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APPLICATION OF SCHLIEREN TECHNIQUE IN ADDITIVE MANUFACTURING: A REVIEW

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1. Abstract

Additive manufacturing has gained a lot of attention in the past few decades due to its significant advantages in terms of design freedom, lower lead time, and ability to produce complex shapes. One of the pivotal factors affecting the process stability and hence the part quality is the shielding gas flow in additive manufacturing. As extremely beneficial for the process, the shielding gas flow is often set at maximum supply to achieve enough gas cover over the substrate. This causes excessive quantity of shielding gas to be unutilized. Realizing the importance of shielding gas, various studies have been carried out to monitor and visualize the shielding gas, and one such technique is Schlieren imaging. Schlieren visualization has been used since the 1800s as a powerful visualization tool to visualize fluctuations in optical density. The Schlieren technique is highly effective for visualizing and optimizing shielding gas flow. This paper aims to provide an overview of Schlieren technique used for visualization of shielding gas and highlights the application of Schlieren in additive manufacturing.

2. Introduction

Additive Manufacturing (AM) is the process of joining materials to make objects from 3D model data, usually layer upon layer [1] and has been in use since the 1980s. AM technology has since undergone over three decades of growth and is currently one of the world's fast-growing advanced manufacturing techniques [2]. The development in additive manufacturing over the past three decades can be classified into three major phases. In its initial phase, it was used as a tool to create prototypes and models, mainly utilized by product designers. AM's second developmental stage involves its application to create completed components (also termed as ‘direct digital manufacturing’). In the third stage, 3D printers are used widely available for use to direct customers at a reasonable price point [3]. As material is deposited layer upon layer, additive manufacturing can produce components of complex parts which cannot be easily manufactured by using conventional methods of manufacturing [4].

Schlieren technique has been in use for about two centuries for imaging and analyzing phenomena in transparent media. The Schlieren method has been commonly used to visualize gas flows in varied applications such as vehicle aerodynamics, ballistics, ventilation methods etc. [5]. This method is particularly helpful for imaging as it generates a natural, easy-to-interpret image of refractive index-gradient fields. Shadowgraph and interferometry are the companions of Schlieren technique, but Schlieren has proven to be more sensitive and better suited for quantitative visualization [6]. Over the years, the Schlieren technique has undergone significant changes, and the latest technology has enabled Schlieren to be applied in advanced research topics. With advanced softwares and digital imaging techniques, the capability of the Schlieren technique has been significantly strengthened. Schlieren has recently been used to visualize the shielding gas flow in various advanced manufacturing techniques. Several vital findings related to nozzle design, gas flow and part quality have been made through the application of Schlieren technique. This paper provides an overview of the Schlieren technique, it's evolution and application of Schlieren technique in AM.

3. Discussion

3.1 Evolution of Schlieren

Schlieren optical imaging system was introduced in the 1800s by Robert Hooke [5]. Schlieren optics proved to be a sound technique for visualizing transparent media [7]. With his rudimentary instruments, Hooke explained the light refraction due to density gradient in his book Micrographia [8]. The knife edge, which is now an important part of the setup to cut off the diffracted rays and increase the sensitivity of the device was introduced by Leon Foucault in the mid-19th century [5,9]. August Toepler, between 1859 and 1864, reinvented Schlieren technique and was given official recognition for this. He studied and proposed theories of Schlieren technique and provided in-depth procedures for designing a Schlieren system [10].

3.2 Basic concepts of Schlieren

The Schlieren technique is based upon the Snell's Law [5,10], which states that light travels with different speeds in different media. While encountering different media in its path, light rays get refracted, and deflect from their original path resulting in Schlieren images [10]. The refractivity (n-1) of any fluid is given by:

$$n-1=\kappa\rho \qquad \text{Equation (1)}$$

where, n is the ratio of the speed of light in vacuum ($3x10^8$ m/s) to the speed of light in the medium. κ is Gladstone Dale coefficient and is about 0.23 cm^3/kg of air in standard conditions and ρ is the density of the fluid.

