Response of Soft Film/Hard Substrate and Hard Film/Soft Substrate Layered Systems Under Small Mass Impact

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***Abstract*-- The impact response of layered systems subjected to small mass impact is studied by the coded finite element program. To simulate impact response, an effective finite element approach in conjunction with the Sun's higher-order beam theory and Kurapati's generalized power law is proposed. Two typical film and substrate combinations, namely, Al/Si as soft film/hard substrate and Si/Al as hard film/soft substrate layered systems are considered. From the present numerical results, it can be seen that a generalized power law applied would be very helpful for estimating the impact responses of layered systems, and impact responses of Si/Al (hard film/soft substrate) layered systems are more sensitive than those of Al/Si (soft film/hard substrate) layered systems in the same film/substrate thickness. That is, this means that soft film/hard substrate layered systems may eventually be protected from impact damage and is more impact resistant than hard film/soft substrate layered systems. And, also, we can observe that in case of Al/Si (soft film/hard substrate) and Si/Al (hard film/soft substrate) layered systems, the interface and impacted surface unlike occurring in static analysis are prone to more failure risk than the other layer, respectively.**

***Index Term*-- Al/Si and Si/Al layered systems, Impact response, Small mass impact, Finite element analysis**

1. INTRODUCTION

The main purpose of the film in layered systems with thin film over the substrate material is to provide absorption to the impact, which puts less stress on the actual substrate. When layered systems are subjected to mass impact that caused by a sufficient heavy and fast impactor, it will break. However, unlike the homogeneous material that fails in a brittle manner, layered systems can reduce the number of dangerous flying fragments as many fragments will be adhered by the film layer.

Sun etc. [1] developed a higher order beam theory with six degrees of freedom for the dynamic response of elastic isotropic beams under impulsive loadings. The dynamic behaviour of composite plates under impact loading has been studied in terms of analytical and numerical work [2]. The effects of film and substrate on indentation behavior of layered systems have been studied in terms of numerical and experimental works [3, 4]. However, when a thin film is deposited on a substrate, the deformation and stress field in the resultant layered systems becomes more complex. The classical Hertz contact law is no longer valid in characterizing the load-depth response for the indentation of layered materials. And it is obvious that the critical indentation depends on the mechanical properties of both film and substrate, such as the ratio of the elastic modulus of film to that of substrate and the indenter geometry. Therefore, a systematic study of the influence of the ratio of the elastic modulus on the film and substrate effects would be very helpful for determining the mechanical properties of films.

In recent, Kurapati [5] suggested that a generalized power law (load-displacement curve) in layered systems vary with the film thickness and modulus. The validity of this generalized power law has been validated with the testing data generated from FEM (ABAQUS). In the present paper, an effective impact finite element theory based on Sun's higher-order beam theory and Kurapati's generalized power law is employed to investigate the response of soft film/hard substrate and hard film/soft substrate layered systems under small mass impact, and then the effect of thickness of film and substrate is investigated. That is, the impact responses such as the time histories for contact force, deflection of target, displacement of impactor, energy, strain and stress during impact event are obtained and compared with each other between the soft film/hard substrate (Al/Si) and the hard film/soft substrate (Si/Al) layered systems.

2. FINITE ELEMENT SIMULATION

Layered systems with film thickness h_f and substrate thickness h_s subjected to small mass impact by a steel ball of radius R with initial impact velocity V_0 as shown in Fig. 1 are considered.

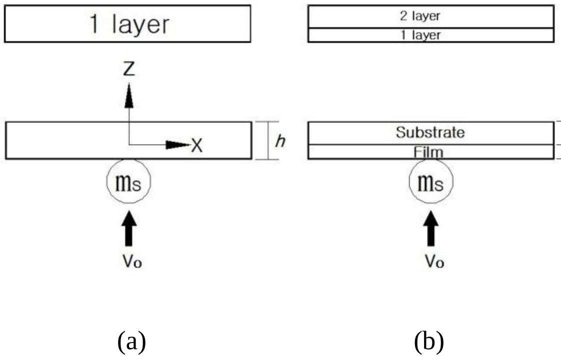
A governing theory with six degrees of freedom is used to analyze on impact response of these beams. The element displacement function is taken as

$$v = a_1 + a_2 x + a_3 x^2 + a_4 x^3 + a_5 x^4 + a_6 x^5 \quad (1)$$

where v is the transverse displacement and a_i are constant coefficients. The three degrees of freedom at each node are the transverse displacement v, the rotation θ and the curvature k, The coefficients a_i in *Eq.* (1) can be replaced by the six generalized nodal displacements at the two end nodes and, as a result, the displacement function can be alternatively expressed in terms of the nodal displacements. For contact force and indentation relation, a generalized power law [5] by fitting data generated using a wide range of film/substrate properties is given as follows

$$F=CE_s \qquad {}^{p} \qquad (2)$$

where F is contact force and δ the indentation. CE_s is contact stiffness. C and p are material constant and power.



