Industrial applications of shock waves

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Abstract: Shock waves have been traditionally considered to be an integral part of flow field features in the area of high-speed aerodynamics. Physically the propagation of shock waves in any media is invariably associated with instantaneous increase in pressure and temperature behind the shockwave. The capability of shock waves to generate non-linear pressure and temperature spikes in the medium of propagation finds very interesting applications in variety of areas such as medicine, biological sciences, material processing, manufacturing, and microelectronic industries. This paper reviews four new industrial applications of shock waves that have been developed in the Shock Waves Laboratory (SWL), Department of Aerospace Engineering, IISc, Bangalore. They are shock wave assisted (a) cell transformation, (b) preservative injection into Bamboos, (c) sandal oil extraction, and (d) removal of micron size dust from silicon wafer surfaces. The shock waves generated in an underwater shock wave generator are exploited in successfully injecting the desired deoxyribonucleic acid into \textit{Escherichia coli} and \textit{Agrobacterium} cells. The vertical shock wave reactor is applicable in successfully injecting the water-soluble chemical preservative (copper–chrome–arsenic) to samples of bamboo. The exposure of sandal-wood samples to shock wave loading in the horizontal diaphragmless shock tube resulted in the drastic reduction (40 per cent) of time required for oil extraction. Further, a new shock wave assisted technique for micron-size dust removal from silicon wafer surfaces has been developed in collaboration with the Interdisciplinary Shock Wave Research Center, Tohoku University, Sendai, Japan. The strong vortex field generated behind the Mach reflection of a shock wave has been used to remove micron size dust particles from the surface of silicon wafers. The salient features of these new industrial applications of shock waves are described in this paper along with some important results.

Keywords: shock waves, cell transformation, preservative injection, oil extraction, dust removal

1 INTRODUCTION

The presence of shock waves is commonly associated with aerospace engineering/astronautics and in particular with supersonic flight. These waves appear in nature whenever the different elements in a fluid approach one another with a velocity larger than the local speed of sound \cite{1}. The shock waves are strong perturbations in aerodynamics that propagate at supersonic speeds independent of the wave amplitude. Such disturbances occur in steady transonic or supersonic flow, during explosions, lightening strokes, and contact surfaces in laboratory devices. The typical thickness of the shock front in air is typically $10^{-7}$ m, very small compared to other characteristic lengths in fluid flow. Physically the occurrence of shock wave is always characterized in a fluid flow by instantaneous changes in pressure, velocity, and temperature.

Shock wave can be classified as weak or strong depending on the value of the pressure jump across the shock; they are also classified as normal or oblique shocks, compression or rarefaction shocks, and direct or reflected shocks. Due to instantaneous changes in fluid velocity and pressure, the shock waves gained lot of attention and are being tried for effective usage in many medical, biological, and industrial applications \cite{2}. It is possible to generate spherical shock waves with typical radius of few millimetres, both in ambient air as well as in water expending energy of the order of few joules. For example, in the laboratory,
spherical shock waves can be generated by focusing an Nd:YAG (neodymium-doped yttrium aluminium garnet) laser beam in ambient air and typically the energy expended in this process is \( \sim 1.38 \) J, which is equivalent to a 0.3 mg of conventional tri-nitro toluene (TNT) explosive. Figure 1 shows the evolution and reflection of spherical micro-shock waves generated by focusing an Nd:YAG pulsed laser beam from planar surface. Considering the amount of energy spent in generating such shock waves, they deserve to be referred to as micro-shock waves [3]. However, these micro-shock waves travelling at supersonic velocity exhibit highly non-linear pressure profile with ultra short rise time (approximately few microseconds) and are completely different from conventional acoustic waves wherein the pressure profiles are more linear with slower rise time (approximately tens of milliseconds). On the other hand, it is possible to generate shock waves of requisite strength in any desired medium using variety of techniques such as micro-explosions, pulsed laser beam focusing, electrical discharge in water, special purpose diaphragmless shock tubes, actuation of piezo-electric array, and even bursting of helium balloons. The peak pressure behind a shock wave ranges from 0.1 \( \sim \) 100 MPa and the typical pulse width can be anywhere from few \( \mu \)s \( \sim \) 50 \( \mu \)s. Whenever the required peak pressure is more than couple of MPa, the generated spherical or planar shock waves are focused using either parabolic or ellipsoidal reflectors.

