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# Noise Emissions in Thermal Spray Operations

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**Acoustic noise generation is an accompanying effect produced during thermal spraying. This type of noise is found both during the preparatory stages, such as grit blasting and compressed air cleaning, and during thermal spraying. A real-time noise meter was used to measure the noise level at frequencies between 63 and 8000 Hz during the operation of powder flame, wire flame, wire arc, air plasma, and high velocity oxygen fuel (HVOF) spraying processes. Noise was reported as either an A-weighted noise spectrum or an equivalent sound pressure level. The effect of different parameters, such as secondary plasma gas type, modes of wire flame torch operation, and use of compressed air cooling were investigated. The results indicated that the turbulence of the gas departing from the torch gives rise to jet noise. High gas flows mainly contributed to the lower frequencies, whereas combustion and plasma generation contributed to the higher frequencies. Noise level was the highest (123 dB(A)) with HVOF spraying and air plasma spraying with the use of a small-diameter nozzle and hydrogen as a secondary plasma gas. All manual operators of thermal spray equipment require hearing protection. The use of different hearing protection devices is discussed and the attenuation provided by each device is reported.**

**Keywords** earplugs, noise emissions hearing protection, safety

## 1. Introduction

Acoustic emissions are generated in response to the release of energy. This has been used as a means of detecting crack initiation and propagation in thermally sprayed materials. Much attention has been directed to the use of this technique for studying the failure of thermal barrier coatings.[1] A high response time is necessary for these types of measurements to have application in the interpretation of coating failure.

Acoustic emissions are also produced during thermal spraying. The introduction of thermal spraying with powder flame spraying produced relatively low noise levels. As spraying processes have developed, it was realized that higher temperatures and gas flows were required to produce a more adhesive coating with lower porosity. These process improvements have led to higher noise levels, and thus the containment of noise has become more important.

The most complex of these is plasma spraying where the arc length constantly changes to produce small variations in the plasma.[2] Use of a high frequency response rate in studying the noise emissions during plasma spraying may provide some insight into the mode of plasma operation. Typical noise measurements in this article consist of a narrower frequency range and a slower response rate to provide a fundamental understanding of noise emissions from thermal spray operations.

### 1.1 Characteristics of Noise

The terms *noise* and *sound* are used interchangeably. Sound is descriptive of useful communication or music, whereas noise represents undesired acoustic emissions. Sound consists of various tones at different frequencies and intensities. Each tone is described by the frequency of the sound wave. Loudness can then be interpreted by the intensity of the tone. By combining a variety of tones, each with a different intensity, it is possible to produce a collection of sound vibrations. The audible range for detecting these sounds in young people lies between 20 and 20 000 Hz. Some examples of the frequency range for various sound sources and the hearing region are shown in Fig. 1.

The human ear has an ability to detect a wide range of sound pressures, ranging from $20 \times 10^{-6}$-20 Pa, typical of noise in some working environments.[3] Measurement of sound intensities would be difficult to conduct accurately using a linear scale, and so a logarithmic scale is used to more closely replicate the response of the human ear.

The decibel (dB), a unit without dimensions, is the logarithm of the ratio of a measured value to a reference quantity. Both the measured and reference sound pressures are measured as root mean squared quantities. The reference sound pressure is $20 \times 10^{-6}$ Pa for sound measurements in air at standard temperature and pressure. The sound pressure value is then calculated according to Eq 1, where the sound pressure is reported with the units of Pa.

$$L_p = 20 \log \frac{p}{p_0} \text{ dB} \qquad \text{(Eq 1)}$$

A direct correspondence of sound pressure values to the sound pressure level in decibels is provided in Fig. 2. This relation shows that doubling the sound pressure ($p$) is equivalent to a 6 dB increase in sound pressure level ($L_p$). The human ear can just detect a sound level change of 1 dB. In terms of power, sound at 2 kHz is just audible at $10^{-12}$ W by a sensitive ear. If this energy were converted to heat at the same rate, it would take 300 million years to raise 1 g of water by 1 °C.[4]

Human perception of loudness also conforms to a logarithmic scale; a 10 dB increase is perceived as about a doubling of

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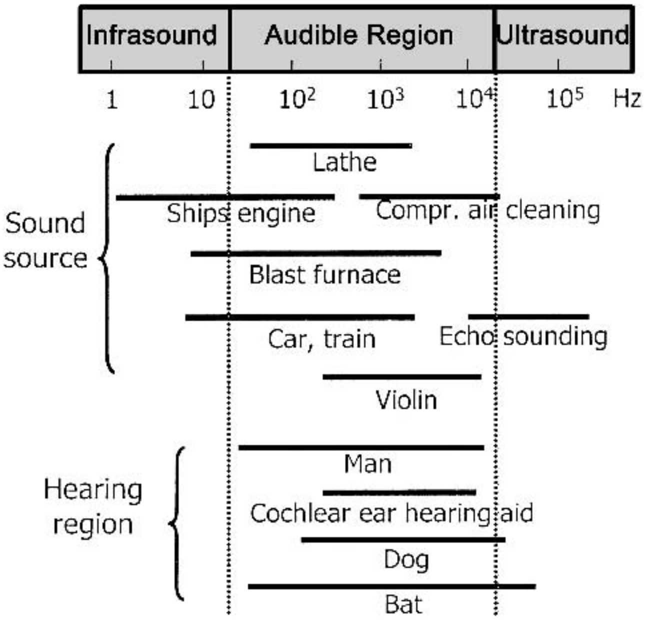