(a) (b)

Fig. 1. Schematic diagram of small mass impact of layered systems. [6, 7]

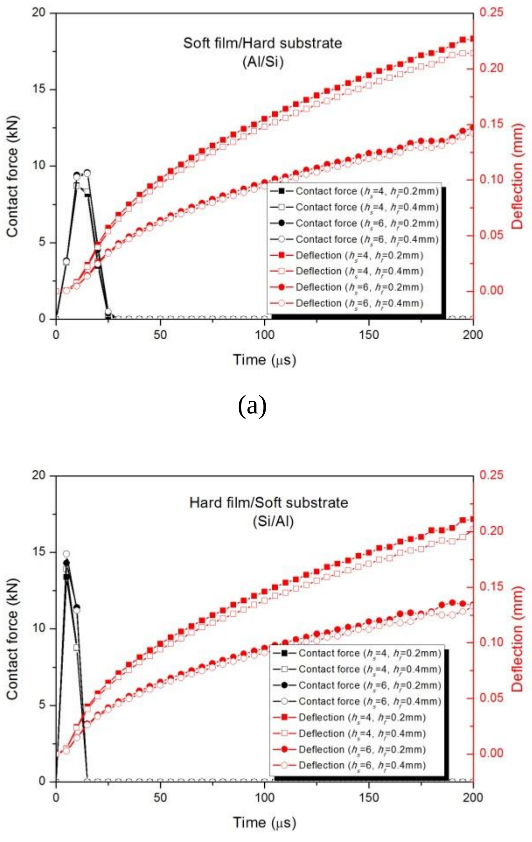
The coded finite element simulations are conducted for the study of the dynamic behavoiurs of four layered beams with variable thickness of film and substrate due to small mass impact. It is applied to a generalized power law that both loading and unloading process are treated as elastic. The beams with dimension of film thickness h_f=0.2, 0.4mm and substrate thickness h_s=4, 6mm are assumed to be impacted at the center by a spherical impactor with diameter 12.7mm and initial impact velocity 10m/s. Film and substrate for this study are assumed to Al for soft and Si for hard material. The models are simply supported on both side edges, in which a thin film is assumed to be completely adhered to a substrate. The material properties of target and impactor for simulation are shown in Table 1. Further similar simulating process were described in detail in Refs. [6, 7].

3. RESULTS AND DISCUSSION

Fig. 2 shows the histories of contact force and deflection for Al/Si and Si/Al layered systems with various thicknesses of film (h_f=0.2 and 0.4mm) and substrate (h_s=4 and 6mm) obtained from the present finite element analysis at velocity 10m/s. It is found that from Fig. 2, the maximum contact force in Sl/Al layered systems is much larger than that of Al/Sl but deflection in Sl/Al a little smaller than that of Al/Sl. This implies that Al as soft film of layered systems may eventually be protected Si from impact damage and Al/Si layered systems are more impact resistant than Si/Al layered systems.

Table I
Material properties of target and impactor for the present study

Materials		Properties
Target (Film & Substrate)	Soft (Al)	$E=75.9GPa$, $\nu=0.33$ $\rho=2700\ kg/m^3$
	Hard (Si)	$E=127\ GPa$, $\nu=0.28$ $\rho=2300\ kg/m^3$
Impactor		$E=200GPa$, $\nu=0.29$ $\rho=7800\ kg/m^3$, $R=6.35mm$ $V_0=10m/s$



(a)

(b)

Fig. 2. Histories of contact force and deflection of (a) Al/Si and (b) Si/Al layered systems (h_s=4, 6mm and h_f =0.2, 0.4mm).