The non-linear instantaneous pressure spike produced for very short time can be used for variety of applications in biological as well as in medical sciences. The shock wave assisted lithotripsy is probably one of the most useful and proven treatments for kidney stones [4, 5] and gall bladder diseases, and is now widely used by doctors in many countries. The shock waves for lithotripsy are usually of microsecond duration with peak pressures ranging 35–120 MPa in a single pressure pulse. The other applications include treatment of pancreatic and salivary stones, and in orthopaedics [6].

While substantial progress has been made in the research related to medical applications of shock waves, to the best of author’s knowledge, there has been no reported work on shock wave-based applications in agriculture and biological sciences. The non-linear instantaneous pressure spike produced for very short time can be used for variety of industrial applications. In the subsequent sections, four innovative industrial applications of shock waves that have been developed in the Shock Wave Laboratory, Department of Aerospace Engineering, Indian Institute of Science, Bangalore are described. They are shock wave assisted (a) cell transformation, (b) preservative injection into bamboos, (c) sandal oil extraction, and (d) removal of micron size dust from silicon wafer surfaces. Despite all these applications are diverse and different from one another, all of them utilize the non-linear pressure and thermal spikes generated by the propagation of the shock wave in the fluid media in a useful fashion.

2 INDUSTRIAL ENGINEERING APPLICATIONS OF SHOCK WAVES

2.1 Shock wave assisted *Escherichia coli* and *Agrobacterium tumefaciens* transformation

Nowadays many of the mind-boggling developments in biological science owe its genesis to the capability...
of biologists in genetically manipulating living cells. Introduction of different macromolecules like DNA (deoxyribonucleic acid), mRNA (messenger ribonucleic acid), proteins, and peptides into living cells is a part and parcel of genetic transformation protocols. Genetic transformation essentially refers to the process of introducing the particular DNA of interest into cell without damaging/destroying the living cell. The process of *Escherichia coli* (*E. coli*) cell transformation is schematically shown in Fig. 2. Since the *E. coli* bacteria is an unicellular organism, it is invariably used as template to validate any new genetic transformation method in the laboratory. Recently [7, 8], an underwater electric discharge unit (Fig. 3) has been developed for carrying out non-contact type genetic transformation. One of the major advantages of the present method over other existing methods is the fact that there is virtually no contamination during the transformation process.

Spherical micro-shock waves (peak overpressures up to 100 MPa) are generated in water by instantaneously depositing electrical energy (100 J) between two stainless steel electrodes (1 mm apart) for about 0.35 μs. The high voltage applied between the electrodes can be varied to generate shock wave of requisite strength. A high precision mechanical traverse system was used to hold microfuge tubes containing bacterial cells with the naked plasmid DNA above the electrodes. The distance between bottom of the tube and electrodes is maintained at 1.5 mm and corresponding pressure measured (PVDF (Polyvinyl difluorine) needle hydrophone, Ms Muller, Germany) inside the test tube was ~60 ± 5 per cent bar. The typical signature of the shock wave loading of the microfuge tube is shown in Fig. 4. It is interesting to note here that the high pressure pulse of ~60 bar amplitude lasts for only ~6 μs.

Exhaustive experimentation has been carried out to standardize the gene transformation protocols. In the beginning due to overdose, the bacterial cells were killed after exposure to shock waves. The DNA transformation efficiency is also measured and compared with one of the standard methods of gene transformation and the results are satisfactory as seen in Fig. 5. Using this method both *E. coli* and *Agrobac. cells* [9] have been successfully transformed. Efficacy of the shockwave transformed *Agrobacterium* in inducing infection and expression of gene of interest (Gus gene) has also been confirmed by transient gene expression assay. The interested readers can see references [8] and [9] for the details on the standard cell preparation and transformation protocols.

