# RESPIRABLE SILICA EXPOSURES DURING DRY MACHINING OF ALUMINUM-SILICON ALLOYS

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## ABSTRACT

Aluminum-silicon alloys are typically machined using metalworking fluids, but potential health hazards associated with their use, combined with the high costs of metalworking fluids and their disposal has stimulated research on dry machining. It has been hypothesized that dry machining may expose machine operators to increased levels of dust, since it is assumed that use of metalworking fluids helps contain machining dust. This is particularly important since many of the alloys on which dry machining is being investigated contain silica, which can lead to the often fatal lung disease known as silicosis.

The goal of this pilot study is to determine if respirable silica exposures occur during the dry machining of aluminum alloys containing silicon, also known as aluminum-silicon (Al-Si) alloys. Another aspect of the project was to compare inhalable, total, and respirable concentrations of dust and silica between various sampling methods during the dry machining of Al-Si alloys. A total of nine samples were collected. Samples were paired to compare respirable dust results using NIOSH Method 0600 versus IOM Samplers and to compare total dust from NIOSH Method 0500 to inhalable dust results from IOM Samplers. Samples were also analyzed for silica content, using x-ray diffraction.

Sample results did not show any respirable silica above the limit of quantification for the analytical methods used. This may be attributable to several factors, including the low silica content of the alloy studied (Aluminum alloy 6061: silica content 0.6% by weight), short sampling periods due to limited stock of alloy, and dilution ventilation caused by repeated opening of the enclosure to change out broken drill bits. Comparisons between the various sampling methods were difficult to determine, due to the low levels of dust and silica generated during the machining process.

The results of this study may lead to future research into silica generation during dry machining of Al-Si alloys, effectiveness of cutting fluids in controlling silica exposures, and comparing various sampling methodologies to each other. Future studies might focus on comparing sample results among Al-Si alloys with differing amounts of silica and exploring results during turning vs. drilling.

## INTRODUCTION

Machining processes, such as milling, grinding, turning, boring, and drilling, typically rely on the use of metalworking fluids (MWFs) to transfer heat away from the cutting zone, lubricate the chip-tool interface, flush away chips, and inhibit corrosion.[1] This “wet machining”, helps decrease tool wear, extend tool life[2], and allows for faster machining. These metalworking fluids include synthetic and semi-synthetic fluids, as well as soluble and straight mineral oils.[3] These types of fluids differ in the amount of petroleum oils, additives, and water that are added.

Dry machining research and practice is moving forward for two major reasons: 1) the potential reduction in cost by minimizing or eliminating the use of cutting fluids which are expensive to use and maintain, and 2) the health and environmental benefits of minimizing metalworking fluid use, termed "green machining".[4] Dry machining provides for significant cost savings, including the costs associated with purchasing metalworking fluids and biocides added to minimize microbial growth, maintaining equipment used to deliver metalworking fluids to the work surface, and ultimate disposal. Manufacturing plants use large amounts of metalworking fluids during machining processes. Costs of metalworking fluids alone can exceed a million dollars per year. [5] Spent metalworking fluid is a waste stream of growing concern, due to the increasing costs of treatment and disposal, that in many cases exceed the original purchase price.[6]

Potential health benefits of using dry machining instead of relying on metalworking fluids are numerous. For example, dry machining may help avoid potential health risks associated with metalworking fluids, such as skin disorders and lung disease. Skin disorders include contact dermatitis, folliculitis, oil acne, and keratoses. Potential lung diseases include hypersensitivity pneumonitis, asthma, acute airway irritation, chronic bronchitis, and impaired lung function. The occurrence of hypersensitivity pneumonitis is most likely attributed to microbial contaminants present in water-based metalworking fluids.[7] The International Agency for Research on Cancer (IARC) concluded that sufficient evidence exists to link mineral oils used in the workplace with cancer.[8]

However, it has been hypothesized that dry machining may expose machine operators to increased levels of dust, since it is assumed that use of metalworking fluids helps contain machining dust. This is particularly important since many of the materials on which dry machining is being investigated contain silica, which could cause exposures that lead to the often fatal lung disease known as silicosis.