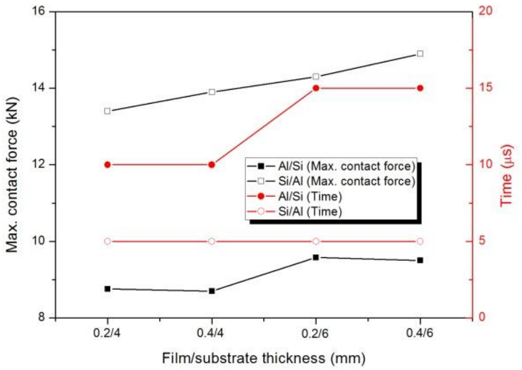


Fig. 3. Relationship of max. contact force, time at max. contact force and film/substrate thickness of layered systems.

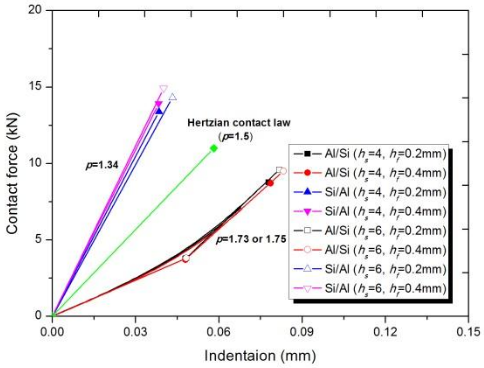


Fig. 4. Relationship of contact force and indentation of layered systems with h=4, 6mm and h_f =0.2, 0.4mm.

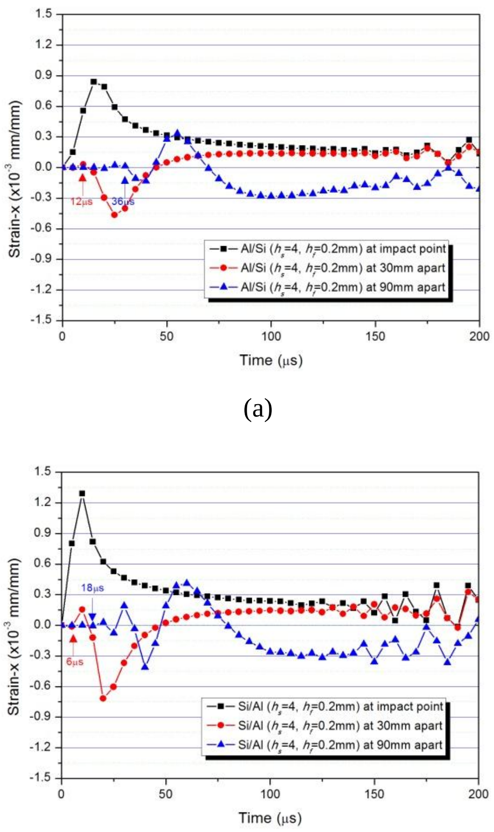
Fig. 3 depicts relationship of maximum contact force, time at maximum contact force and film/substrate thickness of layered systems obtained from Fig. 2. We can see that from Fig.3, in the case of Al/Si (soft film/hard substrate systems), the maximum contact force decreases, though small, with the increase of Al thickness in the same Si thickness but increases with the increase of Si thickness in the same Al thickness. While, in the case of Si/Al (hard film/soft substrate systems), the maximum contact force increases with the increase of Si and Al thickness at the same Al and Si thickness, respectively. That is, increase of Al thickness as soft film tends to reduce contact force though small in amount but increase of Si thickness as hard film to increase contact force.

Relationship of contact force and indentation at layered systems of Al/Si and Si/Al with varying the film and substrate thickness is depicted by the curve as shown in Fig. 4. The contact force is assumed to approach to elastic behavior in the unloading process after it passes the maximum value of the indentation in the loading process. From Fig. 4, it can be seen that the corresponding power p=1.5 of homogeneous system with average material properties of Al and Si materials calculated by a generalized power law is consistent with the Hertzian contact law (p=1.5) but p=1.73 or 1.75 and 1.34 for Al/Si and Si/Al layered systems not consistent, respectively. Results of contact stiffness and power by the present study are depicted in Table 2. From this Table 1, we can observe that in case of Al/Si layered systems, the contact stiffness CE_2 decreases with the increase of the Al thickness for the same Si thickness, while in case of Si/Al layered systems, the contact stiffness CE_2 increases with the increase of the Si thickness for the same Al thickness. In addition, the thickness of substrate does not affect on contact stiffness $CE_{2.}$ This means that increase of Al thickness in Al/Si layered systems is much more impact resistant than the increase of Si thickness in Si/Al layered systems.