**Fig. 1** Frequency range for various sound sources and the range of perception (modified from Ref. 2)

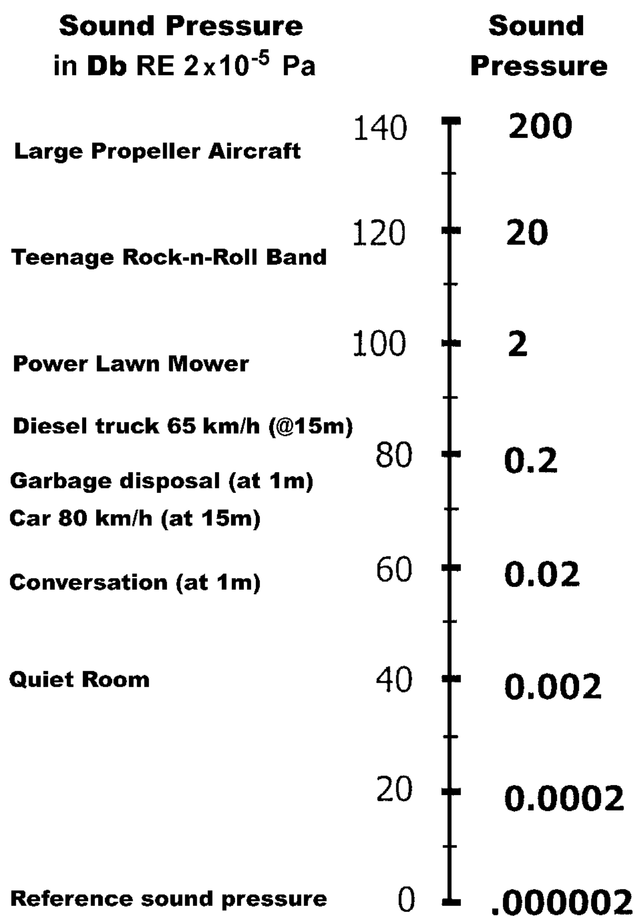


**Fig. 2** Relation between sound pressure in pascals and sound pressure level in decibels compared with 20 μPa

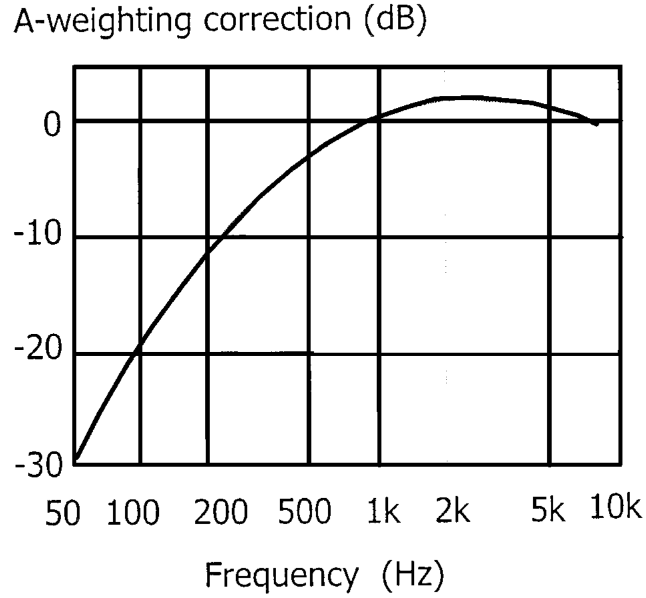


**Fig. 3** The weighting applied to sound pressure levels to replicate the reception of sound by the human ear

loudness. Thus, 30 dB is 10 times more intense than 20 dB and sounds twice as loud.

### *1.2 Measurement of Noise*

The human ear exhibits a nonuniform sensitivity across the range of frequencies. To ensure that the noise can be measured at the same sensitivity as the ear, a filter is built into the measuring instrument with a similar frequency response. This is called an A-weighting filter and conforms to an international standard.[5] Three other weighting filters are also available: B, C, and D.[6] The use of D-weighting is limited to noise measurements of certain aircraft and exhibits a higher sensitivity between 1 and 15 kHz. The B-weighting is also used rarely, like the D-weighting, and exhibits a similar frequency response to the A-weighting, except at frequencies lower than 1 kHZ where it is less sensitive. The C-weighting is essentially uniform in response and represents the true sound pressure as detected by the microphone. Noise measurements made with the use of A-, B-, or C-weighting are referred to as A-weighted, B-weighted, or C-weighted sound levels. The weighting factor is usually included in parentheses to represent the type of weighting that has been applied. At least one weighting is included in a noise meter; the A-weighting is the most common.

Humans are most sensitive to sound in the middle (1-5 kHz) of our frequency perception range (where we talk and sing) and least sensitive at the bottom and top of our range (Fig. 3). The filter is able to provide an adjustment to the sound pressure level at the different frequencies. The most sensitive frequency occurs at about 3 kHz, which corresponds to the natural resonance frequency of the ear canal.[7] This increases the sensitivity of hearing within this frequency region. Below 1 kHz, the ear is less sensitive. Reference to Fig. 3 shows that our ears can tolerate 20 dB more noise at 100 Hz than noise at 1 kHz (The A-scale curve crosses the 100 Hz line at about −20 dB).

Human perception of loudness also involves additional factors such as spectral complexity, dynamic complexity, textural complexity, an individual's variable threshold level, personal preferences, and state of health of the body. Studies of industrial hearing loss have indicated that women retain better hearing sensitivity after they are exposed to the same noise. The health of the individual will also affect the sound perception. Diseases of the external and middle ear reduce the sound transmission to the cochlea and effectively function as physiologic ear protectors in the same way as earplugs and ear muffs.[8]

Because noise can fluctuate widely over a given time period, it is useful to determine an average noise level. The equivalent sound pressure level, $L_{Aeq}$, is a measurement used widely to determine the equivalent continuous sound level that would deliver the same sound energy as the actual A-weighted fluctuating sound.