In a Schlieren setup, (considering a Z type setup as an example), the light produced from the light source passes through one mirror, enters the given medium and then gets refracted. This light beam again passes through the second mirror and reaches the knife edge. As the image has been diffracted by the medium, there would be a shift from its original position as shown in Figure 1. The expression for the shift is given by:

$$\Delta a = f \cdot \varepsilon \qquad \text{Equation (2)}$$

where, f is the focal length of the second mirror and ε is linear in the y component of refraction angle E in the Schlieren object [5]. It can be inferred from the above equation that as the focal length of the mirror used increases, the Δa value increases. Also, as the distance between the two mirrors increases, the y component of the refraction angle increases, thereby increasing the Δa value. A greater value of Δa leads to greater diffraction which produces a higher degree of sharpness in the Schlieren image.

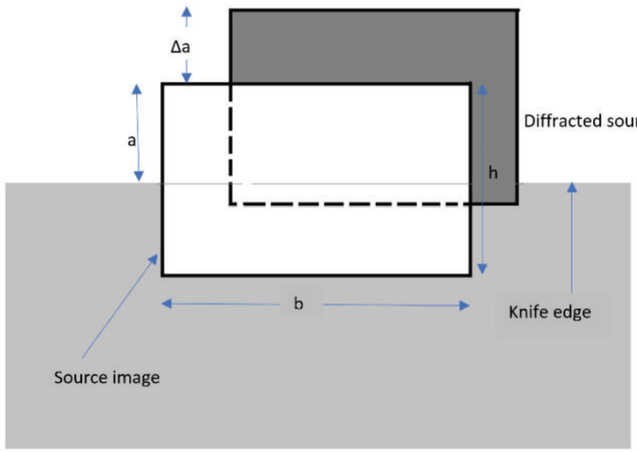

Figure 1: Image of the knife edge plane

3.3 Factors Influencing Image Quality in Schlieren:

3.3.1 The orientation of the slit

To obtain a parallel light beam in the experimental section after getting reflected from the mirrors, an aperture or slit is positioned just in front of the light source [11]. The brightness of the picture obtained from the Schlieren technique is determined by the slit orientation as shown in the Figure 2. There are three orientations of the slit available: vertical, horizontal, and iris. According to Siewert et al. [12], the iris can be used to visualize density gradient in all directions, but the images are characterized by a lower brightness of the image. Evaluation of the geometry influence and slit orientation makes it clear that images with high clarity can be obtained with slits perpendicular to the work piece. It is also recommended that, when working with identical concave mirrors, the shape of the light source must match with the shape of the slit opening. While using an iris as a slit, an LED as a light source would give best results (as LED produces circular beam of parallel light) and while using a vertical slit opening, an elongated rectangular light source is preferable.

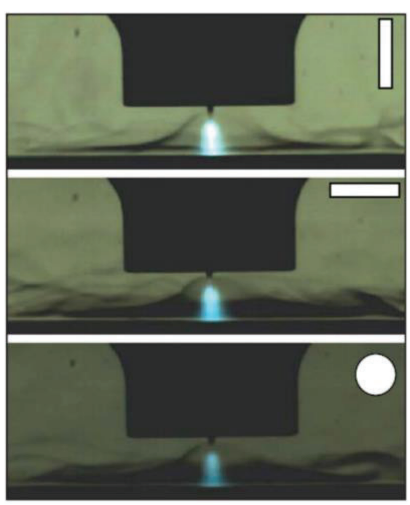

Figure 2: Impact of slit orientation on image brightness. Reproduced with permission from Welding Journal, (January 2014), © American Welding Society

3.3.2 Slit Size

In a Schlieren setup the amount of light entering the system is governed by a slit placed just in front of the light source. With the reduction of the slit width, a lower amount of light would enter the system and hence lesser amount of light would be diffracted. This leads to visualization with lesser variation between density of the components. The sensitivity and measurement range of the Schlieren system are determined by the size and shape of the source slit [5]. The main objective of the slit size variation (specifically in the applications of Schlieren in additive manufacturing processes) is to visualize the type of flow of the shield gas from the nozzle [12]. Siewert et al observed that with the decrease in slit size, the radiation from the arc decreases as depicted in Figure 3 [12]. It can be noted that the brightness of the welding arc increases as the slit size increases (from left to right), because with increase in the slit size, greater amount of light enters the system.

