IOP PUBLISHING MEASUREMENT SCIENCE AND TECHNOLOGY

Meas. Sci. Technol. **19** (2008) 085503 (11pp) doi:10.1088/0957-0233/19/8/085503

A novel ultra-high speed camera for digital image processing applications

A Hijazi[1] **and V Madhavan**[2]

[1] Department of Mechanical Engineering, The Hashemite University, Zarka, Jordan
[2] Department of Industrial and Manufacturing Engineering, Wichita State University, Wichita, KS, USA

E-mail: hijazi@hu.edu.jo

Received 27 March 2008, in final form 22 May 2008
Published 30 June 2008
Online at stacks.iop.org/MST/19/085503

Abstract

Multi-channel gated-intensified cameras are commonly used for capturing images at ultra-high frame rates. The use of image intensifiers reduces the image resolution and increases the error in applications requiring high-quality images, such as digital image correlation. We report the development of a new type of non-intensified multi-channel camera system that permits recording of image sequences at ultra-high frame rates at the native resolution afforded by the imaging optics and the cameras used. This camera system is based upon the concept of using a sequence of short-duration light pulses of different wavelengths for illumination and using wavelength selective elements in the imaging system to route each particular wavelength of light to a particular camera. As such, the duration of the light pulses controls the exposure time and the timing of the light pulses controls the interframe time. A prototype camera system built according to this concept comprises four dual-frame cameras synchronized with four dual-cavity pulsed lasers producing 5 ns pulses in four different wavelengths. The prototype is capable of recording four-frame full-resolution image sequences at frame rates up to 200 MHz and eight-frame image sequences at frame rates up to 8 MHz. This system is built around a stereo microscope to capture stereoscopic image sequences usable for 3D digital image correlation. The camera system is used for imaging the chip–workpiece interface area during high speed machining, and the images are used to map the strain rate in the primary shear zone.

Keywords: high speed imaging, multi-channel camera, non-intensified camera, multi-color illumination, digital image correlation, PIV

(Some figures in this article are in colour only in the electronic version)

1. Introduction

High speed imaging is an important tool in a wide variety of scientific research applications. Imaging requirements such as frame rate, exposure time, number of images in a sequence, image resolution and quality, tri-color versus monochromatic images, etc, depend on the application. Our application involves mapping the velocity and strain rate fields in the primary shear zone (PSZ) during high speed machining, as fully described in [1]. Machining (or metal cutting) is a process in which unwanted material is removed from the surface of a workpiece by moving the workpiece against a hard, sharp, wedge-shaped cutting tool, as shown schematically in figure 1. The material suffers a shear strain of about 200% within a narrow region called the primary shear zone (PSZ) and the total time of transit of a given material point through the PSZ is typically between 1 and 100 μs, resulting in strain rates between 10^4 and 10^6.

In order to map the velocity and strain rate fields in the primary shear zone, digital image correlation (DIC), [2] is performed on a sequence of microscopic images of the chip–workpiece interface region (i.e., the region of interest outlined in figure 1) that are captured during the machining process [1]. The frame rate for the image sequence being used for DIC needs to be between 100 kHz and 10 MHz if several images of a given material point need to be captured within the time of transit of that point through the PSZ. In addition, since the pattern of deformation through the PSZ could show cyclic

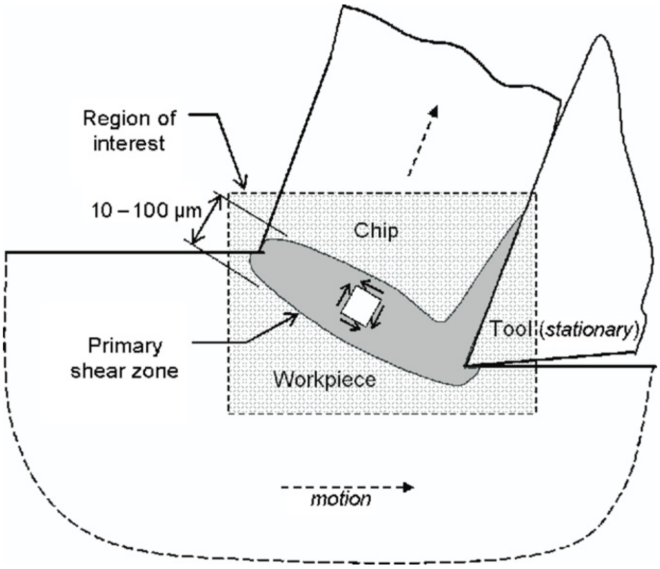

Figure 1. Schematic sketch of orthogonal cutting showing the region of interest.

changes that are of interest, it is desirable to have a capability of obtaining a sequence of several images. Considering this, together with a very small field of view, it is apparent that high-resolution microphotographic images need to be captured at frame rates in excess of one million frames per second (fps). High speed cameras capable of frame rates of 1000 000 fps (1 MHz) and above are commonly referred to as ultra-high speed cameras.

Several onsite demonstrations of multi-channel gated intensified ultra-high speed cameras were carried out. These demonstrations showed that poor spatial resolution and rather large noise in the intensity values of images obtained by this type of cameras make the images unsuitable for high-spatial-resolution DIC. The reduced image quality can mainly be attributed to the use of image intensifiers in this type of cameras. A need was felt for a new type of non-intensified ultra-high speed camera capable of recording a sequence of high-resolution images at framing rates exceeding one million frames per second.

In order to obtain higher quality images, we investigated the use of non-intensified cameras coupled with pulsed laser illumination such as those used for particle image velocimetry (PIV) of high speed flows [3]. Dual-phase cameras commonly used in PIV applications are capable of recording two full-resolution frames on a single CCD in very quick succession (the interframe separation can be as short as 50 ns). This type of camera is typically referred to as a dual-frame camera. In the dual-frame mode of operation [4], the exposure time and interframe separation are controlled by the timing of the pulsed illumination, typically provided by dual-cavity pulsed lasers. However, dual-frame cameras typically require about 100 ms before another pair of images can be recorded.

To scale up the frame count, a straightforward approach would be to construct a multi-channel camera system comprising multiple dual-frame cameras that work in synchronization with multiple dual-cavity pulsed lasers. However, in the dual-frame mode of operation, the exposure duration of the second frame cannot be controlled, i.e., the CCD continues to collect the incident light over the entire time it takes to complete the read-out of the first frame (which takes tens of milliseconds). This means that the second frame of all but one of the dual-frame cameras will be exposed multiple times and thus rendered unusable.

In this paper, we present a novel (patent pending) solution that has resulted in an ultra-high speed camera system that can acquire image sequences at frame rates exceeding 100 MHz without the need for the gating provided by image intensifiers. This is accomplished by using short pulses of illumination of different wavelengths and wavelength selective optical elements to prevent the illumination pulse of one wavelength, intended to expose one camera, from exposing multiple cameras. The solution described herein is applicable to a variety of cameras (even film cameras) and pulsed illumination sources. However, we have chosen to use dual-frame cameras coupled with illumination from dual-cavity pulsed lasers because of their many advantages, including the doubling of the frame count. We present a prototype of this type of camera system comprising four dual-frame cameras and four dual-cavity pulsed lasers, which is capable of capturing high-resolution images at framing rates up to 200 MHz. The prototype system is built around a stereo microscope such that it can obtain a sequence of eight images usable for 2D DIC or four pairs of stereo images usable for 3D DIC [5]. We also present sample results showing the velocity and strain rate fields while machining AISI 1045-HR steel at a cutting speed of 3.3 m s^{-1}.