### 1.3 Hearing Damage From Noise

Noise-induced hearing loss may be temporary or permanent depending on the level and frequency characteristics of the noise, duration of exposure, and susceptibility of the individual. Acceptable noise levels in industry are 85 dB(A) for a period of 8 h. For every 3 dB increase, the working time should be halved. At 94 dB(A), the allowable working time is 1 h. Longer exposure levels can cause a loss of hearing. The pain threshold is at 140 dB(A).

Hearing damage can be temporary or permanent. Temporary damage results in a reduction in sensitivity. The sensitivity can be restored within a period of about 16 h or may last for several weeks in some cases.[9] Permanent hearing loss affects the hair cells, known as cilia, within the inner ear and therefore cannot be corrected with surgical or therapeutic techniques.

Pain is not necessarily experienced before a person becomes aware that hearing damage has taken place. Awareness of noise emissions from the various thermal spray processes should be an aspect well understood by the thermal spray operators. It is the intention of this article to determine the various noise levels and frequency spectra of different processes and indicate the effectiveness of hearing protection in minimizing noise levels.

## 2. Methods

A Brüel and Kjær (Nærum, Denmark) Modular Precision Sound Analyzer (2260 Investigator) is a real-time sound analysis meter that was used for measurement of noise (Fig. 4). Because thermal spray processing involves raised noise levels, a noise detection range of 50-130 dB(A) was selected. The frequency range was fixed to 31-8000 kHz. The instrument is capable of measuring noise emission with a 1 s resolution. This function was not used. A collection time of the noise was set to 30 s to determine an average noise emission. It was noted that longer times (up to several minutes) do not make any difference in the noise signature.

Noise emissions were measured from various thermal spray operations. This included substrate preparation through to the coating operation. Both grit blasting and cleaning of loose debris from the surface with compressed air was initially measured. Grit blasting was performed with compressed air at 275 kPa passing through a 9.4 mm diameter nozzle before emanating into the grit blasting chamber. Noise was measured from a compressed air nozzle with a diameter of 2.2 mm at a supply pressure of 551 kPa. The noise meter was placed 0.4 m away to the side of the noise source. Because the emission frequency is high compared with the dimensions of the source, the sound radiated from the source will emanate more strongly in a narrow beam in front of the noise-emitting device. The directional response of the noise will be more focused as the wavelength increases to higher frequencies. Measurements taken in front of the gun will be higher and those taken behind the gun will be slightly lower.

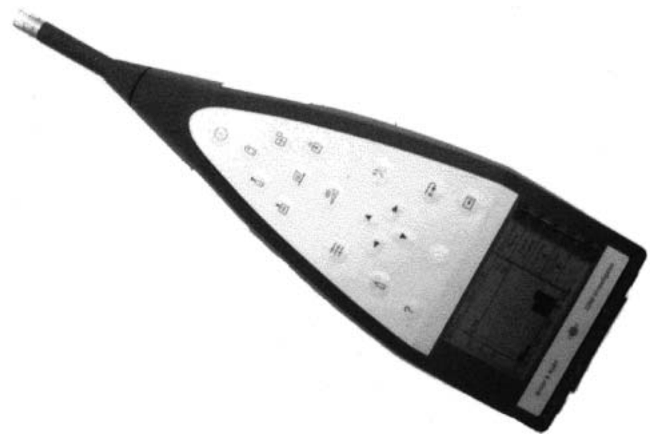

**Fig. 4** A Brüel and Kjær real-time noise measuring instrument

Sound decays exponentially. In free space, noise attenuates by 6 dB for each doubling of the distance from the noise source. In a thermal spray booth, the attenuation up to about a meter from the noise source is no more than 1 dB because of the reflection from the walls, ceiling, and equipment within the room. Noise measurements performed at 0.4 m from the gun can therefore be compared with standard measurements typically made at 1 m from the noise source.

The noise meter was placed 0.4 m alongside the equipment for measuring noise from the thermal spray devices. A powder flame spray gun (Sulzer Metco, Westbury, NY) was set to standard spraying parameters without compressed air cooling and the noise emission was measured. For wire flame spraying with a Sulzer Metco model 12E gun, the effect of compressed air supply was initially measured. With a zinc wire in place, the noise was measured in response to increasing compressed air pressures, namely 69, 173, 241, 310, 379, 448, and 517 kPa. The noise emission was then measured after a flame was established to determine the effect of the flame and the wire feeding through the flame on the noise emission.

A two-wire arc (Easi 150, Praxair Surface Technologies, Indianapolis, IN) was operated at 30 V, 140 A, and an atomizing gas pressure of 460 kPa (airflow of 850 slpm) while spraying steel and the noise was measured to obtain a comparison with the previous thermal spray operations. A parameter study was not undertaken with the two-wire arc because variation of the current values by 60 A, within the operational range of the unit, did not produce any noticeable change in noise level.