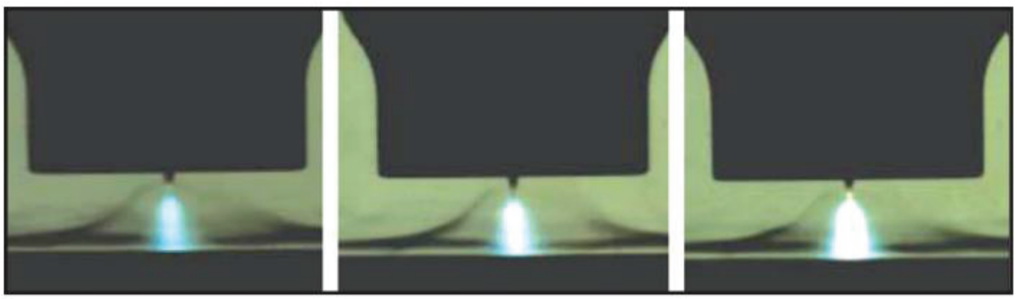

Figure 3: Schlieren aperture slit of 2 × 6 mm (left), 3 × 6 mm (middle), and 5 × 6 mm (right). Reproduced with permission from Welding Journal, (January 2014), © American Welding Society

3.3.3 Color Schlieren

Color Schlieren technique has been widely used since 1985, and it plays a vital role in visualization of the shielding gas in the recent times [13]. Significant advancements in technology has made color Schlieren more robust. Wolter et al. notes that color Schlieren images signifies vector displacements and the angle in the cutoff plane whereas grayscale images are limited to signifying the scalar quantity [14]. The color has an added advantage of sensitivity and hue saturations and color intensity, that can be used for quantitative analysis of the image. In grayscale images, the contrast is uneven while the color images are evenly balanced. It offers additional dimensions when needed to encode the characteristics and enhance the contrast of the data presented. Color Schlieren uses a color-grid cutoff in the place of the traditional knife-edge to produce images with hue variations in place of grayscale values [15]. According to Siewert et al [12], among the four filters of colors (blue, yellow, red, and green), the pair of two colors: blue/yellow and red/green makes the best pair. These enabled turbulences to be visualized with a greater contrast as shown in Figure 4.

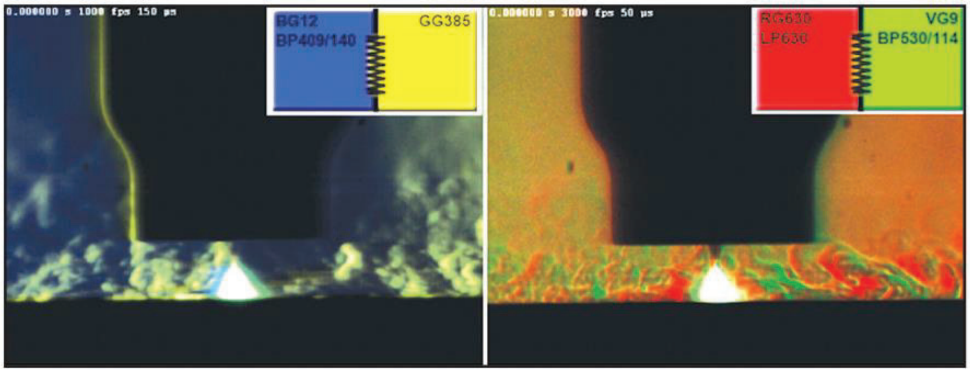

Figure 4: Schlieren images, used filter pairs: blue/yellow (left) and red/green (right). Reproduced with permission from Welding Journal, (January 2014), © American Welding Society

3.4 Recent Developments in Schlieren Technique

3.4.1 The Camera

Traditional cameras with high speed drum, bulky size, rotating mirror and rotating prism have been replaced by the modern digital high speed cameras, reaching up to 2000 frames per second (fps) and with CMOS sensor capabilities [16]. Schlieren technique that's completely based on visualization has also undergone a technological shift. The technique which was resolute to visualization of simple candle plumes is now able to capture images of shock waves produced by a bullet and sonic booms produced by a supersonic airplane. The new era of Digital Single Lens Reflex (DSLR) have completely replaced the SLR cameras with their ease of use and their image clarity. The light source being highly intense in a Schlieren setup, Schlieren images do not need the same exposure that a traditional photograph image would require [16]. Also, the SLRs required a film to store the image and a dark room to publish a photograph. To eliminate this time loss, DSLR comes up with immediate results of the test shots making the Schlieren setup more user friendly. The color balance that once needed numerous films, can be now performed right through the camera. A wide variety of interchangeable lenses are available for the DSLR cameras making the camera more efficient and the lenses have outboard focusing feature which eliminates the use of additional lens.