It is likely that the exposure of shock waves temporarily enhances the cell membrane permeability [10, 11].

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**Fig. 2** Schematic diagram depicting the bacterial cell transformation process

**Fig. 3** Schematic diagram of the underwater shock wave generator used in naked plasmid DNA transformation process

**Fig. 4** Typical variation of the overpressure profile measured using a needle hydrophone, inside the test tube filled with the bacterial cells and the naked plasmid DNA during the cell transformation experiments. The bottom-most portion of the test tube was placed at a distance of 1 mm from the electrode tip.
thus enabling transformation. However, the actual mechanism of shock wave assisted Agrobacterium cell transformation needs to be clearly understood. The technique proposed in this paper holds potential for introduction of different macromolecules including DNA in to different cell types. Currently efforts are focused on commercially viable prototype building, testing followed by commercialization.

2.2 Preservative impregnation in bamboo using vertical shock tube

A number of wood preservatives (chemical formulations toxic to wood decay/destroying organisms like fungi, wood destroying termites, marine borers etc.) and wood impregnating techniques are currently in use for improving bio resistance of timber and bamboo and thereby enhancing service life for different end uses. However, some species of tropical hardwoods and many species of bamboo are difficult to treat, posing technical problems. Bamboo can grow in most places; it is nutritious, checks soil erosion, conserves moisture, repairs degraded land, and sequesters carbon and are useful against global warming. It has got 1500 recorded uses, can replace timber, steel, plastic, even liquor, and wine and estimated to provide 8.6 million jobs in the India, with 136 species, has the richest bamboo resources after China.

In this backdrop, a collaborative research programme was initiated between the Indian Institute of Science and the Institute of Wood Science and Technology, Bangalore, to develop and test a new injection (water-soluble preservatives) system for bamboos using shockwaves. The main focus of the present study is in developing a commercially viable preservative injection system for treating bamboo. Then the obvious question is ‘why bamboo?’ Bamboo is regarded and promoted as an economical substitute for conventional wood especially in the under-developed regions of the world. Bamboos are tall, arborescent grasses belonging to the family Bambuseae. However, in actual applications, bamboo may readily be damaged and destroyed by fungi, insects, and marine borers.

The conventional methods of treatment of bamboo are pressure, hot, and cold treatments, sap displacement method and Boucheri processes. These processes, however, have their own limitations. Dry bamboo is not amiable to preservative treatment. The outer skin comprises of high silica content, thereby forming a good raincoat that prevents both insects as well as preservative from entering the culm. The inner part is covered with a waxy layer that is impermeable as well. Therefore, the preservative can enter only through the conducting vessels, which are not more than 10 per cent of the cross-section. Hence, a new approach in treating bamboo has been envisaged to get deeper penetration of the preservative for better service life. In case of timber, preservative is carried out nearly always on sawn timber. As a result of sawing, numerous vessels and cells open up, considerably easing the penetration of any preservative. Also, timber has rays that provide cross sections between the vessels. Unfortunately, these structural features are not present in bamboo and hence they offer considerable resistance to deep penetration of preservatives. Recently [12] a new shock wave assisted preservative impregnation technique was developed to push watersoluble preservatives into bamboo wood samples in the laboratory.