2. Background

An imaging device consists of an imaging optic (e.g., lens), which collects the light emanating from a target and forms an image of it on a light sensitive medium (photographic film, electronic image sensor, etc) located at the real image plane. High speed imaging is almost as old as imaging itself dating back to the early 19th century [6]. With the very long exposure times (several seconds) necessary for capturing images back then, high speed imaging gave the ability to take still images of objects in motion. The significance of high speed imaging stems from the fact that it provides means for observing high speed phenomena that cannot otherwise be resolved.

2.1. *Basics of electronic image sensors*

The capabilities of solid-state electronic imaging sensors have recently experienced rapid development and they have almost entirely replaced the use of photographic films. An electronic image sensor consists of a matrix of capacitor-like storage elements, known as pixels, formed on an oxide-covered silicon substrate. This type of sensor, which is known as the metal oxide semiconductor (MOS) sensor, relies on the photoelectric property of silicon to convert the incident light to electrical charge. As an optical image is projected on the imaging sensor, the photons reaching each pixel generate an electrical charge, usually electrons, the magnitude of which is proportional to the local intensity of light at that pixel. After the sensor has been exposed to light for a period of time (the integration or exposure time), a pattern of charges is collected in the pixels (i.e., a frame is captured). The pattern of charges is then read out to a storage device, freeing the sensor to capture another image. The two most widely recognized types of MOS sensors are the complementary metal oxide semiconductor (CMOS) and the charge-coupled device (CCD). Both the CMOS and CCD sensors were invited around the same time, however due to the more complicated design of CMOS sensors, the CCD technology developed much faster and CCD sensors became more dominant.

The basic difference between CCD and CMOS sensors is in the way an image (i.e., the pattern of charges collected in the pixels) is transferred out of the sensor after it has been captured. In the most basic type of CCD arrays, known as the 'full frame' CCD [7], once a photogenerated pattern of charges is collected in the pixels due to exposure to the incident radiation, the incoming light is shuttered. Below the image section there is another row of similar storage elements, which are not photosensitive (i.e., shielded from light), known as the read-out section. The charges in the pixels are transferred down one row at a time into the read-out section, which in turn transfers charges along the row then the electric charges are converted to voltage and transferred out through the output amplifier. Once the analog signal (corresponding to charge level in each pixel) exits the sensor, it is then digitized and transferred to a storage device. Since the serial transfer of the charges through the read-out section takes a relatively long period of time, an external shutter (mechanical, magneto-optic or electro-optic) is typically used in order to avoid 'smear' of the image (i.e., the pick up of charges during the transfer period) [7]. Once the entire frame has been read out, the shutter can then be opened to capture the next frame. In a CMOS sensor, on the other hand, each pixel has its own charge-to-voltage conversion, and in the modern designs, the sensor also includes amplifiers, noise correction and digitization circuits, so the sensor outputs digital signal. The design of a CMOS sensor allows the signals to be transferred out of the pixels in parallel, and thus the read-out speed can be much higher than that of a CCD sensor. However, the other functions which are integrated into the pixels increase the design complexity and reduce the area available for light capture, which is known as the 'fill factor'. Also, with each pixel doing its own conversion, uniformity is lower. Each of the two types of sensors has its advantages and disadvantages. For scientific imaging applications, the most significant advantages of CCDs, as compared to CMOS, are the higher sensitivity and dynamic range (where both are due to the higher fill factor) and the lower noise level, whereas the most significant disadvantage is the low read-out speed.

The most commonly used types of CCD arrays are shown schematically in figure 2, the 'frame-transfer' CCD, 2(a), and the 'interline' CCD, 2(b) [6, 7]. A frame-transfer CCD is divided into two identical sections, namely, the image section, which is photosensitive, and the storage section, which is shielded from light. At the end of the time allowed for charge collection (i.e., the exposure time or the integration time), the entire array of charges in the image section is quickly transferred (parallel transfer) to the storage section in a process known as frame-transfer, whereupon the imaging section is ready again to acquire one more image. The frame is then read out of the storage section by serial transfer through the read-out section. The interline CCD, figure 2(*b*), works in a similar manner except that the storage section is in the form of shielded columns spaced between the columns of the imaging pixels. At the end of the exposure time, the charge in each pixel is transferred to the storage pixel adjacent to it and then read out in the usual way. In the interline CCD, the pattern of charges can be transferred to the storage sections in a faster manner as compared to a frame-transfer CCD, due to the fact that the charge in each pixel is transferred directly to its corresponding storage element. However, the fact that there are insensitive regions in the image area makes the interline CCDs less suitable for scientific applications [7].

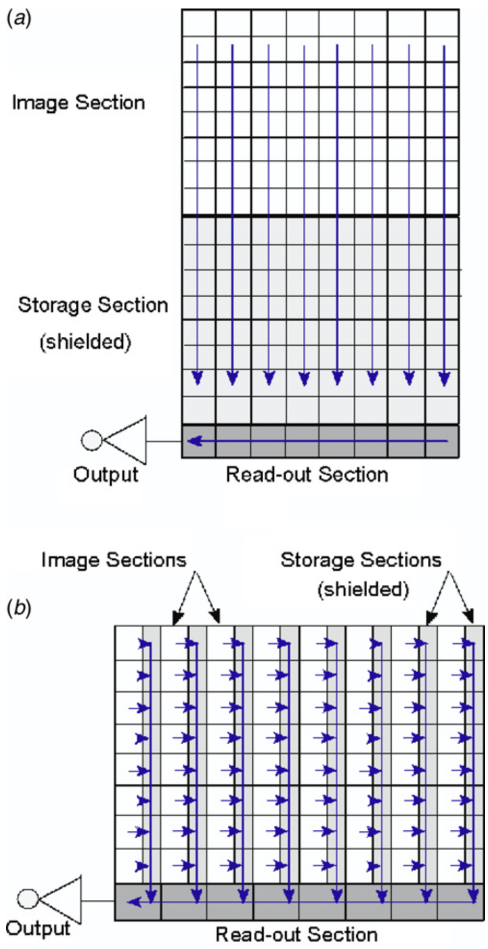

Figure 2. Common types of CCD arrays: (*a*) frame-transfer CCD, (*b*) interline CCD.

One of the advantages of frame-transfer and interline CCD arrays over the basic 'full frame' CCD is the minimal smearing arising from the fact that charges are transferred from the imaging pixels much faster using parallel transfer. In many frame-transfer and interline CCD arrays, a frame can be transferred to the storage section in less than a microsecond. Therefore, for these types of CCDs, the need for an external shutter (to avoid smearing) is practically eliminated. With the elimination of external shuttering, electronic shuttering can be used instead to control the exposure time. Electronic shuttering is realized by removing the photogenerated charge within the CCD array during the time period preceding the beginning of the exposure (typically achieved by reverse clocking the charges to a drain), allowing charge to accumulate for the required exposure time, followed by frame-transfer of the image to the storage section [6].

2.2. *High speed imaging*

A wide variety of high speed cameras, with framing rates ranging from 1 kHz to 200 MHz, are currently available commercially. In common usage, the term ‘high speed camera’ is used for cameras capable of capturing image sequences as well as for single shot cameras. A single shot high speed camera is a camera capable of capturing a high speed image (i.e., an image with a very short exposure time) that appears to freeze the motion of a moving object. The speed of such a camera simply refers to the inverse of the exposure time. On the other hand, high speed cameras being discussed here, which are the most common and practical, are those capable of capturing a sequence of high speed images with very short interframe separation. The speed, or frame rate, of such a camera refers to the inverse of the interframe time, while it is naturally understood that, for all practical purposes, the exposure time is less than, or at most equal to, the interframe time.