3.4.2 LED as a light source

The light source for the Schlieren technique consisted of spark gaps, lasers, xenon tubes, arc lamps and incandescent filament lamps in the 20th century [5]. Light Emitting Diode (LED) was in its nascent stages of development back then. By 2000s, LEDs had advanced tremendously and was being used for numerous scientific applications [17]. The LEDs stood as a non-coherent light emitter and an inexpensive light source alternative for Schlieren technique. The narrower the light source is, the sharper would be the image produced [16], and hence LED stands as a great option, as it can effectively produce a light beam of 15^{o}. Focusing it directly onto the first Schlieren lens or the mirrors can eliminate the need for condenser and a slit [18]. Spark gaps, which were considered as a light source earlier were hazardous to use, more expensive and not durable [19]. The LED source offers both alignment and high-speed imaging pulsed output. Only a laser source could provide a pulse width enough to freeze the motion earlier for PIV and Schlieren velocimetry applications [16]. However, lasers posed eye safety hazards and hence LEDs replaced them as a reliable and robust light source for Schlieren imaging.

3.4.3 Background oriented Schlieren

The most significant recent developments in this domain is certainly the background-oriented Schlieren. Unlike a conventional Schlieren setup, background oriented Schlieren eliminates the use of expensive mirrors, lasers and the knife edge [20]. It uses a background with a lot of fine detail. Light from the light source falls on the background film, which then passes through Schlieren S (any substance which has a different density than air and is able to diffract the light) placed in the test area as shown in Figure 5 and is then visualized using a camera. Using digital imaging software, the two images (one with Schlieren S placed and the other without) are compared and the disturbances caused by the diffraction are captured [16]. A small spot on the background seen as the dashed line in Figure 5, is shifted by refraction by the media. The shift Δy can be calculated by comparing images of the background, with and without the medium in the test area. The deflection angle can be calculated after measuring Δy and hence the density of the medium is known.

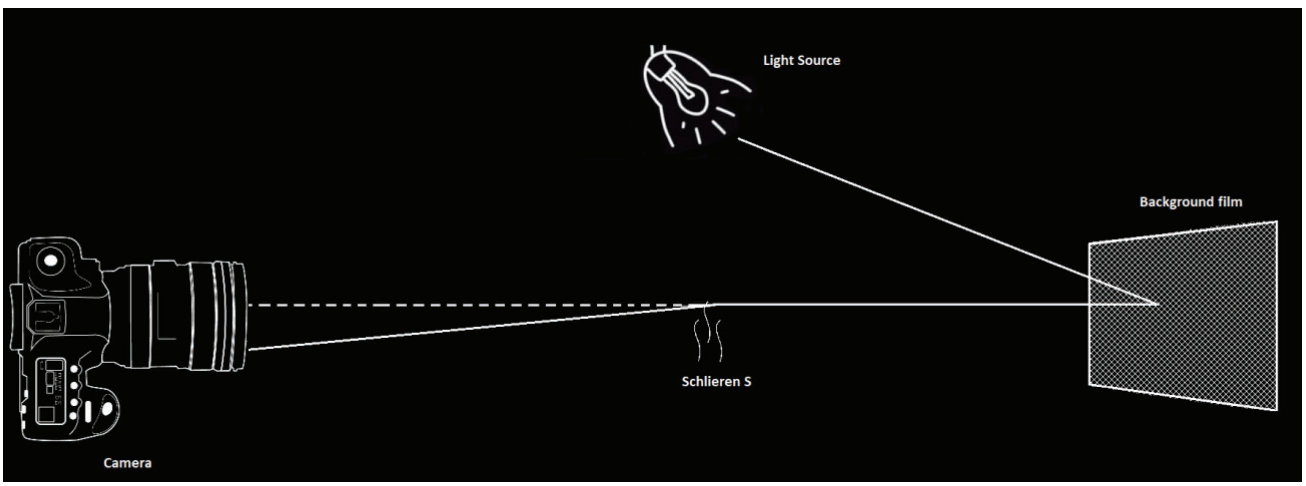

Figure 5: Schematic diagram of Background Oriented Schlieren

As most portions of the traditional Schlieren setup are eliminated, the background oriented Schlieren is inexpensive, small, and accurate. This technique can be combined with particle image velocimetry (PIV) as well to produce visualizations [21]. Another added advantage that this technique has is that it produces a field of view which cannot be achieved in conventional Schlieren methods. The field of view can be at least half the size of the background [16] and large objects like helicopters or supersonic aircraft can be visualized using wide natural background [22] as shown in Figure 6.