Three plasma spray torch nozzle configurations were used for spraying. Chosen spraying parameters included a typical parameter combination for spraying with a variation in secondary plasma gas flow. Conditions chosen were for deposition of a

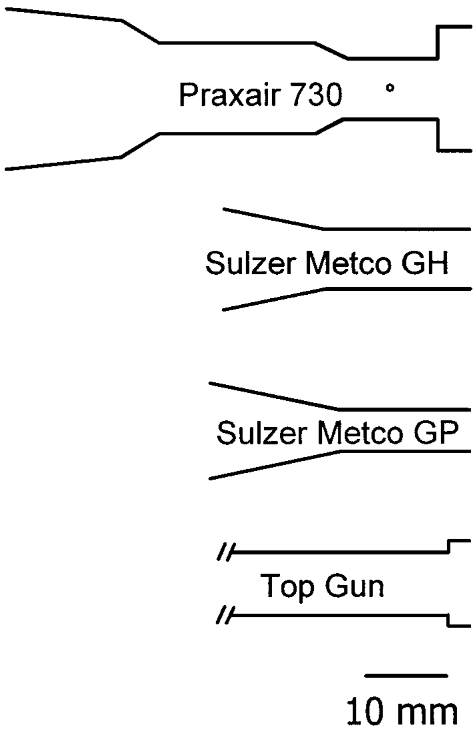


**Fig. 5** Nozzle geometry for the SG-100 730 (Praxair), GH nozzle (Sulzer-Metco), GP nozzle (Sulzer-Metco), and the end section of the Top Gun nozzle (Praxair). Gas flow is from left to right.

NiCrAl with the SG-100 torch (Praxair), alumina-titania and AlSi-polyester with the 3MB torch (Sulzer Metco) using the GH and GP nozzle, respectively. The SG-100 torch with a 730 nozzle was operated at 42 V, 750 A, an argon flow of 52 slpm, and helium flow rates of 9, 14, and 19 slpm. The 3MB torch with a GH nozzle was ignited with an argon primary gas (set to a flow rate of 38 slpm) and enthalpy increased by using different amounts of hydrogen. A flow rate of 0, 5, and 9 slpm of hydrogen while the amperage was maintained at 500 A produced voltages of 40, 60, and 70 V, respectively. The corresponding flow of hydrogen on the flow meter (Sulzer-Metco) was 0, 5, and 15 units. For comparison, a GP nozzle was used to determine the increase in frequency response. The spraying conditions were 70 V, 500 A, an argon flow of 85 slpm, and a hydrogen flow rate of 2 slpm. The nozzle geometry for these nozzles is shown in Fig. 5.

A high velocity oxygen fuel (HVOF, Praxair HV 2000) gun consumes the most gas in comparison to other processes. Cooling gas incident on the workpiece adds to the total gas consumption for torch operation. A noise measurement was made with the HVOF torch operating at 140 kPa propane, 520 kPa oxygen, and 42 kPa of nitrogen with and without air cooling jets. The supply of compressed air for cooling was at 550 kPa passing through a 5 mm diameter nozzle.

## 3. Results and Discussion

### 3.1 Noise Emission During Surface Preparation

The sound intensity emanating from the grit blasting operation was very similar to that of a compressed air gun. The grit blasting equipment used compressed air at 276 kPa and a large orifice to carry the abrasive. Grit passing through the nozzle either impacts the substrate material or the metallic walls of the enclosure. The intensity of sound produced from this operation when no substrate was being cleaned was 95 dB(A). The dominant frequency was 62 Hz, close to the frequency in the power supply. Harmonics in noise spectra are common and this could contribute to a noise component at higher frequencies.

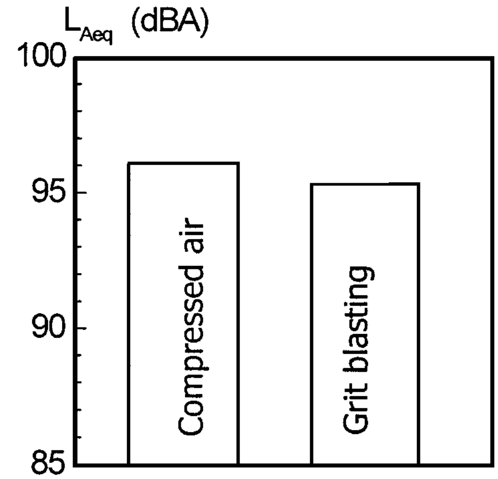


**Fig. 6** Noise emissions from grit blasting at 276 kPa and use of compressed air at 551 kPa

Use of compressed air for cleaning debris from the workpiece is typically conducted within the grit blasting enclosure to ensure that loose grit does not become airborne. The reading was taken at a supply pressure of 550 kPa. This produced a value of 96.3 dB(A) (Fig. 6). The high-pitch noise produced during compressed air use and grit blasting suggested a contribution from high frequencies. Brüel and Kjær[3] reported a range of 500-20 000 Hz for compressed air.

### 3.2 Flame Spraying

The effect of gas pressure on noise emissions was ascertained with the wire flame gun. Compared with the powder flame gun, the gas flows were higher with the wire flame gun. The major contributor to the flow was compressed air. This gas passes through a small ring-like gap around the central wire. The small gap thus produces a high velocity stream of compressed air. Even at a low supply pressure, the sound intensity is at a level of 80 dB(A). An increase in compressed gas pressure produces a linear increase in noise emissions (Fig. 7). Not surprisingly, the noise emission from the wire flame gun operating with compressed air, but without the flame and wire feed, 95 dB(A), is very close to the noise emissions from grit blasting and compressed air cleaning.