The major limitation on the maximum frame rate that can be achieved using CCD image sensors is imposed by the time needed to read out the captured image(s) from the image sensor. The read-out speeds of most CCD cameras range between 10 and 40 MHz, with 10 MHz being the most typical. For instance, a 10 MHz read-out speed means that, for a 1 megapixel sensor, it would take about 0.1 s to read a full frame (i.e., the framing rate is 10 Hz). With increasing read-out speeds, the read-out noise also increases, therefore using higher read-out speeds is not necessarily desirable.

A variety of techniques can be used to overcome this limitation on the maximum framing rates imposed by the read-out time. One of these techniques relies on reducing the size of the image to be read out (i.e., the pixel resolution) in order to reduce the read-out time and therefore increase the frame rate. Binning, the averaging of neighboring pixels, and windowing, using a subset of the sensor for image capturing and read-out, are two techniques that are used with high resolution CCDs in order to reduce the size of the image and consequently increase the frame rate. Another technique that can be used to achieve much higher framing rates is similar to ‘windowing’, in the sense that a subset of the CCD array is used for each image. However, the pixels representing different images are interleaved; each set of pixels representing an image is exposed at one particular time, and instead of reading out each individual image as it becomes available, the images are kept on the CCD until a number of images are recorded on the CCD and they are all read out together [8, 9]. Furthermore, it is also possible to increase the frame rate by dividing the CCD into multiple regions which are read out simultaneously through separate read-out sections [10]. High speed cameras using a combination of these techniques can acquire image sequences at frame rates of the order of 1 kHz to 100 kHz. However, these techniques cannot be used to increase the read-out speed by several additional orders of magnitude, as would be required to achieve truly high speed capture of high-resolution images.

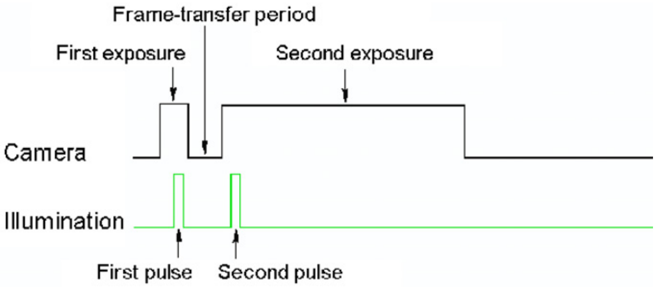

Figure 3. Camera exposures and timing of the illumination pulses for dual-frame mode of operation. Note that the interframe time cannot be less than the frame-transfer time.

A new type of imaging sensor known as *in situ* storage image sensor (ISIS) is capable of recording 100 consecutive frames with 312 × 260 pixel resolution at a framing rate of 1 MHz [11]. The concept of the ISIS CCD is similar to that of the interline CCD (figure 2(*b*)) where it has a local memory interspersed within the image section, but instead of having a single storage element for each pixel, multiple elements are available. During the image-capturing phase, image signals are transferred to the *in situ* memory without being read out of the sensor, and the number of obtainable frames in a sequence is equal to the number of storage elements installed in each pixel. The storage elements in this type of sensor occupy 87% of the total area of each pixel which means that the photosensitive area of each pixel (i.e., the fill factor) is only 13%. Therefore, there are some concerns that such sensor may not be suitable for applications involving PIV or DIC since there is a high chance that two completely different areas of field of view will be captured in any two successive frames.

2.3. *High speed dual-frame cameras*

The use of short duration illumination pulses permits the operation of frame-transfer or interline CCDs in a special mode known as ‘dual-frame’ wherein two images can be recorded in very quick succession [4]. In this mode of operation, the first image is captured at the time the first illumination pulse is incident on the subject, typically close to the end of the exposure time of the first frame, and immediately after the frame is transferred to the storage section, the second illumination pulse is used to expose the subject during the exposure time of the second frame. Figure 3 illustrates the timing for camera exposure and the illumination pulses in this mode of operation. Note that, though the exposure of the first frame can be controlled by the electronic shuttering technique described previously, the exposure of the second frame continues for the entire time it takes for the first image to be read out from the storage section. However, though the exposure time of the second frame is very long, the illumination pulse duration defines the ‘effective’ exposure time. This approach allows the acquisition of a pair of images, one in the image section and the other in the storage section. Thus, in the dual-frame mode of operation the camera can capture two frames in very quick succession, and then has to wait for hundreds of milliseconds (the read-out time of the two frames) before it can capture another pair of images. The minimum interframe separation is limited by the frame-transfer time, which can be as small as 50 ns for the most recent models. Cameras optimized to minimize the frame-transfer time and aimed entirely at this mode of operation are referred to as dual-frame cameras, and a variety of such cameras are available commercially.

It should be noted that the illumination should be provided in the form of a pulse that ends before frame transfer begins in order to prevent smearing. Otherwise, smearing during frame-transfer will be significant, since the frame-transfer time is not small when compared with the effective exposure time (i.e., the duration of the illumination pulse) and interframe separation. It should also be apparent that this method of image recording is more suitable for low ambient light conditions since the actual exposure time of the second frame is relatively long.

To realize operation at the minimum interframe time that these cameras will allow, namely, the frame transfer time, pulsed illumination has to be provided by sources that are bright enough to adequately expose the CCDs within a time interval that is a small fraction of the frame transfer time, shortly before and shortly after the transfer of the first frame. Pulsed lasers are increasingly being used as the illumination source where they are capable of providing up to 1 J of illumination within pulse duration as short as a few nanoseconds. If a single laser head is used to produce a train of pulses at a very high repetition rate, the energy per pulse will be very small and not sufficient for many imaging applications. Therefore, when multiple pulses with very short inter-pulse separation are needed, multiple synchronized laser heads are typically used. Dual-frame cameras are usually used in conjunction with dual-pulse (dual-cavity) Nd:YAG lasers for PIV in high speed flows. This type of camera is capable of capturing full-resolution images of good quality; however, the maximum frame rate is limited by the frame-transfer time and the number of obtainable frames is limited to two.

2.4. Acquiring high-resolution image sequences at ultra-high speeds

In order to capture sequences of more than two full-resolution images at ultra high speeds, multiple cameras combined into multi-channel cameras systems are typically used. Multi-channel cameras consist of multiple CCDs or cameras sharing the same viewing axis (using beam splitter(s), rotating mirror, rotating prism, etc), which are triggered in very quick succession to capture a sequence of images [6]. By the use of multiple cameras, the frame rate limitation imposed by the read-out time is eliminated and multiple images, corresponding to the number of internal cameras or CCDs, can be recorded.

In the most commonly used type of multi-channel cameras, known as a gated intensified camera, the light collected by the objective lens is delivered to the internal CCDs/cameras using a beam-splitter that splits the image into multiple identical images (multiple beam-splitters arranged in a branching configuration can also be used). Each of the internal cameras has an image intensifier comprising a photocathode screen that emits photoelectrons proportional to the image intensity, a microchannel plate that uses the avalanche effect to amplify the electron current, a scintillator that reforms a visible image and a CCD optically coupled to the scintillator screen to form an electronic image. The ability to switch the microchannel plate on or off rapidly is used as an external shutter to control the exposure time (exposure times down to about 1.5 ns can be achieved) and the exposure sequence of the CCDs/cameras. The shuttering provided by the intensifiers removes the requirement that the illumination be pulsed. Typically illumination is provided in the form of a single flash of light of duration long enough to capture a sequence of frames. The second function of the intensifier is to amplify the received light (gains up to 10^3 are commonly used) which helps reduce the relative importance of read-out noise. Though frame rates in excess of 100 MHz can be achieved with such cameras, the resolution of the images is limited by the resolution of the intensifiers, which (currently) is 76 line-pairs mm^{-1} at best. Also, use of image intensifiers reduces image quality due to distortion caused by the coupling optics, cross-talk between adjacent pixel elements caused by the microchannel plate and due to the fact that shot noise is also amplified by the intensifier. Note that, since image intensifiers are expensive, each of the intensified cameras is usually a dual-frame camera such that the frame count is doubled.