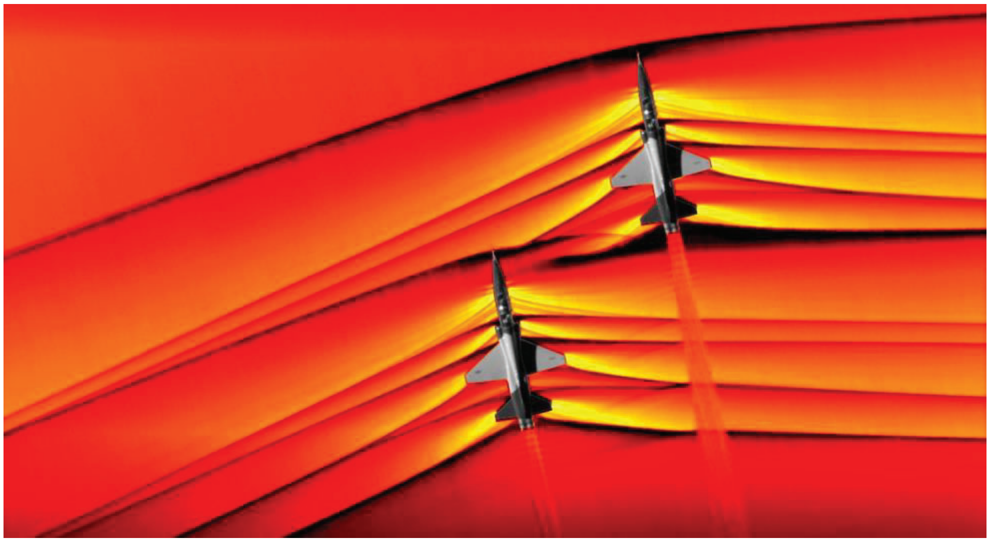

Figure 6: Use of Schlieren technique for measuring the strength and position of shockwaves caused by supersonic planes. Image reproduced from NASA.

3.5 Schlieren In Additive Manufacturing

Non-thermal atmospheric-pressure plasma jets are gaining a lot of attention as a promising tool for additive manufacturing [23]. Instead of using a large nozzle for the shielding gas, micro capillaries have emerged as alternatives for localized processes. The dynamics of gas outside the capillaries and the behavior of the charged particles towards the inert gas are pivotal in deciding the efficiency of the capillaries. Hence, to design and control such micro plasma jets, a closer look on the functioning and understanding the plasma and gas-surface interaction is essential.

As the micro jets are invisible to the human eye or a normal DSLR, Schlieren technique is being used to determine the flow from the micro plasma jets [23]. In the study by Bradley et al. [23], it was observed from the Schlieren images that the micro jets maintained a laminar flow up to 54 mm from the nozzle and then the outflow turned into turbulent. The regions of laminar and turbulence flow can be easily distinguished as indicated in Figure 7. Hence Schlieren technique can be effectively used in applications which require the type of flow to be studied.

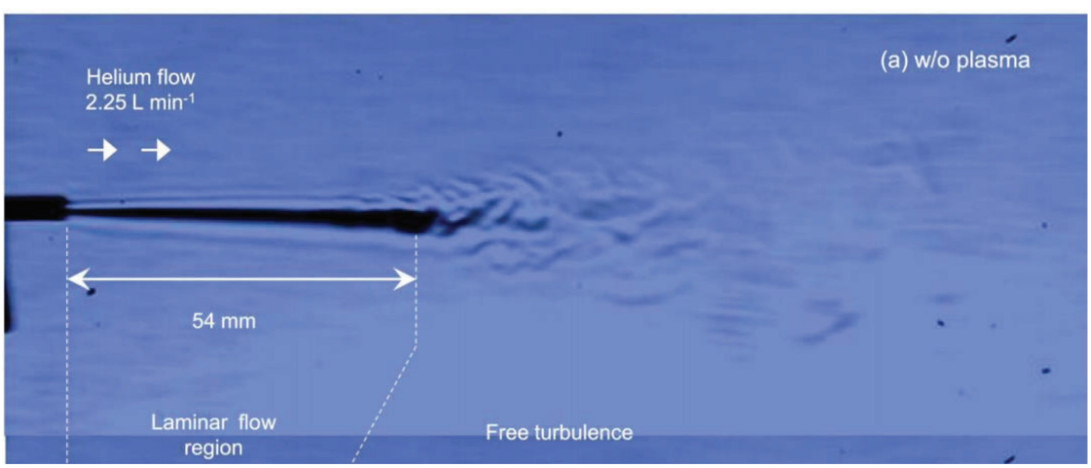

Figure 7: Schlieren image showing the variation in flow from a nozzle.