Jet noise is produced at gas velocities greater than approximately 100 m/s.[3] Gas velocity in thermal spray operations needs to be significantly higher than this value to accelerate the molten droplets toward the substrate. As compressed gas exits a nozzle, a sudden velocity change is established between the jet and the surrounding air. This generates high frequency noise from the shearing region adjacent to the nozzle and lower frequency noise from the large-scale turbulence downstream. Gas-

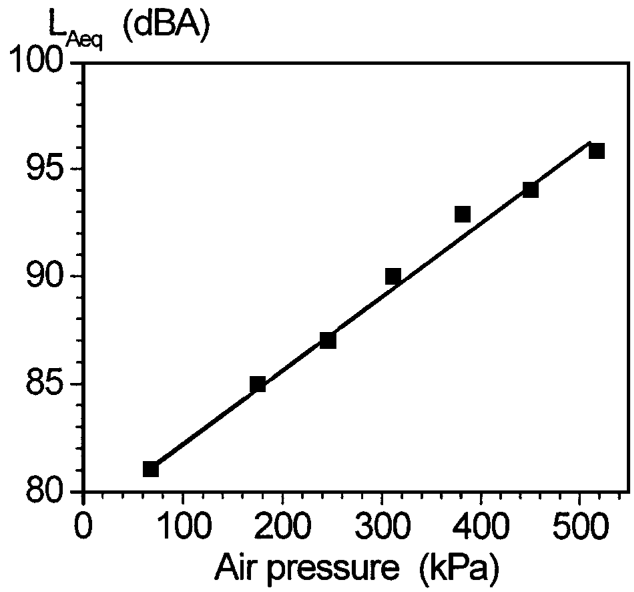


**Fig. 7** Relationship between gas supply pressure and the noise intensity produced at the nozzle of a wire flame spray process

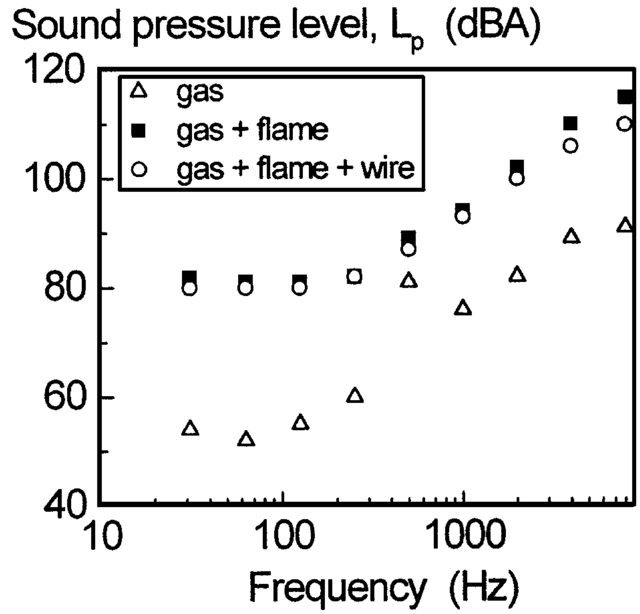


**Fig. 8** The noise emission from a wire flame spray gun with (△) compressed air, (■) compressed air and a flame, and (○) compressed air, flame, and wire feed

jet noise produces a broadband spectrum, with a higher intensity at larger frequencies.

Addition of the flame to the compressed air source increased the noise level to 117 dB(A). Combustion of acetylene with oxygen produces a higher jet velocity, steeper gas velocity gradient, and an accompanying increase in turbulence. If a metal zinc wire is passed through the flame, the noise is slightly lower at 114 dB(A). This could be attributed to a cooler flame resulting from energy uptake from the metal wire, but also to the entrained metallic droplets in the plume that decreased the turbulence arising from the liquid droplet saturated hot flame (Fig. 8).

The noise level signature shows the effect of torch operation on the different frequency emissions. It is noteworthy that the addition of wire to the flame only causes a decrease at the higher frequencies by about 4 dB(A).

In comparison, powder flame spraying uses lower gas flows, because an atomizing gas is not necessary. The noise emission arising from the powder flame was 99 dB(A), and exhibited a uniform level intensity for all frequencies above 500 Hz. The wire flame torch in comparison already showed a decrease in intensity at higher frequencies, starting at about 2 kHz.

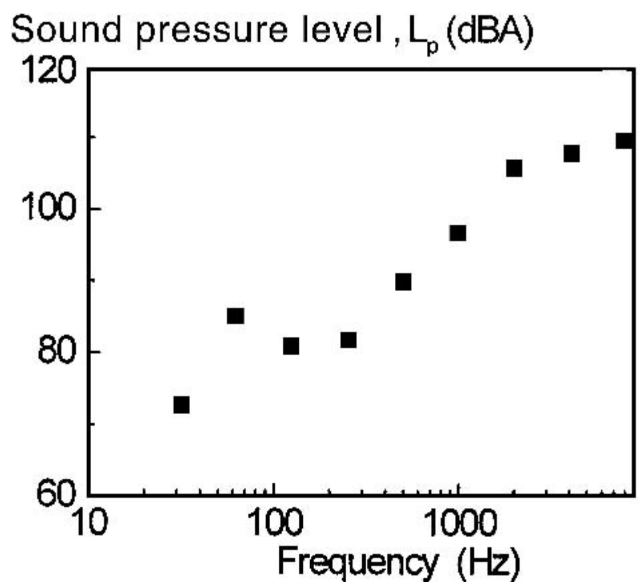


**Fig. 9** Noise emission from a two-wire arc unit in spraying stainless steel at 30 V and 148 A

### 3.3 Arc Spraying

Two-wire arc spraying produced a comparable noise signature to that of wire flame spraying (Fig. 9). The lower frequencies exhibited greater intensity, indicating that the arc contributes bass-like tones. The noise level produced was 113 dB(A). The NiAl wire was sprayed at 30 V and 148 A (4.4 kW). Noise levels of 111 and 116 dB(A) have been reported when spraying steel at conditions of 24 V and 200 A (4.8 kW), and 32 V and 500 A (16 kW), respectively.[10] These results are comparable to the results of this study. Lower power levels are needed for melting other wires such as Ni-Al and aluminum bronze, and hence the noise is typically lower by several decibels.