There have been also some attempts to devise multi-channel non-intensified high speed cameras [12, 13]. Such cameras consist of multiple frame-transfer or interline CCDs/cameras sharing the same viewing axis using a beam-splitter. This type of camera works in synchronization with pulsed illumination sources (typically a laser), where the pulses’ duration and separation define the effective exposure time and interframe separation for the captured images. Note that pulsed illumination is necessary or otherwise smearing will be significant since the frame-transfer time is not small anymore when compared to the exposure time. Also, it should be noted that the interframe separation between two successive frames is limited by the frame-transfer time, since no external shuttering is provided. In addition, there are practical limitations on the total number of internal CCDs/cameras that can be used because the light collected by a single objective lens needs to be split among several CCDs/cameras. Multi-channel non-intensified cameras working according to this technique have been reported to be able to capture four full-resolution consecutive images at frame rate up to 1 MHz [13].

In addition, there are other types of multi-channel non-intensified ultra-high speed cameras such as the rotating mirror camera [6] and the Cranz–Schardin camera [14]. In the rotating mirror camera, a mirror rotating at a very high speed is used to deliver the incoming light to the internal cameras one at a time. However, images captured using rotating mirror cameras are not suitable for use in PIV or DIC because they suffer some loss of resolution due to image drag resulting from

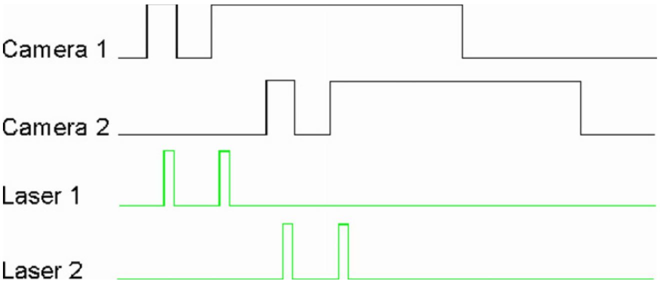

Figure 4. Example cameras and lasers timing for a multi-channel camera system comprising two dual-frame cameras and two dual-cavity lasers.

the rotation of the mirror. The Cranz–Schardin camera is based on the principle of using multiple spatially- and temporally-shifted light pulses to capture a sequence of images using spatially-shifted cameras. The object that is to be imaged is placed between the cameras and the light sources. An additional lens is placed between the light sources and the cameras such that it will direct the light coming from any of the spatially shifted light sources, only, to the camera corresponding to the spatial location of that light source. However, this type of camera can only be used in very limited imaging applications where the light passes through the imaging scene without significant scattering, such as in shadowgraphy and photoelasticity.

3. Approach

The review presented above, of the capabilities and limitations of the high speed imaging techniques and technology, shows that there remains a need for an ultra-high speed imaging system capable of capturing a sequence of high-resolution non-intensified images, especially for applications involving DIC or PIV.

A simplistic approach would be to construct a camera system consisting of multiple dual-frame cameras, sharing the same viewing axis using beam-splitter, that work in synchronization with multiple dual-cavity pulsed lasers. The exposure of the image sensors would be synchronized with multiple sources of pulsed illumination, where the pulses' duration and separation define the effective exposure time and interframe separation for the captured images. Figure 4 provides an exemplary timing diagram for a system comprising two dual-frame cameras synchronized with two dual-cavity lasers. The exemplary system represented by the figure is supposed to capture a sequence of four consecutive images. However, from the figure it is clear that, since the exposure time for the second frame of each of the dual-frame cameras is very long (typically about 125 ms), the second frame of camera 1 is exposed by three laser pulses (2, 3 and 4), and hence rendered unusable. In general, it can be stated that, for a system comprising n dual-frame cameras, the second frame of each camera except that synchronized with the last laser pulse will be exposed by multiple laser pulses. Thus, one can only obtain $n+1$ images in a sequence using a system comprising n dual-frame cameras (the remaining $n-1$ images will be bleared due to exposure by multiple pulses).

In addition to the limitation on the number of obtainable frames, it should be noted that the minimum interframe separation cannot be less than the time needed for frame-transfer. Otherwise, even the first image of each camera will be exposed by multiple laser pulses during the frame-transfer process and thus the image will be smeared. Referring to figure 4 for illustration, imagine that the first pulse of laser 2 was timed between the first and second pulses of laser 1. In such case, the first image of camera 1 will be smeared. Thus, the framing rate of the multi-channel camera cannot exceed that of a single dual-frame camera. Furthermore, the use of beam-splitters that divide the light collected by the front optics between the multiple cameras cuts down the light received by each of the cameras, necessitating the use of higher power pulses for illumination.

In multi-channel intensified cameras, the addition of an image intensifier in front of each of the internal cameras provides means of exposure control and that enables the camera system to overcome the above-mentioned limitations. In order to be able to overcome these limitations, without the need for image intensifiers, some optical property of the illumination pulses has to be employed in order to prevent light pluses intended to expose one camera from exposing other cameras. A technique has recently been proposed for simultaneously obtaining velocity fields in two parallel light sheets in order to obtain the complete velocity gradient tensor [15]. This technique, known as dual-plane PIV, is based on the use of two light sheets having orthogonal polarizations along with polarizing filters in front of the cameras, so that the first set of cameras sees the light scattered from the first light sheet only and the second set of cameras sees only light scattered from the second light sheet [16]. The use of different polarizations of light permits an alternate method for exposure control, to prevent the light pulses meant to expose one camera from also exposing other cameras. If this has been used in the setup comprising two dual-frame cameras given above as an example, it would have permitted that system to obtain four singly exposed frames. However, extending this to additional numbers of cameras is infeasible. In addition, there might be some concerns about using light of orthogonal polarizations for illuminating 'relatively rough' solid surfaces, such as the case in DIC applications, where the light reflected off the surface may have different polarizations causing cross-talk between the images.

We have devised a similar, but more powerful, solution that has resulted in a novel multi-channel ultra-high speed camera system capable of capturing sequences of full-resolution, high-quality images using multiple non-intensified cameras. The essence of the idea is to use multiple light pulses of different wavelengths for illumination and to use dichroic (i.e., wavelength selective) beam-splitters in the imaging optics to route light of each wavelength to one particular camera intended to receive that wavelength. Figure 5 illustrates the concept of using multiple dichroic beam-splitters to direct light of a particular wavelength to one particular camera. Multiple light pulses of different wavelengths (each pair having the same wavelength) are used for illuminating the target, and a single objective lens is used to collect the light