Anilli et al. in [24] used selective laser melting (SLM) to produce single and double chambered laser cutting nozzles. SLM nozzles can be lightweight, have inner channels and can be created in any complex shapes. Nonsymmetrical nozzles have also gained attention in recent years and these can't be manufactured by using conventional manufacturing methods and hence additive manufacturing stands as a solution to this problem [25]. Anilli et al. used gas atomized 18Ni300 maraging steel powder for the producing nozzles using additive manufacturing for the experimentation. A conical convergent single chamber and corresponding double chamber nozzles of 1 mm size were manufactured as shown in Figure 9. The gas flow through these nozzles was then tested using Schlieren imaging technique. The setup consisted of five mirrors, diffracting more light than a conventional z type Schlieren setup as shown in Figure 8.

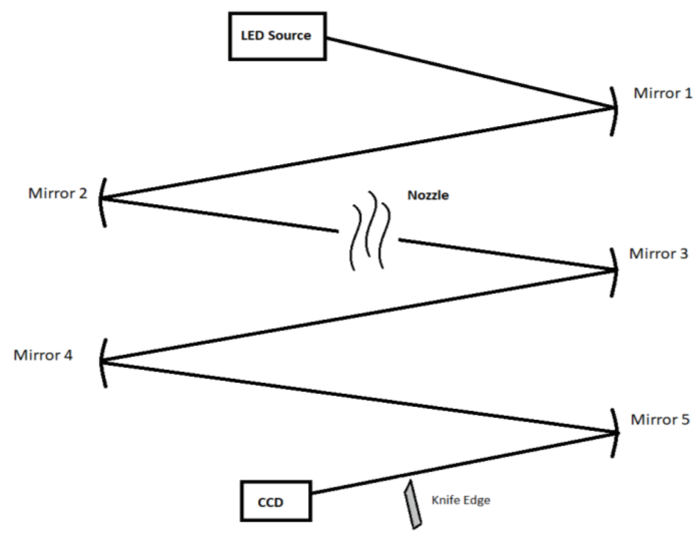

Figure 8: Schematic diagram of the Schlieren setup.

Figure 9 Axial section of conical convergent single chamber (a) and corresponding double chamber nozzle (b)

The light source which was chosen for the experimentation was a white LED. With the help of Schlieren imaging, the gas flow dynamics in stationary conditions were studied at 15 bar of pressure. Three nozzles: standard, SLM as built, and SLM post processed were tested using Schlieren technique.

It was observed in a standard nozzle that a bell-shaped shock wave front which collapses to a transverse shock wave, making the first part of the flow separated. Considering the SLM as built nozzle, the bell shape was maintained and had retracted closer to the nozzle. This was due to the irregularities in the inner surface of the nozzle and irregular profile of the manufactured hole. Hence to achieve a smoother profile, the nozzles had undergone finishing through electrochemical machining (ECM) and abrasive flow machining (AFM). In the case of the post processed nozzle, whose inner surfaces were smoothed also with a more regular hole size, the flow resembled that of the standard nozzle. From the results of Schlieren visualization, it was concluded that nozzles made from SLM required post processing. The inner surface and the roundness of the hole play a substantial role in nozzle production. Here Schlieren technique played a crucial role in determining the optimal nozzle specification, the nozzles that had been subjected to post processing have met the desired performance. It was also found that AFM using SiC as abrasive particles was an adequate solution for improving nozzle tip quality as it reaches the effective processing pressure at the nozzle tip

Shielding gases are fundamental components of several arc welding components. Though the main role of the shielding gas is to protect the melt pool against atmospheric gases, it also acts as a medium for the flow of electrical current between the electrode and the workpiece in the plasma jet. Though most of the shielding gases consist of inert gases such as argon, adding other gases such as carbon dioxide, oxygen or helium, improves arc formation, heat transfer, material weld ability or gas coverage [26]. Several other benefits such as refinement of weld structure and thus improving the mechanical properties of the weld were noted by pulsing the shield gas [27,28]. The dynamics of melt pool are affected by alternating the shield gases [29]. The effects of alternating argon and helium in Gas Tungsten Arc Welding (GTAW) were visualized through Schlieren imaging, and the arc characteristics and flow rates were analyzed by contrasting the image sequences of pure and premixed gas flows [26].