### 3.4 Plasma Spraying

Plasma spray torches have a larger nozzle size compared with flame spray guns to accommodate the plasma heating source. Injection of gas through the gun raises the noise to levels just under 80 dB(A).[11] In an ignited gun running at 30 kW (40 V, 750 A) with argon and helium in an SG-100 torch, the noise level is increased to an operating level of 112 dB(A). An increase of helium flow from 9-14 and then to 19 slm has a small effect on the overall noise output. Increase in flow has the most influence

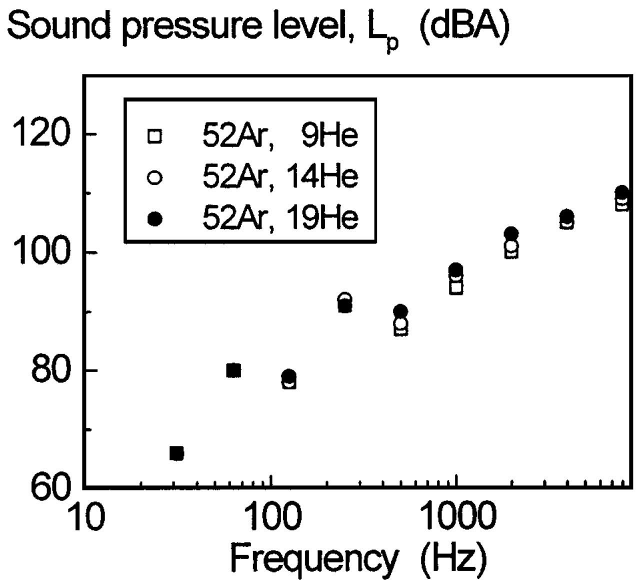


**Fig. 10** Noise emission from a SG-100 gun (Praxair) operated at increasing amounts of helium secondary gas. The corresponding noise equivalent sound pressure values ($L_{Aeq}$) are 110, 112, and 113 dB(A), respectively.

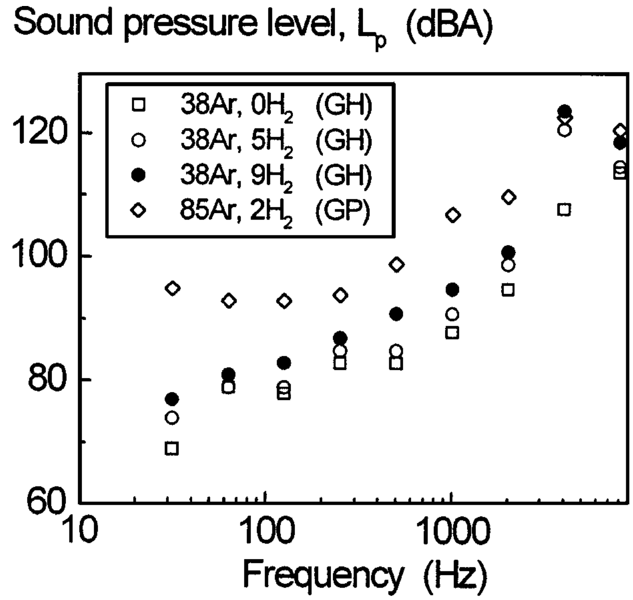


**Fig. 11** Noise emission from the 3MB plasma spray torch (Sulzer-Metco) operated at increasing amounts of hydrogen secondary gas. Nozzle type is indicated in brackets. The corresponding noise equivalent sound pressure values ($L_{Aeq}$) are 115, 123, 125, and 126 dB(A), respectively.

within the 500-2000 Hz range, producing an overall increase in noise of 3dB. The equivalent sound pressure increases from 110-112 and further to 113 dB(A).

In a 3MB torch equipped with a GH nozzle and operating with argon and hydrogen at 35 kW (70 V, 500 A), a distinct whistle was noted. Hydrogen produces a large change in gas volume, after undergoing dissociation and ionization, leading to a high degree of turbulence. Frequencies emitted during plasma operation with an argon and hydrogen gas were expected to be very high because of the whistle-like emission. A fixed range of the noise meter did not allow sampling at >8000 Hz. The intensity of the emission was 118 dB(A), an increase of 6 dB from torches operated with an argon/helium gas combination. The same difference in intensity has been noted by others.[11]

The noise signature of the Ar/$H_2$-generated plasma displayed peak intensity at 4 kHz, producing a noise more concentrated to the higher frequencies. The Ar/He plasma noise emission produced a steadier rise in the noise emission toward the higher frequencies (Fig. 10 and 11).

Larger amounts of hydrogen did not change the shape of the noise spectrum (Fig. 11). It is noteworthy that only a small amount of hydrogen was required to produce an increase in noise level. Further increases in hydrogen content only acted to increase the lower frequency response. The $L_{Aeq}$ values for conditions corresponding to 0, 5, and 9 slm $H_2$ were 115, 123, and 125 dB(A), respectively. A change in nozzle from a GH to GP increased the exit velocity of the gas. An increase in the low frequency response could have arisen from the extra turbulence downstream because of a faster moving gas stream or possibly from a harmonic of the power supply.

Compressed air is occasionally used as a source of air cooling alongside the trajectory of the hot jet. Two ports are located symmetrically on directly opposing sides of the torch. Such a cooling device creates a slower decrease in jet velocity and lowers the turbulence. Because the cooling jets are intended mainly for cooling of the workpiece, their arrangement is not usually optimized to minimize turbulence around the circumference of the plasma jet.

### 3.5 HVOF Spraying

The high velocity spray technology uses a jet nozzle for acceleration of gases. One naturally expects a higher noise emission from this process attributed to the higher gas velocity. A noise reading ($L_{Aeq}$) of 122 dB(A) was recorded during operation. The noise emissions generally sounded louder than a plasma operating with Ar-$H_2$ plasma gas, but did not appear to have the high frequency whistle. Noise levels at frequencies greater than 500 Hz were consistently higher than those noted in other thermal spray technologies.