Table II
Results of contact stiffness and power by *Eq.* (2)

Layered system	Al/Si				Si/Al			
Substrate thickness (h_s, mm)	4		6		4		6	
Film thickness (h_f, mm)	0.2	0.4	0.2	0.4	0.2	0.4	0.2	0.4
Contact stiffness (CE_2, N/mm^p)	0.757E6	0.715E6	0.757E6	0.715E6	0.105E7	0.111E7	0.105E7	0.111E7
Power (p)	1.75	1.73	1.75	1.73	1.34	1.34	1.34	1.34

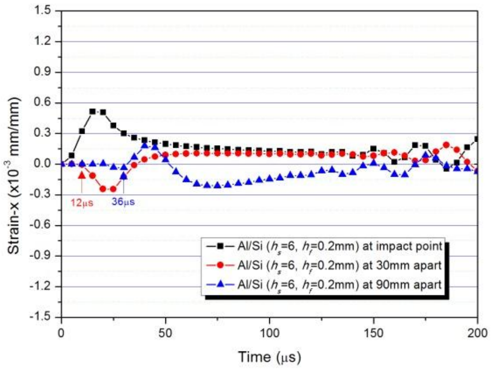
Next, Figs. 5 and 6 show the dynamic strain histories of Al/Si and Si/Al layered systems with h_s=4mm, h_f =0.2mm and h_s=6mm, h_f =0.2mm at three points (0, 30, 90mm apart from the impact point) on the surface S3 which is opposite to the impacted surface in layered systems, respectively. The present numerical results for Al/Si and Si/Al layered systems are compared with the wave propagation theory for homogeneous system with average material properties of Al and Si materials. From the Figs. 5 and 6, the magnitude and response time of the strains in the Si/Al layered systems are larger and faster than those of Al/Si during the impact event at the same substrate thickness because hard Si material has more stiffness than soft Al material, while the magnitude of the strains decreases with the increase of the substrate thickness for the same film thickness. In Figs. 5 and 6, the first dynamic strain responses of Al/Si and Si/Al layered systems at 30mm and 90mm apart from the impact point occur at around 12μs, 36μs and 6μs, 18μs after the initial impact, respectively. From these results of the dynamic strain responses, the transverse wave velocity of Al/Si and Si/Al layered systems become 2500m/s and 5000m/s, respectively. We can predict that transverse wave velocity of Si/Al layered systems is much faster than that of Al/Si layered systems. Theoretical comparison on transverse wave velocity of layered systems needs to be reviewed later again with other researcher's paper if it can be found.



(a)

(b)

Fig. 5. The dynamic strain histories of (a) Al/Si and (b) Si/Al layered systems with h_s=4mm and h_f =0.2mm at each point on surface S3.



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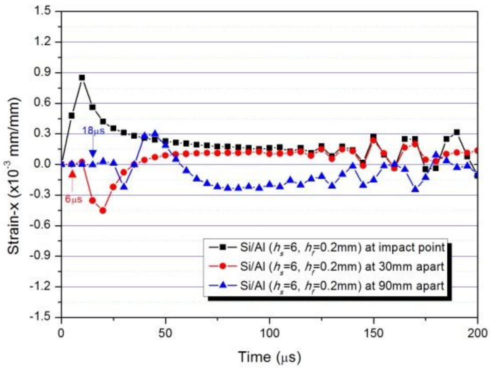


(b)

Fig. 6. The dynamic strain histories of (a) Al/Si and (b) Si/Al layered systems with h_s=6mm and h_f =0.2mm at each point on surface S3.

Fig. 7 shows contact force-deflection curves on layered systems at impact velocity 10m/s. The maximum contact force does not occur at the maximum deflection. It shows a typical wave-controlled impact that the contact force and beam deflection are never in phase [8].

The numerical results for impactor velocity and energy histories in four layered systems are given in Fig. 8. The velocity and energy at the time zero are the initial velocity and energy of impactor at which the impactor hits the target. Velocity curves of Fig. 7(a) decrease and take negative values and remain constant by time. These negative values represent rebound velocity of the impactor. Minimum kinetic energy in Fig. 7(b) occurs when velocity is zero. At these curves, the lowest tip of the curve shows minimum kinetic energy and the end of curve that remains constant shows the rebound energy. And, also, the energy difference between initial energy and rebound energy becomes absorbed energy by target. Fig. 9 shows the relationship of energies and thickness of film and substrate obtained from the results of Fig. 8.