A vertical shock tube (internal diameter, 50 mm; wall thickness, 12 mm) with 1.5 m driver and 2 m driven sections separated by a metallic diaphragm has been built for carrying out the preservative injection experiment. Figure 6 shows the schematic of the vertical shock tube in the Shockwaves Lab in IISc, Bangalore. The water-soluble CCA (copper-chrome-arsenic) solution (4 per cent) is filled up to half-meter length in the driven section tube before the experiment. Samples of Dendrocalamus strictus species (30 × 2.5 × 1.00 cm³) prepared from defect-free culms of dry bamboo is fixed to end flange of the shock tube. The entire bamboo test specimen is immersed in the CCA preservative solution. Helium is used as the driver gas and 1.5 mm thick metal diaphragms are used for generating the shockwaves. The samples are exposed to 30 ± 5 per cent bar overpressure for about 300 microseconds in the shock tube. Each sample is subjected to repeat (three shots) shockwave

![Fig. 5](image-url) The DNA transformation efficiency obtained from present experiments in comparison to the one of the conventional KCM (potassium, chlorine, and magnesium) method of bacterial cell transformation.
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loading during the preservative injection studies. The experimental samples are divided into three groups, each comprising six samples of bamboo. Three different treatment techniques like pressure treatment, hot and cold processes, and shockwave assisted treatment have been carried out to estimate the level of penetration and the retention of the chemical preservative in the bamboo specimen. Figure 7 shows the amount of preservatives retained in bamboo samples after shock wave treatment. Also shown in the same graph are the preservative retention obtained from conventional methods. Clearly the shockwave assisted preservative injection system appears to be more efficient compared to the conventional methods. The average data on treating with CCA preservative is also recorded in all the split bamboo samples. The absorption, penetration, and retention in the treated samples are measured and the chemical analysis of the sample has been recorded in all the treatment methods (Table 1). Further, the amount of time involved in the treatment is only about 10 min including the time required for changing the diaphragm during the tests whereas time involved up to 3 h in conventional treatment systems. Although, not shown here, when the bamboo samples are subjected to single shot shockwave loading, the results were only comparable to conventional technique and in some cases deep penetration was not possible. Shock waves are compressive in nature.

Recently [15], a new shock wave assisted diaphragmless shock wave reactor was built to treat vatta wood slats that are used to make pencils. Figure 8 shows the photograph of the pencils manufactured using the wood treated with shock waves. It is anticipated that the new method of preservative impregnation will result in appreciable reduction in the production cycle time in the pencil manufacturing industry. It appears that the permeability of the bamboo samples is enhanced because of repeated shock propagation through the specimen. Hence the preservative is able to penetrate through the outer hard skin thereby facilitating better retention of the chemical after the treatment. Currently further targeted studies are underway to confirm the actual mechanism of shock wave assisted liquid preservative impregnation into wood.

Table 1 The tabulated results from the chemical analysis of the bamboo samples after the preservative injection by different methods

<table>
<thead>
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<th>Chemical</th>
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<th>Hot and cold process</th>
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<tr>
<td>Copper</td>
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<td>3.78</td>
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Fig. 6 Schematic diagram of a vertical shock tube facility in IISc that was used for preservative impregnation studies into bamboo samples

Fig. 7 The amount of copper–chrome–arsenic preservative retained in the wood samples after shock loading. Also shown in this graph are the results obtained from preservative impregnation studies using conventional methods.

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Fig. 8  Pictorial view of the pencils made from the vatta wood slats that were treated in the shock wave reactor. The water-soluble preservative was impregnated in these wood slats using the new vertical diaphragmless shock wave reactor

2.3 Sandal oil extraction enhancement using shock waves

India is a virtual treasure house to many rare and useful species of wood. Sandalwood (Santalum album L.) is one such indigenous species found in abundance in the southern part of the Indian peninsula, widely used for variety of pharmaceutical and medicinal applications. The principal product extracted from the heartwood of the sandal tree is the oil, popularly referred as the East Indian sandalwood oil. Heartwood from sandal trees upon distillation yields the oil that is characterized by a unique long-lasting characteristic aroma, and as a result it is also used in the manufacture of variety of perfumes and cosmetics. Sandal oil has earned a prominent position in incense sticks, cosmetics, fragrance, and soap industries. It is also found useful in medicine as an antiseptic, antipyretic, diuretic, expectorant, treatment of bronchitis, and urinary infections. However, the use of sandal oil as a base in perfume manufacturing has far outweighed its use in medicine. By itself it is a mild, long-lasting sweet perfume, but the industry finds that it can blend well with other perfumes and does not impart its fragrance when used as a base [15].