During thermal spraying, it is common to use air extraction equipment and several air cooling jets. The noise emissions from the combined effects of all equipment influence the overall noise. For example, two noise sources operating side-by-side at 80 dB(A) can increase the sound level by 3 dB. If the secondary noise source is less intense, then there will be a negligible effect on the noise. When the second noise source is up to 10 dB(A) louder, the noise will increase by 3 dB. The air cooling used in HVOF spraying has a noise level of 110 dB(A). This is lower compared with the noise from the HVOF; however, the use of two cooling jets in addition to the torch increases the $L_{Aeq}$ by 1 dB (Fig. 12). Despite the small increase in the noise level, the air cooling will contribute to the lower frequencies and thus will appear to have a much greater effect on the apparent noise level.

A comparison of the thermal spray processes can be made, marking the minimum noise level and the variation possible with different parameter settings (Fig. 13). HVOF produced the high-

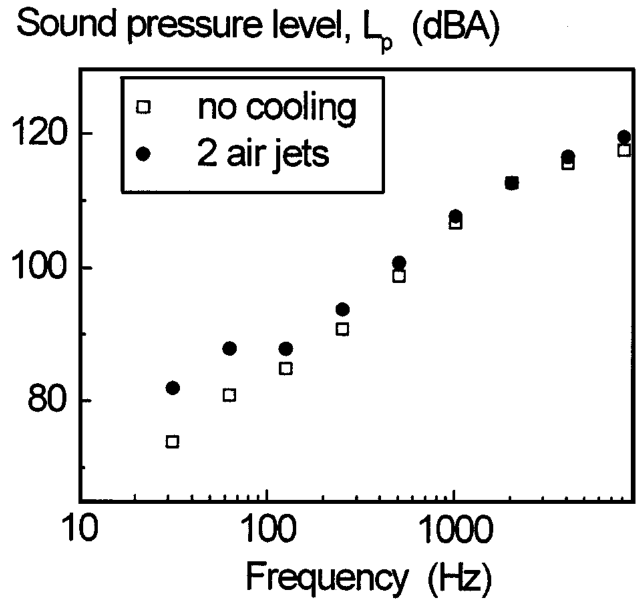


**Fig. 12** Noise emission from a HVOF torch with and without air cooling

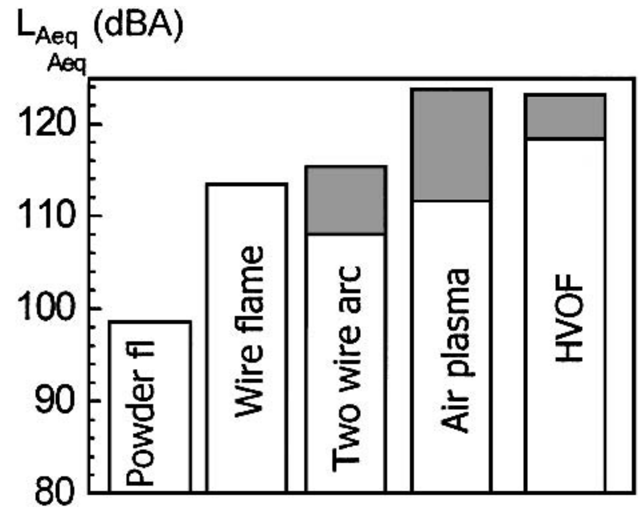


**Fig. 13** The sound intensity measured as $L_{Aeq}$ for the different thermal spray processes

est level of noise, regardless of operating condition. Following this was air plasma spraying, which exhibits the largest range. The noise increased when the secondary plasma gas was changed from helium to hydrogen and further increased when a smaller diameter nozzle was used. The atomizing spray processes (wire arc and wire flame) required large volumes of gas and thus exhibited intermediate noise levels of 108-116 dB(A).

Other thermal spray technologies include the Praxair detonation gun (D-gun), the cold spray process, and water-stabilized plasma. All of these processes use large volumes of gas and are expected to produce noise levels similar to those of HVOF.

The cold spraying operation is enclosed, thus the operator is isolated from the coating operation. The noise level outside of this enclosure has been documented as 70-90 dB(A).[12] This lower limit is quite normal for noise levels outside acoustic cabins enclosing plasma and two-wire arc processes.

The D-gun has been documented as producing noise levels up to 150 dB(A). The periodic explosions are more detrimental to human health than continuous noise because of the shock from the fast change in noise level. A burst of noise is known to alter endocrine, neurological, and cardiovascular functions in many individuals. For this reason, the D-gun is operated from outside of a noise-insulated enclosure.[9]

Lowering gas flow can lower noise in each of the thermal spray guns. A lower gas flow will generally lower the heat content of the flame and thus lead to a lower spray rate. A 3-5 dB reduction has been found for combustion wire spraying.[10]

For arc-generating equipment such as twin-wire arc and air plasma, a lower noise can also be achieved by lowering the current. It must be noted that such situations must be accompanied with a decrease in material feed rate and hence are not very practical.

Compressed air contributes to the noise in thermal spraying, especially when the gun is not ignited. Several options are available to decrease the noise by about 10-20 dB.[4] A multiple-jet diffuser nozzle consists of multiple jets over the same cross-sectional area. This decreases the noise emission mainly by reducing the jet core size, but also because of a reduction in large-scale turbulence. A restrictive diffuser that consists of sintered metal on the inside of the nozzle can also reduce the high-velocity core. In both of these methods, the reduction in jet-noise is at the expense of jet thrust. By passing some of the compressed gas around and over the nozzle, a minimal reduction in mass flow rate arises. The shearing action is reduced, leading to lower noise.