It can be seen that from Figs. 8 and 9, rebounded energy of Al/Si layered systems at identical film/substrate thickness is larger than that of Si/Al layered systems and at the same layered systems increases with the increase of substrate thickness, while film thickness does not affect so much on rebounded and absorbed energies.

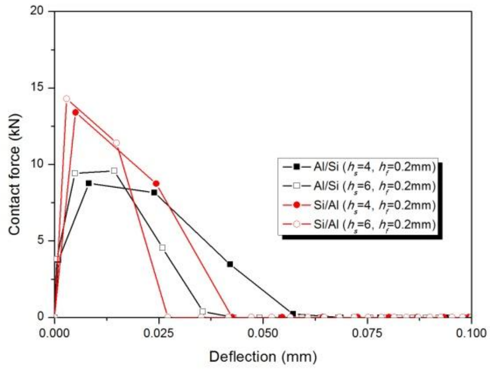
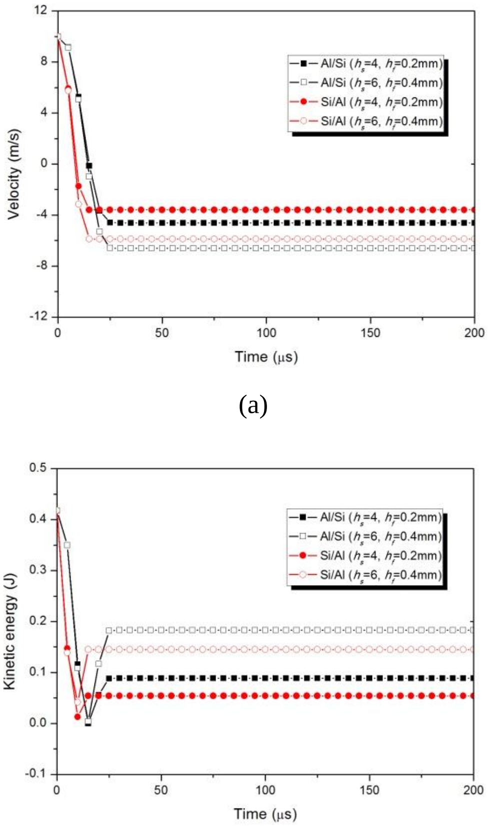


Fig. 7. Relationship of contact force and beam deflection of layered systems (h_s=4, 6mm and h_f =0.2mm).



(a)

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Fig. 8. The (a) velocity and (b) energy histories of layered systems (h_s=4, 6mm and h_f =0.2, 0.4mm).

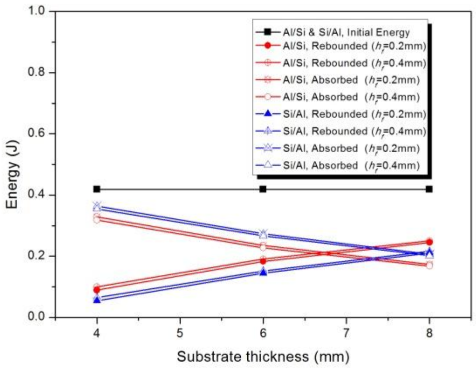
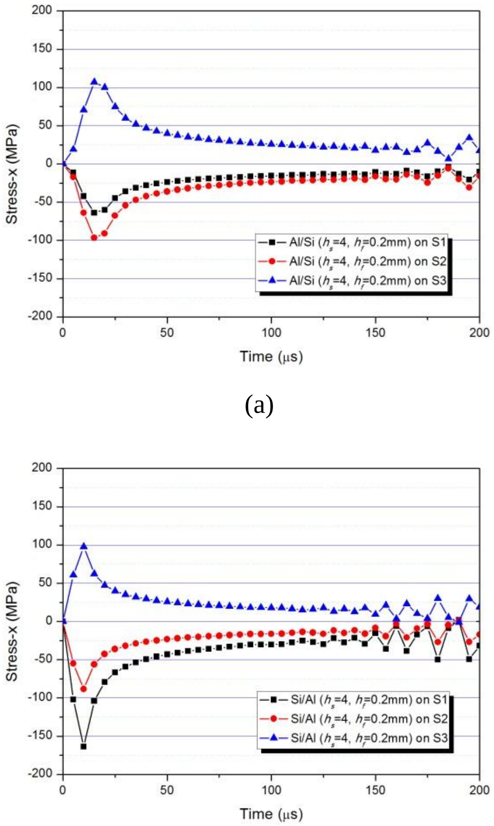


Fig. 9. Relationship of energies and thickness of film and substrate.