Steam distillation is commonly employed for both estimation as well as extraction of sandalwood oil. In steam distillation, at least 50 g of heartwood powder is required for estimating the amount of oil in a given sample and this invariably results in considerable damage to the tree. Recently Arun Kumar et al. [16] have also developed a non-destructive and easier method to estimate the oil content in sandalwood in the laboratory. However, this hexane solvent-based extraction process typically extends up to 18 h. In this backdrop, a new shock wave assisted oil extraction method is developed [17], which will not only increase the commercial yield of the oil but at the same time substantially reduce the extraction time scales.

Figure 9 shows the schematic of the experimental set-up. The cylindrical samples (diameter, 2.5 mm; length, 25 mm) are attached to the end flange having 50 mm constant area diaphragmless shock tube. A fast acting pneumatic valve is used to generate shock waves and the sandalwood specimen is subjected to high pressure conditions (15 ± 5 per cent bar) at the end wall of shock tube for about 1 ms. After the experiment, the samples are removed from the shock tube for further extraction of oil using solvent extraction technique. Then slightly burnt aroma emanated from the wood samples. Although, electron spectroscopy for chemical analysis (ESCA) – not described here – studies indicate the formation of silicon in the samples exposed to shock waves. Further studies are underway to understand the detailed chemistry during interaction of shock wave with sandalwood.

It is observed (not shown here) that both the rate and quantity of oil extracted from the sandalwood specimen exposed to shock waves is clearly higher than the respective control specimen in all the samples tested during the course of the study [17]. The amount of oil extracted in different sandalwood samples drawn from different trees after shock wave loading shows an increase in the range of 4.56 to 58.51 per cent compared to the oil extracted from samples which were not exposed to shock waves. It is also interesting to note that the rate of oil extraction in the samples exposed to shock waves is substantially enhanced during the initial 30 min of the extraction process compared non-destructive oil extraction techniques. However, the rate of extraction remains more or less the same for the subsequent time interval across the treated and control samples.

The scanning electron micrographs (Fig. 10) reveal that there is a change in the physical structure in case of samples exposed to shock waves. The study further revealed warty structures on the surface of the cross-section in addition to micro-fissures and cracks in the radial direction. These changes can be attributed to the compressive effect in the sandalwood specimen.
exposed to shock waves. The interior oil globules might have been ruptured bringing the oil to the surface. Subsequently these samples when immersed in solvent might have extracted more oil than the non-destructive sandal oil extraction technique. However, more studies are necessary to understand the fundamental effects of shock wave interaction on the wood anatomy. Further, gas chromatography (GC) (AIMIL NUCON GC 5500) studies using diethylene glycol succinate (DEGS) column (stainless steel) under isothermal conditions (160°C oven temperature) have been carried out to check whether the quality of sandal oil extracted is affected due to shock wave loading. The constituents (not shown here) of the sandal oil extracted are compared between exposed and control core samples, showed very little variation in the intensity of the peaks observed (santalol) in the sample exposed to shock waves and the control specimen. This is a clear indicator that there is virtually no effect of shock wave loading on the quality of the sandal oil extracted.

The results from the study indicates that both the rate of extraction as well as the quantity of oil obtained from sandalwood samples exposed to shock waves are higher (15–40 per cent) compared to non-destructive oil extraction methods. The squeezing of the interior oil globules in the sandalwood specimen due to shock wave loading appears to be the main reason for enhancement in the oil extraction rate. This is confirmed by the presence of warty structures in the cross-section and micro-fissures in the radial direction of the wood samples exposed to shock waves in the scanning electron microscopic studies.