The potential health effects to workers from silica dust generated during dry machining of these alloys have not been extensively studied. Therefore, the purpose of this research is to provide information about the potential exposures in this rapidly developing concept of dry machining.

### Aluminum-Silicon Alloys

Aluminum and its alloys are commonly used in various applications, especially the automotive industry, where it is popular in items such as panels and engine components. More aluminum in cars means less weight, which can improve fuel economy. Aluminum also offers advantages such as corrosion resistance and heat tolerance. The same lathes, drill presses, and milling machines commonly found in metalworking shops are routinely used on aluminum alloys. These alloys may be turned, bored, milled, or machined at very high speeds.[9]

Aluminum alloys are comprised of aluminum along with varying amounts of manganese, silicon, copper, magnesium, lead, bismuth, nickel, chromium, zinc, or tin to produce an array of alloys with specific properties for very different purposes.[10] The aluminum industry uses a standardized numbering system to distinguish one alloy from another. Wrought alloys use a four-digit system, with the first digit signifying the principal alloying element. Cast alloys use three digits, with the first digit also denoting the principal alloying element. However, the numbering system for cast alloys does not parallel the one used for wrought alloys. For example, an initial 3 indicates the principal alloying element is silicon in cast alloys and manganese in wrought alloys.

Many of the most commonly used aluminum alloys contain silicon, and are known as aluminum silicon (Al-Si) alloys. For wrought aluminum alloys, the 4xxx and 6xxx series contain silicon. The principal alloying element for the 4xxx series is silicon, while the 6xxx series also includes magnesium. For cast aluminum alloys, the 3xx.x series contains silicon combined with magnesium or copper, or a combination of both elements. The 4xx.x series also contains silicon, but no magnesium or copper.

The Al-Si alloy studied in this project is alloy 6061. The composition of alloy 6061 is: Si (0.6%), Mn (0.28%), Mg (1.0%), Cr (0.2%), and Al (remainder).[11] It is especially useful in applications where welding is involved or high strength and corrosion resistance are required. It is also known for its good machinability. It is often used in auto body components, brackets, suspension systems, driveshafts, bumper reinforcements, brake cylinders, and fuel delivery systems.[12] It is also used in cylinders used for scuba diving, mountain bike frames, rims, and seat posts, and the aerospace industry.

## Silica Hazards

The primary hazard associated with dry machining of Al-Si alloys is associated with free silica. However, ACGIH states that physical overloading of the respiratory clearance mechanisms and chemical toxicity most likely produce synergistic effects.[13] Therefore, the potential for synergistic effects between dusts and free silica generated during the dry machining process creates an even more interesting risk assessment for the industrial hygienist.

Silica-induced fibrosis, otherwise known as silicosis, is the disease most associated with respirable crystalline silica exposure. At least 1.7 million U.S. workers are potentially exposed to respirable crystalline silica each year.[14] It is an incurable, debilitating, and often-fatal lung disease. Other diseases associated with crystalline silica include tuberculosis, chronic renal disease, and lung cancer. Silicosis in humans may be either chronic or acute, in nature.

Chronic silicosis has a long latency period, usually 10 or more years. Macrophages engulf silica particles that reach the alveoli in attempt to remove the foreign matter from deep in the lungs. These particles can damage the macrophages, causing the release of enzymes that subsequently increase deposition of connective tissue in the damaged area.[15] In other words, fibrous tissue develops and grows around silica particles that are deposited into the lungs.[16]

Acute silicosis can also occur among workers with very high exposures to respirable silica over a relatively short period of time (i.e., months to a year).[17] Prior to death, symptoms include coughing, labored breathing, fever, weight loss, and rapid progression of respiratory failure. It is almost always fatal, since there is no known treatment. Death occurs usually in one or two years.(21-22)