Fig. 10 shows the dynamic stress histories on each layer of two layered systems. The surface S1, S2 and S3 in layered systems mean “the impacted surface”, “the substrate surface” and “the opposite surface of impact” as shown in Fig. 1, respectively. It is shown that stress in x-direction on the surface S1 of Si/Al layered systems is much larger than that of Al/Si layered systems, in particular, stress on the surface S1 of Al/Si layered systems is smaller than that on the surface S2, while on S1 of Si/Al layered systems is larger than that on S2 because of stiffness of the impacted surface.

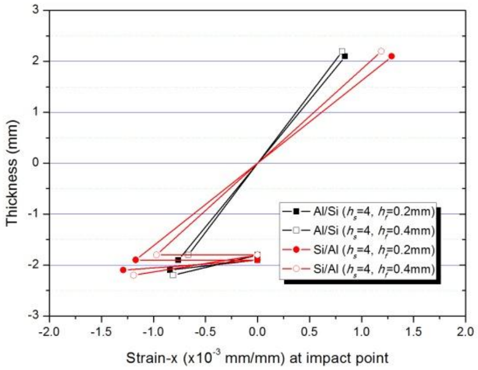
Figs. 11 and 12 depict the variations of strain and stress through the layer of four layered systems at impact point. All strain components in Fig. 11 vary linearly as a whole through the thickness despite its discontinuity between film and substrate, whereas the variation of stress in Fig. 12 shows its discontinuity due to a significant difference in the modulus values between film and substrate. Additionally, strains and stresses on the surface S1 of four layered systems approach to zero and are rapidly changing on the surface S2. Stresses on the surface S1 in Al/Si layered systems are smaller than those on the surface S2, however, on the surface S1 in Si/Al layered systems larger than those on the surface S2. Kurapati [6] was shown that the maximum stress in static analysis for soft film/hard substrate occurs right underneath the indenter whereas for the model which is hard film/soft substrate the value is observed at the interface of film and substrate. However, we can observe that by this impact analysis, the opposite case of static analysis is true. That is, the maximum stress for soft film/hard substrate (Al/Si) occurs at the interface of film and substrate, whereas for hard film/soft substrate (Si/Al) the value is observed right underneath the indenter. Hence for Al/Si layered systems, the interface is prone to more failure risk than the other layer, whereas for Si/Al layered systems, the impacted surface is prone to more failure risk than the other layer.

Fig. 13 depicts the relationship of stress and substrate thickness on each layer of layered systems with h_s=4, 6, 8mm in h_f=0.2 and 0.4mm, respectively. From Fig. 13, we can see that stress of Si/Al layered systems in each substrate thickness on the surface S1 is higher in (-) value than that of Al/Si layered systems regardless of film thickness but that on the surface S2 and S3 doesn't make a big difference like that on the surface S1.

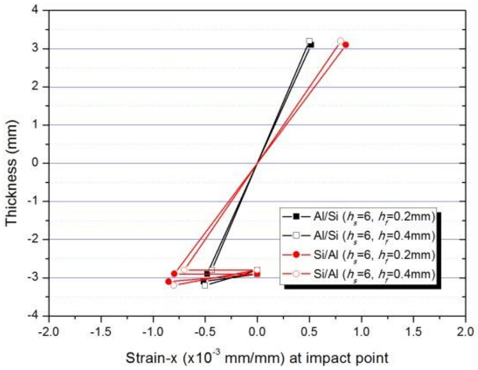


(b)

Fig. 10. Dynamic stress histories through the layer (a) Al/Si and (b) Si/Al layered systems with h_s=4mm and h_f =0.2mm on each surface at impact point.