2.4 Shock wave-assisted dust removal from silicon wafer surface

Micron and sub-micron particulate contamination is believed to be responsible for more than 80 per cent yield loss in semi-conductor industries. With the ever shrinking device sizes in the micro-electronic industry, there is an urgent need to come up with more effective dry cleaning techniques. This study describes the development of a novel shock wave assisted technique [18, 19] for removing sub-micron dust particles from silicon wafer surfaces. Figure 11 shows the photograph of the high-speed rotor with grooves along with the pneumatic fixtures for mounting the silicon wafers for cleaning experiments. The depth of the angular groove is 5 mm and three such grooves are made on the rotor at 120° apart. Various types (not discussed here) of surface corrugations have been tried to arrive at the best possible geometric configuration for dust removal experiments. Silicon wafers are mounted in the vicinity (1–2 mm stand-off distance) of a high-speed (60000 r/min) corrugated cylinder (diameter, 140 mm; length, 45 mm). The high strength aluminium alloy rotor is powered by a bi-directional 3-phase alternating current (AC) induction water-cooled motor that operates at 240V and maximum power of 5 kW. The rotor itself is supported on both the sides with ceramic bearings with maximum permissible axis vibration of about 30 microns at peak speed. This is the most critical part of the device since the silicon wafer surfaces are mounted very close to the rotating surface. Provision is made to generate a sonic jet coming from the axial direction in between the stationary wafer surface and the spinning rotor.

In this study, sub-micron size dust removal experiments have been carried out by using the corrugated cylinder spinning at supersonic edge speeds (380 m/s) in the vicinity of 80 mm diameter silicon
wafer surfaces. The sub-micron particles (tungsten and aluminium dioxide) of known size are used to contaminate both plain as well as patterned (with circuit etching) silicon wafer surface in this study. The particles are deposited on the wafer by preparing a solution of known quality of particles in anhydrous alcohol. The alcohol evaporates after a short period leaving behind a stain of the particle clusters on the wafer surface. Microscopic images of the surface of the wafer are taken before and after the cleaning process. Figure 12 shows the results from the cleaning experiments carried out using 0.7 μm tungsten particles. The photographs clearly show that the micron size particles have been removed using the present technique in both plain and patterned silicon wafers. In practice, it is the dust on the wafer surface that originates mostly from the deposition of silicon dioxide particles during the circuit etching process carried out in clean rooms. However, efforts to remove 0.10 μm aluminium dioxide particles deposited on the wafer surface yield only partial results. The microscopic adhesive forces like van der Waals, covalent, and the capillary forces, between the particle and the wafer surface are rather substantial with the decrease in the particle diameter which complicates the task of removing them from surface. In any case these are still early days before the device is integrated to the assembly lines in the micro-electronic industry. Issues such as the role played by the jet in removing the dust from the surface, the macro and micro characteristics of the complex fluid structure interaction in the narrow gap between the rotor and the wafer surface, and the identification of critical control parameters influencing the cleaning process have to be resolved in future studies.

3 CONCLUSIONS

To the researchers in the area of compressible flows, occurrence of shock waves is nothing new. However, utilizing the instantaneous increase in pressure and temperature behind a propagating shock wave in any medium, it is indeed possible to come up with interesting industrial applications of shock waves. In this paper, four such industrial applications developed in the Shock Waves Laboratory in IISc have been reviewed. Using shock waves generated in an underwater shock wave generator, the desired plasmid DNA has been successfully injected into *E. coli* and *Agrobacterium* cells. With the help of vertical shock wave reactor, water-soluble chemical preservative (copper–chrome–arsenic) has been successfully injected to samples of bamboo. Utilizing the same technique, shock wave-based preservative impregnation reactor has been developed for pencil manufacturing industry. Subjecting the samples of sandalwood to shock wave loading in the horizontal diaphragmless shock tube, resulted in drastic reduction (40 per cent) in the time required for oil extraction. Further, a new shock wave assisted technique for micron-size dust removal from silicon wafer surfaces has been developed in collaboration with the Interdisciplinary Shock Wave Research Center, Tohoku University, Sendai, Japan. The strong vortex field generated behind the Mach reflection of a shock wave has been used to remove micron size dust particles from the surface of silicon wafers.

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