Bitharas et al. in [26] studied the use of alternating shielding gas flow in GTAW. In this study, it was noted that pure argon diffracted lesser light than helium. Being heavier than air, argon at 5 l/min spread out from the nozzle and covered the work piece, hence preventing it from oxidation. At a higher flow rate of 10 l/min, argon formed eddies near the workpiece mixing with the surrounding air.

In the case of pure helium, large dark patches were found in Schlieren images in hot as well as cold conditions. Unlike argon, lesser vortex formations were observed in the case of helium due to higher viscosity and greater buoyant forces. Helium comparatively covered larger surfaces of the workpiece than argon. 50% duty cycle which refers to switching argon and helium alternating for equal intervals of time was used at the time of experimentation. Two switching sequences: 2 Hz and 8 Hz were investigated in this study. With the help of Schlieren technique, it was observed that, images of 8 Hz were brighter than images of 2 Hz.

As it can be noted from the above examples: the type of gas flow, nozzle design and shielding gas, are all important parameters for additive manufacturing applications. Schlieren technique hence can be used as an effective means to monitor and control these parameters to produce a higher quality additive manufactured component.

4. Summary and Conclusion

This paper provides an overview of the Schlieren technique, evolution of Schlieren, and application of Schlieren in AM. Though Schlieren has been in practice since the 1800s, the latest digital technology has propelled the rapid evolution of this technique. Orientation and slit size are amongst the pivotal factors in Schlieren that influence the clarity of the image produced. With the advent of DSLR cameras, the experience of Schlieren imaging has turned more robust and user friendly. LEDs are being considered as a viable alternative to the conventional arc lamps and laser sources due to their ability to act as a narrow light source, hence producing images with better clarity. Schlieren imaging has been utilized to determine the type of flow, nozzle design applications and alternating shielding gases - all of which are important parameters from additive manufacturing standpoint. Hence, Schlieren can be used as a powerful tool for controlling key parameters to produce high quality components for additive manufacturing applications.

References

1. J. Alcisto, A. Enriquez, H. Garcia, S. Hinkson,T. Steelman, E. Silverman, P. Valdovino, H. Gigerenzer, J. Foyos, J. Ogren, J. Dorey, K. Karg, T. McDonald, and O.S. Es-Said, “Tensile Properties and Microstructures of Laser-Formed Ti-6Al-4V”, JMEP, 2011, vol. 20(2), pp.203–212.
2. D. D. Gu, W. Meiners, K. Wissenbach and R. Poprawe, “Laser additive manufacturing of metallic components: materials, processes and mechanisms”, International Materials Reviews, 57:3, 133-164, 2012.
3. Mojtaba Khorram Niaki and Fabio Nonino, “Additive manufacturing management: a review and future research agenda, International Journal of Production Research”, 55:5, 1419-1439, 2017, DOI: 10.1080/00207543.2016.1229064
4. E. Herderick, Additive Manufacturing of Metals: A Review, Proceedings of MS&T_11, Additive Manufacturing of Metals, Columbus, OH
5. Settles G S 2001 *Schlieren and Shadowgraph Techniques: Visualizing Phenomena in Transparent Media* (Berlin: Springer)
6. Full-Scale Schlieren Flow Visualization - Gary S. Settles†, Elizabeth B. Hackett†, James D. Miller†, and Leonard M. Weinstein, Proc. Intl. Symposium on Flow Visualization,

September 11-14, 1995, Seattle, Washington: Flow Visualization VII, ed. J. P. Crowder, Begell House, New York, Sept. 1995, pp. 2-13