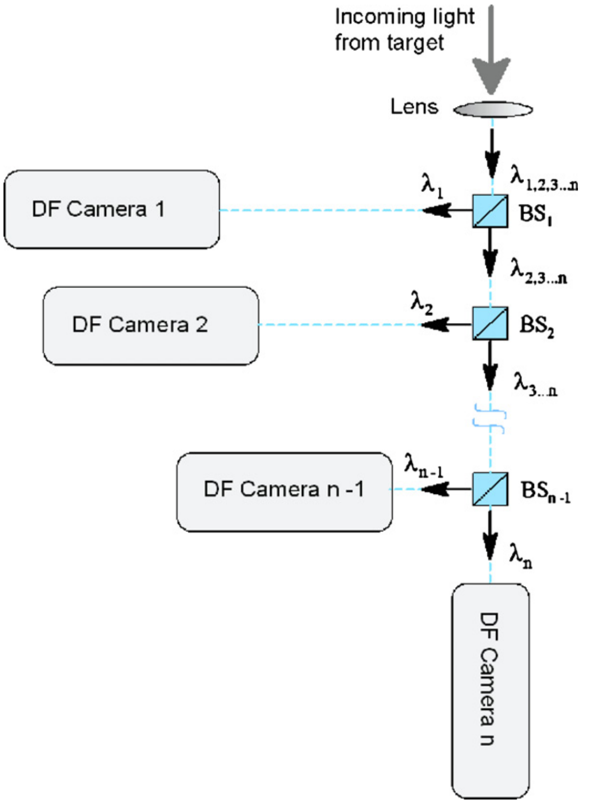

Figure 5. Schematic of one possible arrangement of beam-splitters and cameras to illustrate the concept of routing each wavelength of light to a specific camera, thereby achieving as much control over interframe time as permitted by the illumination system, rather than being limited by the camera (annotations: BS—beam-splitter, DF—dual-frame).

emanating from the target. Beam-splitters 1 through $n-1$ reflect wavelengths λ_1 through λ_{n-1}, respectively, thereby directing light of each wavelength to the appropriate camera without unnecessary loss of light intensity. The use of light pulses of different wavelengths for illumination and dichroic beam-splitters guarantees that both frames of each camera will be usable, if dual-frame cameras were used. While figure 5 illustrates the concept of using different wavelengths of light for control of the exposure where the beam-splitters are arranged in a sequential configuration, other configurations, such as a branching configuration, can also be used.

4. Prototype camera system

A wide variety of commercially available components (cameras, pulsed illumination sources, timing generators, lenses and optical components) can be used to build a multi-channel non-intensified high speed camera system according the concept described earlier. Our prototype camera system, shown schematically in figure 6, consists of four dual-frame cameras mounted on a stereo microscope, such that each pair of cameras shares one viewing axis. Using a stereo microscope permits stereoscopic observation of targets such that 3D DIC can be performed. A Leica-MZ16 stereozoom microscope is used for the prototype. The microscope has two objectives (1× and 2× PlanAPO) mounted on a rotating nosepiece, and has a 0.71× to 11.5× internal zoom capability such that a wide range of magnifications corresponding to fields of view from 5 mm to 0.35 mm can be realized. The dichroic beam-splitters placed in each of the light paths and the narrow-band-pass filters placed in front of each of the cameras (see figure 6) ensure that each of the four illumination wavelengths reaches one camera only. Also, the narrow-band-pass filter placed in front of each camera helps in reducing the effect of ambient light on the second frame of the dual-frame cameras. The dual-frame cameras used here are the Imager-Intense (SensiCam-QE) cameras, each of which is capable of capturing two 1376 × 1040 pixel images having 12 bit dynamic range with a minimum interframe separation of 500 ns. Though other models of dual-frame cameras having a higher framing rate are available, this camera was chosen because of its low noise-to-signal ratio and high quantum efficiency (as high as 62%). The microscope and the cameras are rigidly mounted onto a base plate which holds these in the same configuration with respect to one another. The whole base plate can be translated in three directions to focus on the target point of interest and can be rotated about two axes to provide complete freedom in terms of the relative orientation of the cameras with respect to the target.

The illumination pulses are generated using four dual-cavity Q-switched Nd:YAG lasers (Ekspla model NT 342) each of which can give two collinear pulses of 5 ns (FWMH) duration, with any required interframe separation. The fundamental harmonic of the Nd:YAG laser is 1064 nm, and the frequency can be doubled or tripled to give pulses at 532 nm or 355 nm. The second harmonic wavelength of the Nd:YAG, 532 nm, is used as one of the illumination wavelengths while the three other wavelengths (440 nm, 600 nm and 650 nm) are obtained by using optical parametric oscillators (OPOs) pumped by the third harmonic wavelength, 355 nm. Though a variety of wavelength shifters can be used for obtaining the other wavelengths, OPOs were chosen because they are relatively inexpensive and can be tuned to any desired wavelength. While the OPOs being used are capable of producing more than 10 mJ per pulse in each of the wavelengths used, pulse energies of the order of 100 μJ to few millijoules have been found to be sufficient for imaging, depending upon the target, magnification and aperture size used. Furthermore, the relative energies of the pulses at each of the four wavelengths are adjusted according to the spectral quantum efficiency curve of the cameras (assuming that the target being imaged has uniform spectral reflectivity which is pretty much the case for steel and aluminum), by adjusting the delay between the flash lamp and the Q-switch, such that the average intensity level of images obtained by each of the four cameras are comparable. However, if the target being imaged has non-uniform spectral reflectivity, such as copper for instance, the relative pulse energies need to be adjusted based on actual images of the target at the different wavelengths. Also, when needed, further fine tuning of the relative intensity levels can be realized through the image acquisition software by applying a uniform shift to the intensity level of the different cameras. The illumination pulses coming