The seriousness of exposures to silica was reaffirmed in 1997, when silica was classified as a human carcinogen (Group 1) by the International Agency for Research on Cancer (IARC).[18] In 2000, ACGIH revised the threshold limit value-time weighted average (TLV-TWA) for respirable silica (quartz) from 0.1 $mg/m^3$ to 0.05 $mg/m^3$, due to evidence that fibrosis probably does occur in workers exposed to levels near the 0.1 $mg/m^3$ level. ACGIH believes even subtle fibrosis undetected by chest x-ray may be a risk factor for lung cancer, and an A2 notation (Suspected Human Carcinogen) was adopted.[19]

Separate TLVs exist for the other two major forms of crystalline silica, cristobalite and tridymite. The TLV's are both 0.05 $mg/m^3$ for the respirable particulate fraction. Cristobalite and tridymite exposures occur less often, although both are capable of causing silicosis.

### Particle Size-Selective Sampling

Size-selective sampling is important since potential heath effects are often determined by how deeply particles penetrate into the respiratory tract. The American Conference of Governmental Industrial Hygienists (ACGIH) recommends that particle size-selective threshold limit values be expressed as inhalable, thoracic, or respirable, as defined below:[20]

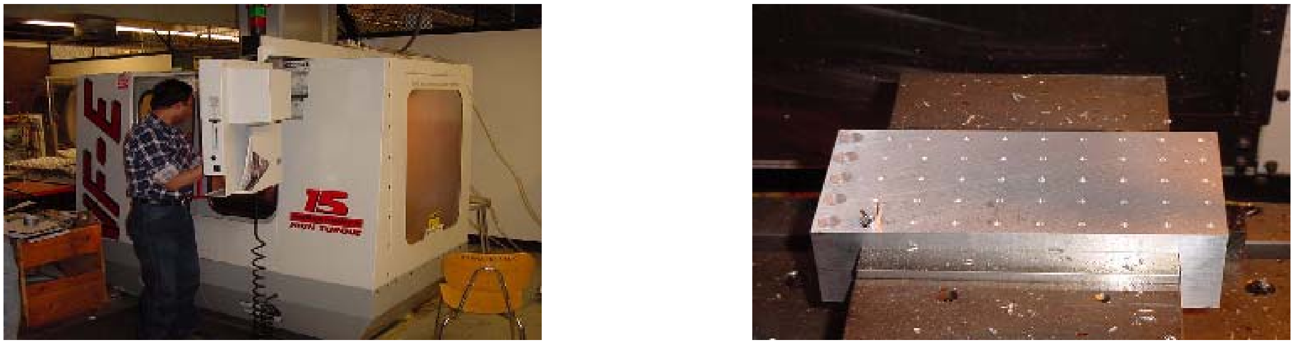
- Inhalable: 50% cut point of 100 μm (i.e., the particle diameter which is captured with 50% efficiency is 100 μm); hazardous when deposited anywhere in the respiratory tract
- Thoracic: 50% cut point of 10 μm; hazardous when deposited anywhere in the lung airways and gas exchange region
- Respirable: 50% cut point of 4 μm; hazardous when deposited in the gas exchange region

The respirable fraction is of importance since it is the particle size capable of penetrating to the gas-exchange region of the lung where long-term retention occurs.