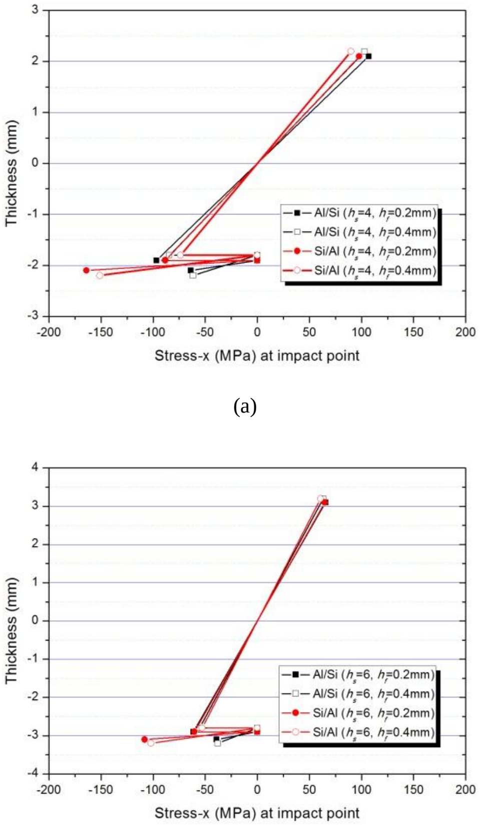


(a)



(b)

Fig. 11. Variations of strain through the layer of layered systems with (a) h_s=4mm and h_f =0.2, 0.4mm and (b) h_s=6mm and h_f =0.2, 0.4mm at impact point.



(b)

Fig. 12. Variations of stress through the layer of layered systems with (a) h_s=4mm and h_f =0.2, 0.4mm and (b) h_s=6mm and h_f =0.2, 0.4mm at impact point.

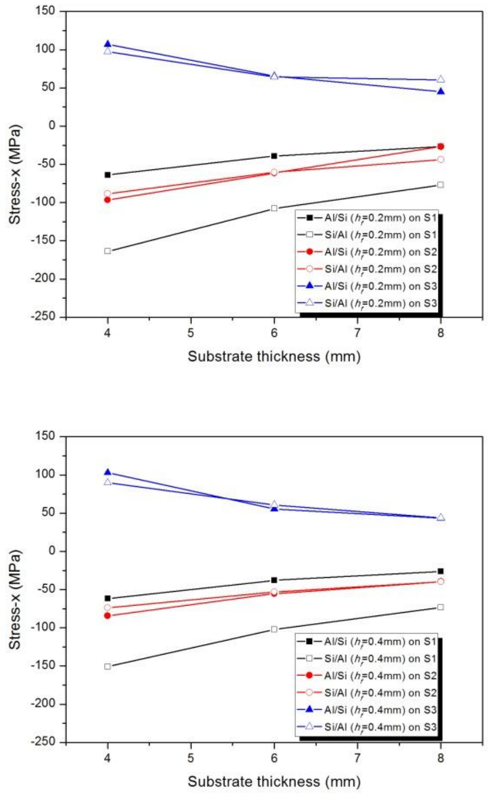


Fig. 13. Relationship of stress and substrate thickness on each layer of layered system with film thickness (a) h_f=0.2mm and (b) h_f=0.4mm.

4. CONCLUSION

The impact response of soft film/hard substrate and hard film/soft substrate layered systems subjected to small mass impact is investigated using an effective finite element approach in conjunction with Sun's higher-order beam theory and Kurapati's generalized power law. In this work, the responses such as the time histories for contact force, deflection of target, displacement of impactor, energy, strain and stress of Al/Si and Si/Al layered systems during impact event are obtained and compared with each other between Al/Si as soft film/hard substrate and Si/Al as hard film/soft substrate layered systems. From the present numerical results, it can be seen that a generalized power law applied would be very helpful for estimating the impact responses of layered systems. Impact responses such as contact force, energy, wave propagation, strain and stress in Si/Al (hard film/soft substrate) layered systems are more sensitive than those of Al/Si (soft film/hard substrate) layered systems in the same film/substrate thickness. That is, this means that soft film/hard substrate layered systems may eventually be protected from impact damage and is more impact resistant than hard film/soft substrate layered systems. In addition, in case of soft film/hard substrate, the interface between film and substrate unlike occurring right at underneath of the indenter in static analysis is prone to more failure risk than the other layer, while in case of hard film/soft substrate layered systems, the impacted surface unlike occurring at the interface in static analysis is prone to more failure risk than the other layer.

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