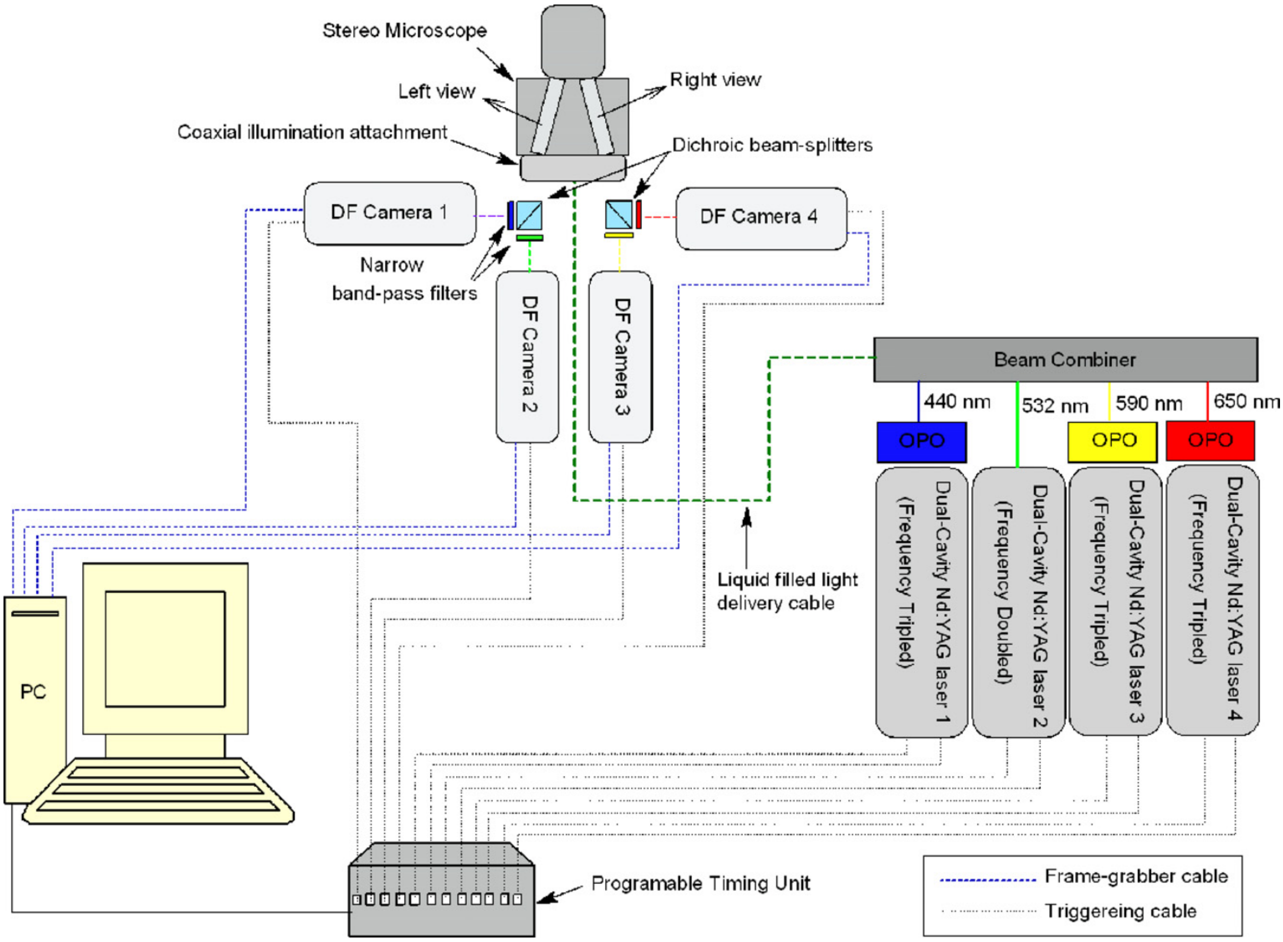

Figure 6. Schematic of the prototype ultra-high speed camera system.

from the four dual-cavity lasers are combined along a single axis using high-pass dichroic mirrors. The illumination pulses are then delivered through a liquid-optic cable to the coaxial illuminator module of the stereo microscope. The liquid-optic cable helps decohere the light reaching the target so that speckle patterns are not observed in the images. A picture of the prototype camera system being used in our lab is shown in figure 7.

The cameras are controlled through the camera control cards which communicate with the camera to setup the operating parameters such as the exposure time and to download the images. A programmable timing unit (PTU) is used to send the triggering signals to the lasers and the cameras. Twelve channels of the timing generator are used for triggering the lasers and the cameras, one channel for each of the four cameras and one channel for triggering each of the eight laser pulses. Note that for cameras running in the dual-frame mode, only one trigger signal is needed per camera in order to initiate the first exposure while the timing of the second frame is controlled by the second illumination pulse. Though two trigger events are needed to trigger each laser pulse (one for the flash lamp and one for the Q-switch), however, by using the rising and falling edges of the trigger signal to trigger the flash lamp and the Q-switch, respectively, one channel is used for triggering each laser pulse. The PTU used has a time resolution of 50 ns and thus can run the camera system at a frame rate up to 20 MHz. For shorter interframe intervals down to 5 ns (corresponding to a frame rate of 200 MHz), and event based triggering, a custom built circuit consisting of photodiodes, digital delay generators and high speed comparators is used.

The DaVis StrainMaster software package is used to communicate with and control the cameras, setup the laser triggers, setup trigger delays to compensate for signal propagation delays, etc. It is also used for carrying out calibrations of the imaging system at each of the zoom settings used and for carrying out 2D and 3D DIC.

5. Discussion

The design concept presented in this paper facilitates the fabrication of a multi-channel ultra-high speed camera capable of a capturing a sequence of high quality images usable in DIC or PIV applications. It should be apparent that this concept is quite general and is applicable to a variety of camera types and pulsed illumination sources. According to the concept described here, a system comprising n dual-frame cameras, each of which is limited to a maximum framing rate of f, can be used to acquire a sequence of $2n$ frames at a framing rate up to nf, as illustrated for the prototype camera in the timing diagram in figure 8(a). Specifically, eight frames can

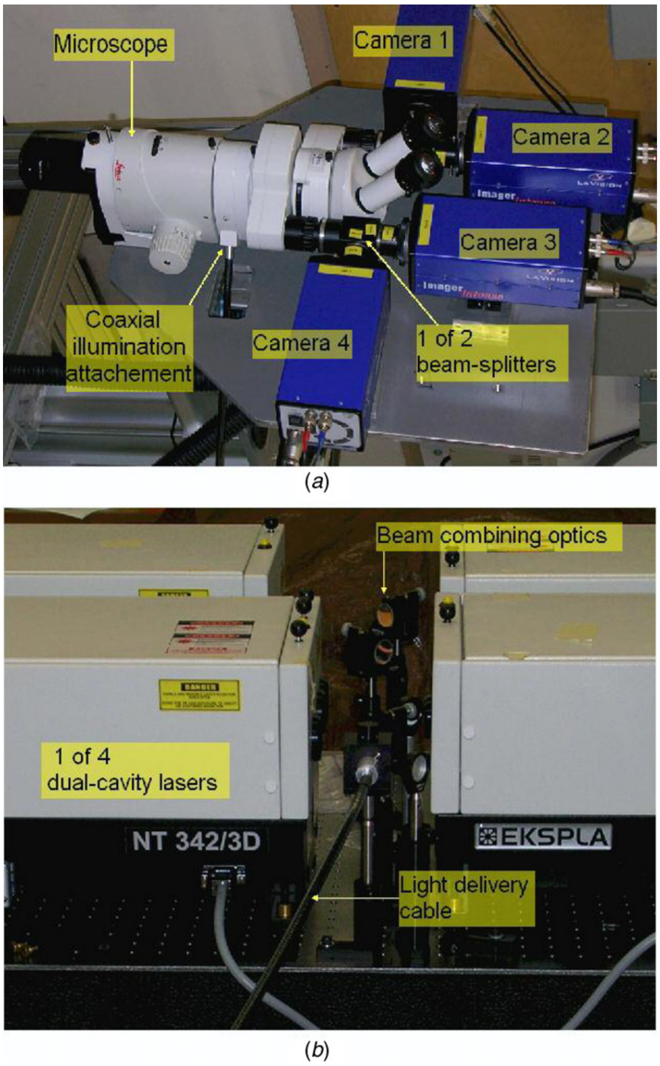

Figure 7. Pictures of the prototype camera system: (*a*) the four dual-frame cameras mounted on the stereo microscope, (*b*) the four dual-cavity lasers and the beam combining optics.

be obtained at a framing rate of 8 MHz using the four 2 MHz dual-frame cameras used in the prototype system.

Furthermore, the camera system is able to acquire image sequences with interframe times much shorter than the limit on interframe time imposed by the frame-transfer time of one camera. Indeed, a sequence of n frames with arbitrarily small interframe separation can be recorded simply by triggering light pulses of different wavelengths λ_1 through λ_n in a sequence during the first exposure of the cameras. Due to the frame-transfer time required by the cameras to be ready for the second exposure, the illumination system needs to pause till frame transfer is complete, before issuing another sequence of n pulses to expose the second frames of the cameras. Thus two arbitrarily rapid sequences of n images each can be obtained using a camera system comprising n dual-frame cameras, in little more than the frame-transfer time for a camera. Figure 8(*b*) shows, as an example, a pulsing sequence to capture two sets of four images at a frame rate of 20 MHz for each set. Issues such as multiple exposures of the frames and image smear during frame transfer do not arise because the dichroic beam-splitters guarantee that the pulse of wavelength λ_i will expose only the ith camera, and none of the others. In addition, the prototype camera system can also be used to capture pairs of stereo images usable for 3D DIC without the need to use identical beam-splitters and filters along the two stereo viewing axes. This can be done simply by trigging laser pulses of two different colors (corresponding to two cameras observing the target from the two different viewing directions) simultaneously. Figure 8(*c*) illustrates an example of the laser pulsing sequence in order to obtain four pairs of stereo images at a framing rate of 4 MHz.