7. H. G. Taylor and J. M. Waldram, “Improvements in the schlieren method,” Journal of Scientific Instruments, vol. 10, no. 12, pp. 378–389, 1933
8. Hooke, R. *Micrographia.* J. Martyn & J. Allestry, London,1665.
9. S. Mitra, M. Chaskar, and S. Phadke, “Design and fabrication of a simple schlierenscope,” American Journal of Physics, vol. 49, no. 2, pp. 158–161, 1981
10. *Amrita Mazumdar “Principles and Techniques Of Schlieren Imaging Systems”* Columbia University July 18, 2013
11. *NASA*, NASA, www.grc.nasa.gov/www/k-12/airplane/tunvschlrn.html.
12. Siewert, Erwan & Wilhelm, Gerald & Hässler, M & Schein, Jochen & Hanson, T & Schnick, M & Füssel, U. (2014). Visualization of Gas Flows in Welding Arcs by the Schlieren Measuring Technique The influence of typical welding parameters on the gas flow for the GTAW, GMAW, and PAW processes is demonstrated using the high-speed Schlieren technique. Welding Journal. 93. 1S-5S.
13. Settles, G.S Colour-coding schlieren techniques for the optical study of heat and fluid flow. *International Journal of Heat & Fluid Flow,* **6**(1):3-15, 1985
14. Wolter, H. Schlieren, Phasencontrast, und Lichtschnittverfahren. *Fundamentals of Optics, Handbuch der Physik* Vol. 24, Springer-Verlag, Berlin,pp.555-654, 1956.
15. Settles, Gary S, and Michael J Hargather. “A Review of Recent Developments in Schlieren and Shadowgraph Techniques.” *Measurement Science and Technology*, vol. 28, no. 4, 2017, p. 042001., doi:10.1088/1361-6501/aa5748.
16. Settles, G. S., Hargather, M. J., "A review of recent developments in schlieren and shadowgraph techniques," Measurement Science and Technology
17. Yam, F.K, and Z Hassan. “Innovative Advances in LED Technology.” *Redirecting*, 22 Dec. 2004, doi.org/10.1016/j.mejo.2004.11.008.
18. Willert C E, Stasicki B, Klinner J and Moessner S 2010 Pulsed operation of high-power light emitting diodes for imaging flow velocimetry Meas. Sci. Technol. 21 075402.
19. Fuller, P. Shock Waves (1999) 9: 353. https://doi.org/10.1007/s001930050196
20. “Background-Oriented Schlieren Technique.” *Wikipedia*, Wikimedia Foundation, 22 May 2018.

21. H Richard and M Raffel. "Principle and applications of the background oriented schlieren (BOS) method" Measurement Science and technology, vol. 12, no. 9, 2017, doi: 10.1088/0957-0233/12/9/325
22. Heineck J T, Banks D, Schairer E T, Haering E A and Bean P 2016 Background oriented schlieren (BOS) of a supersonic aircraft in flight AIAA J. submitted (AIAA Paper 20163356) (doi:10.2514/6.2016-3356)
23. Bradley, James W., et al. "Schlieren Photography of the Outflow from a Plasma Jet." *IEEE Transactions on Plasma Science*, vol. 39, no. 11, 2011, pp. 2312–2313., doi:10.1109/tps.2011.2157940.
24. Anilli, Marco, et al. "Additive Manufacturing of Laser Cutting Nozzles by SLM: Processing, Finishing and Functional Characterization." *Rapid Prototyping Journal*, vol. 24, no. 3, 2018, pp. 562–583., doi:10.1108/rpj-05-2017-0106.
25. Anilli, Marco, et al. "Additive Manufacturing of Laser Cutting Nozzles by SLM: Processing, Finishing and Functional Characterization." Rapid Prototyping Journal, vol. 24, no. 3, 2018, pp. 562–583., doi:10.1108/rpj-05-2017-0106.
26. Bitharas, I., Campbell, S., Galloway, A., McPherson, N. and Moore, A. (2016). Visualisation of alternating shielding gas flow in GTAW. *Materials & Design*, 91, pp.424-431.
27. B.Y. Kang, Y.K.D.V. Prasad, M.J. Kang, H.J. Kim, I.S. Kim, The effect of alternate supply of shielding gases in austenite stainless steel GTA welding, J. Mater. Process. Technol. 209 (2009) 4722–4727.
28. O.M. Novikov, A.S. Persidskii, E.P. Rad'ko, A.V. Baranovskii, B.A. Khasyanov, Effect of changes in the composition of the gas shielding medium on the properties of arc welded joints in aluminium alloys, Weld. Int. 27 (2013) 222–225, http://dx.doi.org/10.1080/09507116.2012.715891
29. S.W. Campbell, A.M. Galloway, N.A. McPherson, Techno-economic evaluation on the effects of alternating shielding gases for advanced joining processes, Proc. Inst. Mech. Eng. B J. Eng. Manuf. (2011), http://dx.doi.org/10.1177/0954405411408353 (0954405411408353).