The action of the compressed air on an impinging surface also influences the noise emission. When the compressed air flows over a sharp edge or discontinuity, additional noise is generated from as low as 250 Hz.[4] This noise, identified as impingement noise, can be minimized by reducing the turbulence from the jet as it flows over a cavity or obstruction.

### 3.6 Hearing Protection Devices

Use of hearing protection is mandatory for operators who conduct manual spraying or investigation of the spray equipment during operation. The noise spectrum has revealed that the noise emission from thermal spray devices is highest within the region of the ear's highest sensitivity (1-5 kHz). Various hearing protection devices are available. Earplugs, worn in the external ear canal, may be premolded, formable, or custom-molded to fit the ear of the user. Earmuffs, worn against the opening to the external ear offer an alternative. Details of these and other hearing protection devices were discussed by Lempert.[13]

The effectiveness of these hearing protection devices is dictated by the pathway of sound to the inner ear.[14] Factors that influence noise attenuation include air leaks, hearing protector vibration, transmission through materials, and bone and tissue conduction. Of these, transmission through materials has the least reduction, especially for earplugs that have a smaller surface exposed to the noise.

Air leaks may be formed between the earplug and the ear canal or the earmuff and the pinna (the outer ear), and can reduce

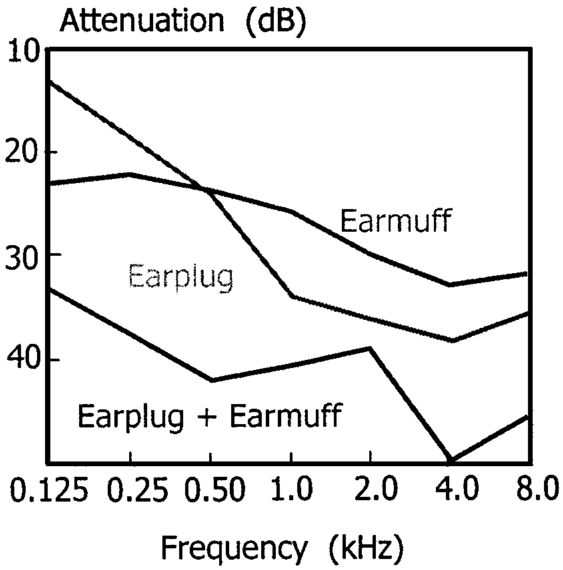


**Fig. 14** Attenuation of noise with different hearing protection aids

the attenuation by as much as 5-15 dB over a broad frequency range. The primary reduction is at low frequencies.

Hearing protector vibration occurs when earplugs move in a piston-like manner as a result of the compliance of the ear canal soft tissue. Earmuffs can also vibrate against the head as a mass/spring system. This loss limits the attenuation at 125 Hz to about 30 dB for earplugs, to 40 dB for foam inserts, and 25 dB for earmuffs.

Sound can be conducted through bone and soft tissue. When the hearing protection device is totally effective in blocking the other sound pathways, a limitation is reached because of bone conduction. The level of noise reaching the ear by bone conduction is about 40-50 dB below the sound level entering through the ear canal.[15]

Generally, foam earplugs have the best noise attenuation.[16] The performance, however, is dependent on the depth of insertion. They need to be inserted correctly to produce the required noise reduction. A typical noise reduction ratio (NRR) quoted on the packaging of the foam earplug may be 30 dB. Relating this to the A-weighted sound levels, the noise reduction is effectively 7 dB less than the documented value.[17] For a 30 dB noise reduction ratio foam insert, the effective average attenuation is then 23 dB.

The best attenuation is observed when an earplug is used in combination with an earmuff (Fig. 14). The incremental gain varies from 0-15 dB over the better hearing protection device. Above 2 kHz it is observed that the earplug/earmuff combination provides the same attenuation as the human skull. The resistance to noise travel through the bone will then be less and the external noise will be channeled through the skull to the middle ear.

Hearing protection is also effective in protecting the eardrum from stray hot particles that may occur in the thermal spray environment. A hot particle that may find its way onto the eardrum can damage the membrane and lead to hearing damage.[9]

Active noise reduction offers another means of decreasing the noise input to the ears. An active cancellation system can be included in the earmuff and would consist of three components—a microphone, electronic processor, and speaker. A microphone inside the earcup detects the incoming noise and sends the input to an electronic processor. An out of phase signal is then sent back to the earcup, where it is added to the existing sound through a speaker in the dome to provide noise reduction. This produces a noise reduction that is most effective for frequencies less than 1 kHz.[18] Because the noise emission in thermal spraying is concentrated at the higher frequencies, the use of active noise cancellation in thermal spray operations has limited application. Furthermore, the attenuation characteristics of active noise cancellation devices are only slightly better than that achieved with foam earplugs.[16]

Although the vowel sounds are concentrated at frequencies less than 500 Hz, the consonants carry most of the meaning within the 1-6 kHz region. The consonants are a lower intensity sound compared with that of the vowels. A 15% loss of the consonants is sufficient to make speech unintelligible. Although communication is not usually conducted in the spray booth, the intense noise at greater than 1 kHz suggests that communication in the vicinity of thermal spray torches would be difficult.

## 4. Conclusions

Noise emissions from thermal spray processing were above the levels that require hearing protection. The noise produced from thermal spray devices that were investigated varies from 96-125 dB(A). A higher noise emission is typically produced by high gas flows passing through the gun nozzle. Processes that aim to produce higher temperatures and velocities are thus accompanied by high noise levels. Noise dominates the upper frequency levels above 2 kHz. Hearing protection is recommended for reducing the noise levels to produce a safe working environment.

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