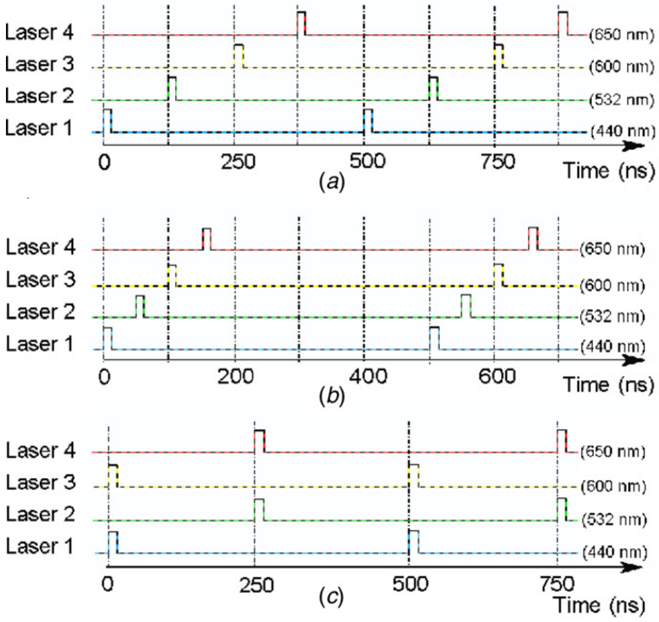

Figure 8. Examples of the pulsing sequence of eight laser pulses at four different wavelengths in order to (*a*) obtain eight frames at a framing rate of 8 MHz using the four dual-frame 2 MHz cameras, (*b*) obtain two groups of four frames at a framing rate of 20 MHz each using the four dual-frame 2 MHz cameras, and (*c*) obtain four pairs of stereo images usable for 3D DIC at a framing rate of 4 MHz using the four dual-frame 2 MHz cameras. Note that the time interval between any two pulses of the same wavelength should be $\geqslant$500 ns, which is the time needed for frame-transfer. Also, though not shown in the figure, it should be realized that the camera corresponding to each of the different wavelengths is triggered slightly before (about 10 ns) the first laser pulse of that wavelength and the first exposure ends shortly after the laser pulse (similar to that shown in figure 3).

The only limits on the minimum interframe time within each image sequence are imposed by the duration of the illumination pulses and the jitter and rise time of the electronics used for triggering the laser pulses and controlling the cameras. Therefore, for the prototype camera system presented here, the maximum frame rate is determined to be 200 MHz since the illumination pulses have 5 ns duration. With picosecond pulsed lasers and highly reflective targets (as long as the laser power absorbed is not high enough to damage the target), it may be possible for the camera system to achieve higher framing rates than heretofore achieved (in the GHz range).

As is apparent, the prototype system described in this paper was developed and configured for use in microscopic imaging applications. However, based on the same concept,

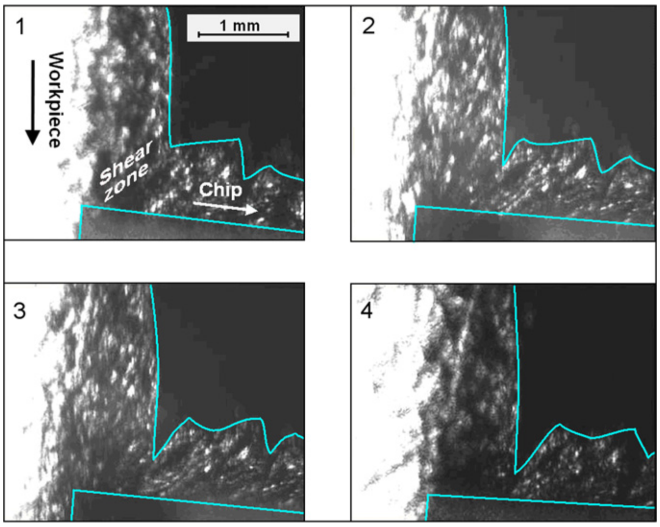

Figure 9. A sequence of four frames obtained at a frame rate of 100 kHz while machining pre-heated steel alloy at 3.3 m s^{-1}. Note that while this low frame rate is useful for showing the gross motion of the chip, a frame rate of about 1 MHz is needed to perform DIC on such images.

similar camera systems can be developed for use in more conventional types of applications. In fact, such camera systems have the potential to be used in any type of application in which the luminous intensity of the targets, either due to the background or due to self-emission, is much less than that due to the incident illumination pulses. In addition, if only the first frame of each camera is to be used for capturing an image sequence, the low-ambient light requirement of the dual-frame mode of operation may significantly be relaxed. While the level of pulse energy provided by the OPOs being used in the prototype system (in the order of 10 mJ) might be sufficient for some limited PIV applications, such as micro-PIV [17] for instance, however, it should be recognized that most of the conventional PIV applications require much higher illumination–pulse energy (at least an order of magnitude higher than what the OPOs can be provide) due to the fact that only a very small fraction of the illumination is reflected off the seeding particles. In order to provide higher illumination-pulse energy (for conventional PIV applications), pulsed illumination of different wavelengths can be produced by using different lasing mediums, through diode or dye-lasers that fluoresce in different wavelengths, or by using other types of wavelength shifters such as Raman shifters. For other types of high speed imaging applications, especially those that can accommodate pulse durations approaching 1 μs, lower cost illumination options such as the use of xenon flash lamps with filters, laser diodes, etc, can be considered if the illumination level and exposure duration provided by those are acceptable. Furthermore, the use of massive banks of relatively inexpensive high power light emitting diodes (LEDs) of different colors might be another feasible option for constructing a low-cost illumination system; especially since it has been demonstrated to be feasible in the Cranz–Schardin configuration [14] and since it has been shown [18] that pulses down to 1 ns duration can be generated using LEDs.

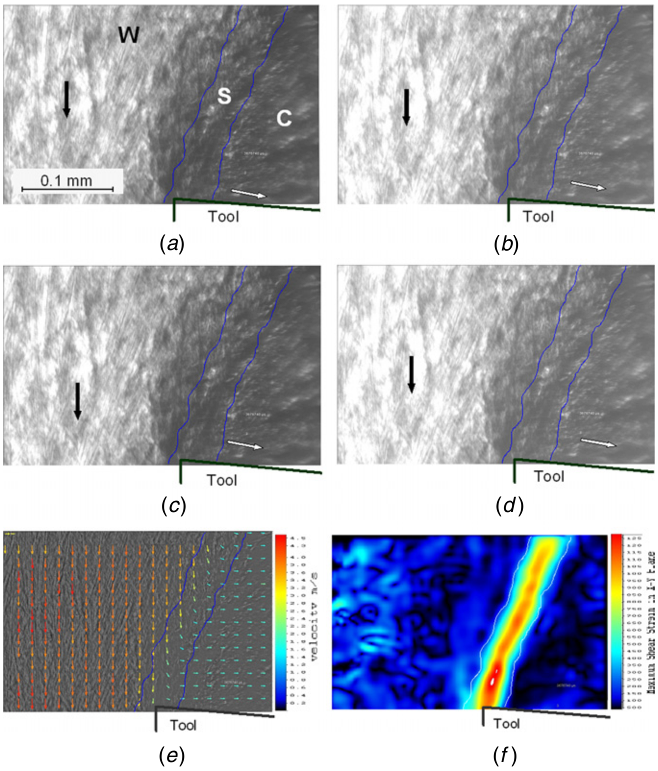

Figure 10. Process by which the velocity field and strain rate are obtained for AISI 1045 HR at a cutting speed of 3.3 m s^{-1} with a 5° rake tool. (*a*) and (*b*) stereoscopic pairs (left and right) of images taken at $t = 0$; (*c*) and (*d*) stereo pairs at $t = 1$ μs; (*e*) velocity vectors between $t = 0$ and $t = 1$ μs; and (*f*) fringes of shear strain rate (annotations: W—workpiece, S—shear zone, C—chip).

