max} -loadig velocity V relations are shown in Fig.13. The working load P_{max} slightly increases with V . For comparison, the P_{max} values in the punchings without back plate are shown in the same figure. The rate dependences show the same trend as those in straight cutting and the strength of fibers[6].

Figure 9 Punching test set-up for quasi-static tests (tools; from Figure 2-(D)(E))

Figure 10 Typical $P-\delta$ relations showing pulsations in P (quasi-static punching)

Figure 11 Photos of punched aramid 4 laminates discs by impact punching test, (A); Duralumin back plate, (B); PMMA back plate ($V=11\text{m/s}$)

Figure 12 Typical input and output traces in impact punching

Figure 13 Loading rate effect on working load in punching works of 4 laminates (with and without back plate, $D=10\text{mm}$)

Figure 14 Examples of processed aramid laminates by SRSP technique (quasi-static) (A); $D=10$ and 20mm hole punching and side cutting, (B); cross-sectional view of punched plate $D=10\text{mm}$, (C)(D); examples of non-circular hole punchings, (E); formed dumbbell specimen

4.4 Availability of SRSP technique

The availability of SRSP method has been investigated. Figure 14-(A) shows some examples of deep holes punched in 15 laminated composites ($t=6.3\text{mm}$, $D=10$ and 20mm , the aspect ratios $AR=D/t$ of the holes are 1.6 and 3.2). Figure-(B) shows the cross-sectional view of the punched hole in 6.3mm thick plate ($D=10\text{mm}$). The example shows that formation of deep holes up to $AR \sim 1.6$ is possible. Figure 11-(C) and (D) show such non-circular holes as long and hexagon shaped ones punched in 8 laminates, indicating that holes in any shape can be formed. As is shown in Figure 14-(A) (bottom side, arrowed) and Figure-(E), laminated plate can be formed from its outside. These examples suggest that simple forming processings are also possible. By these examples through the punching and forming works including the processings in thick laminates, it can be summarized that the developed SRSP technique will cover a wide range of processings of aramid composites. The developed processing will be applied directly to engineering use. Although these punching works were only studied at low velocity range ($V < 10^{-3}\text{m/s}$), it will be possible to process them at such slow impact velocity as $V \sim 10\text{m/s}$.

5. CONCLUSIONS

Not only by clamping tightly around punched or formed region of aramid laminates but also by restraining them from its rear face, a new processing technique of aramid plate has been developed. The developed technique has been named strong restraining shear processings (SRSP). Quasi-static and impact punching works were performed by the technique. The obtained results are summarized as follows;

- (1) Circular holes can be punched out in aramid laminates (the thickness $1.6 \sim 6.3\text{mm}$) without any left fine fibers around punched hole as far as the aspect ratio of the hole is larger than about 1.6. Non-circular holes can be punched out in the same manner. The finishing by the technique is quite excellent one which has never been realized,
- (2) Forming works of simple shape are also possible as far as die and hollow punch can be prepared. The developed technique can be quickly used for practical applications, and they will realize quite economical and convenient processings,
- (3) Although the working load increases as the forming velocity V gets larger, the rate effect is less sensitive at $V < 10\text{m/s}$. The trend is quite preferable for high speed processings in aramid laminates. By improving protection techniques of the tools, high speed processings will be available in engineering.

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