6. Sample results

The ultra-high speed camera system is being used for obtaining microscopic images of the chip–workpiece interface region (see figure 1) during high speed machining [1]. Figure 9 shows a sequence of four images acquired at a frame rate of 100 kHz while cutting pre-heated steel alloy at a cutting speed of 3.3 m s^{-1}. A typical sequence of images captured by the prototype camera system at such frame rate will comprise eight consecutive frames, however due to the similarity of the images only four frames are shown. This sequence of images was captured at a relatively low magnification (the field of view is approximately 3.5 mm × 2.5 mm), and is shown for illustrative purposes where one can observe the overall nature of the chip formation process. For a cutting speed of 3.3 m s^{-1} and a feed of 150 μm per revolution, images need to be captured at a magnification of 23× and a frame rate of about 1 MHz in order to map the deformation accurately, due to the high strain-rate deformation that takes place in the shear zone.

Figure 10 shows a typical set of two stereo pairs obtained using two of the cameras (each pair is captured simultaneously by two cameras) with an interframe separation of 1 μs between the two sets of stereo pairs (*a*–*b* and *c*–*d*) while cutting AISI 1045HR at 3.3 m s^{-1}. The images are captured at the maximum magnification level where the field of view in these pictures is approximately 350 μm × 250 μm, with each pixel covering a 0.27 μm × 0.27 μm area. For 3D DIC, each pair of images obtained simultaneously from the left and right perspectives (*a* and *b* for instance) is correlated to locate the same features in both the views. By the application of triangulation to the positions of corresponding points in the images in the two views, the topography of the surface at the time of observation is obtained. By cross correlating images at two times, and using the topographical information determined by triangulation, the three components of displacement at each point on the surface are obtained, as shown in figure 10(*e*). The velocity field can be obtained by dividing the displacement by the time interval, provided the time interval is sufficiently short to obtain an instantaneous spatial velocity field rather than a time averaged material rate. The gradient of the velocity field yields the strain rate field, from which the equivalent strain rate can be obtained, see for instance, figure 10(*f*). By correlating the images obtained while translating the workpiece without cutting it, it is found that images can be processed to result in a strain data point every eight pixels (a spatial resolution of 2 μm) with a strain noise less than 0.1% strain [1].

7. Concluding remarks

A novel multi-channel non-intensified ultra-high speed camera system comprising multiple dual-frame cameras and pulsed illumination sources is presented. The camera system is based on the idea of using light pulses of different wavelengths and routing light of a particular wavelength to only a particular camera using dichroic beam-splitters so that the exposure timing can be controlled by the timing of the light pulses. The concept is quite general and is applicable to a variety of cameras and pulsed illumination sources. This concept allows the interframe separation to be infinitesimally small and results in a camera system where non-intensified cameras can be combined together to capture a sequence of high-resolution images at ultra-high speed. A prototype of the camera system was built around a stereo microscope and consists of four dual-frame cameras and four dual-cavity lasers. The prototype camera system is capable of capturing a sequence of high-resolution images usable for 2D or 3D DIC at framing rates up to 200 MHz. The camera system is being used with good success to capture high-resolution microscopic images of the PSZ during high speed machining, which yield strain measurements at spatial resolutions down to 2 μm with noise less than 0.1%.

Acknowledgments

We are pleased to acknowledge the financial support by the National Science Foundation (Grant numbers: DMI-0116675 and DMI-0421394, Program Manager: George Hazelrigg). The prototype camera system is available in the Manufacturing Processes Research Lab at Wichita State University (http://engr.wichita.edu/vmadhavan/MPRL.htm).

References

[1] Madhavan V, Mahadevan D, Sheshadri A, Yegneswaran K, Adibi-Sedeh A, Hijazi A and Saket-Kashani M 2008 Experimental determination of velocity and strain rate fields in metal cutting *J. Mech. Phys. Solids* at press
[2] Sutton M, Wolters W, Peters W, Ranson W and McNeill S 1983 Determination of displacements using an improved digital correlation method *Image Vis. Comput.* **1** 133–9
[3] Willert C, Raffel M, Kompenhans J, Stasicki B and Kahler C 1996 Recent applications of particle image velocimetry in aerodynamic research *Flow Meas. Instrum.* **7** 247–56
[4] Lecordier B, Mouqallid M, Vottier S, Rouland E, Allano D and Trinite M 1994 CCD recording method for cross-correlation PIV development in unstationary high-speed flows *Exp. Fluids* **17** 205–8
[5] Luo P, Chao Y, Sutton M and Peters W 1993 Accurate measurement of three-dimensional deformations in deformable and rigid bodies using computer vision *Exp. Mech.* **33** 123–32
[6] Ray S 1997 *High Speed Photography and Photonics* (Bellingham, WA: SPIE Press)
[7] Burt D 1995 Extending the performance limits of CCD image sensors *GEC J. Res.* **12** 130–40
[8] Nebolsine P, Snyder D and Grace J 2001 MHz class repetitively Q-switched high-power ruby lasers for high-speed photographic applications *Proc. AIAA* 2001-0845
[9] Lowrance J, Mastrocola V, Renda G, Swain P, Kabra R, Bhaskaran M, Tower J and Levine P 2004 Ultra-high frame CCD imagers *Proc. SPIE* **5210** 67–75
[10] Smith G, Phillips P, Middleton M and Archibald A 1994 High-speed CCD read-out camera system *Proc. SPIE* **2273** 61–70
[11] Etoh G *et al* 2003 An image sensor which captures 100 consecutive frames at 1000 000 frames/s *IEEE Trans. Electron Devices* **50** 144–51
[12] Willert C, Stasicki B, Raffel M and Kompenhans J 1995 Digital video camera for application of particle image velocimetry in high-speed flows *Proc. SPIE* **2546** 124–34
[13] Gray C, Skopp D, Wieneke B and Reckers W 2001 High-speed PIV using high-frequency diode-pumped solid state laser and multi-frame CCD *Proc. Int. Cong. on Instrumentation in Aerospace Simulation Facilities* p 135
[14] Bretthauer B, Meier G and Stasicki B 1991 An electronic Cranz–Schardin camera *Rev. Sci. Instrum.* **62** 364–8
[15] Kaehler C and Kompenhans J 1999 Multiple plane stereo PIV—technical realization and fluid-mechanical significance *Proc. Int. Workshop on PIV* p 281
[16] Hu H, Saga T, Kobayashi T, Taniguchi N and Yasuki M 2001 Dual-plane stereoscopic particle image velocimetry: system set-up and its application on a lobed jet mixing flow *Exp. Fluids* **31** 277–93
[17] Shinohara K, Sugii Y, Aota A, Hibara A, Tokeshi M, Kitamori T and Okamoto K 2004 High-speed micro-PIV measurements of transient flow in microfluidic devices *Meas. Sci. Technol.* **15** 1965–70
[18] Veledar O, Byrne P, Danaher S, Allen J, Thompson L and McMillan J 2007 Simple techniques for generating nanosecond blue light pulses from light emitting diodes *Meas. Sci. Technol.* **18** 131–7