## MATERIALS AND METHODS

### Sampling Strategy

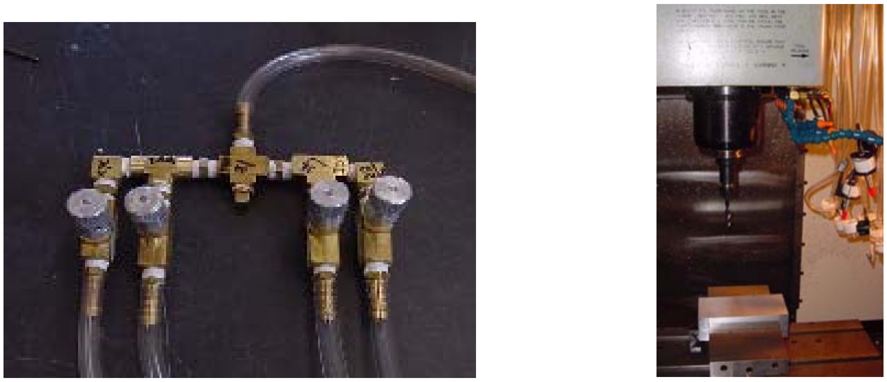
A Haas VF-0E Vertical Machining Center was used to perform dry drilling of 50 holes on a block of alloy 6061. It is almost entirely enclosed, with only a small gap on the top to facilitate moving parts. See Figure 1a and 1b. Various bit speeds and feed rates were used during drilling, primarily to fulfill requirements of unrelated research. Machines were not run for a full 8-hour day, due to the limited supply of alloy.



(a) (b)

Figure 1  Haas VF-OE Vertical Machining Center (a) and a block of 6061(b)

Three high flow pumps were used simultaneously to collect air samples. Each pump was connected to a manifold using Tygon® tubing. This manifold consists of four ports that allow four samples to be collected simultaneously. For dry machining, the fourth port, which is reserved for oil mist sampling, was not used. Each port on the manifold was connected via Tygon® tubing to the particular sampling media used to collect air samples. Flow rates were adjustable for each port. Sampling trains were suspended to within one foot of the drill bit from an existing gap in the top of the cabinet. See Figure 2a and 2b.



(a) (b)

Figure 2  Four-port manifold (a) and sampling trains adjacent to drill bit (b)

Although air sampling outside the enclosure is more representative of potential exposures to workers, performing the sampling inside the enclosure provides a worst-case, relatively controlled environment.

## Sampling Methods

NIOSH Methods 0500, 0600, and 7500 were followed while conducting air sampling. In addition, IOM samplers were used to measure inhalable and respirable dust. This sampler does not have an approved NIOSH Method. A summary of sampling methods is shown in Table I.

Table I
Summary of Sampling Methods

| | **NIOSH 0500**[21] | **NIOSH 0600** | **IOM Sampler** | **NIOSH 7500** |
|---|---|---|---|---|
| Analyte | Particulates not otherwise regulated, total | Particulates not otherwise regulated, respirable | Inhalable & respirable dust | Silica (crystalline) |
| Sampler | 37-mm cassette closed-face, total dust | SKC Aluminum cyclone<br>37-mm cassette 3-piece) | SKC IOM sampler, with multi-dust foam plug | SKC Aluminum cyclone<br>37-mm cassette (3-piece) |
| Medium | PVC, 5 µm, pre-weighed | PVC, 5 µm, pre-weighed | 25 mm PVC, 5µm; cassette assembly pre-weighed | PVC, 5 µm |
| Flowrate | 1-2 L/min | 2.5 L/min | 2 L/min | 2.5 L/min |
| Analysis | Gravimetric | Gravimetric | Gravimetric | XRD |
| LOD | 0.02 mg | 0.02 mg | 0.02 mg | Quartz: 0.01mg<br>Cristobalite: 0.02 mg<br>Tridymite: 0.02 mg |

LOD: limit of detection; "a stated limiting value designating the lowest concentration that can be detected and that is specific to the analytical procedure used." [22]

LOQ: limit of quantification; "a stated limiting value designating the lowest concentration that can be quantified with confidence and that is specific to the analytical procedure used."[23]

Total dust samples were collected using a 37-mm closed-face cassette with a 4-mm diameter inlet, in order to collect dust for gravimetric analysis in accordance with NIOSH 0500. Each cassette contained a five-micron polyvinyl chloride (PVC) filter.

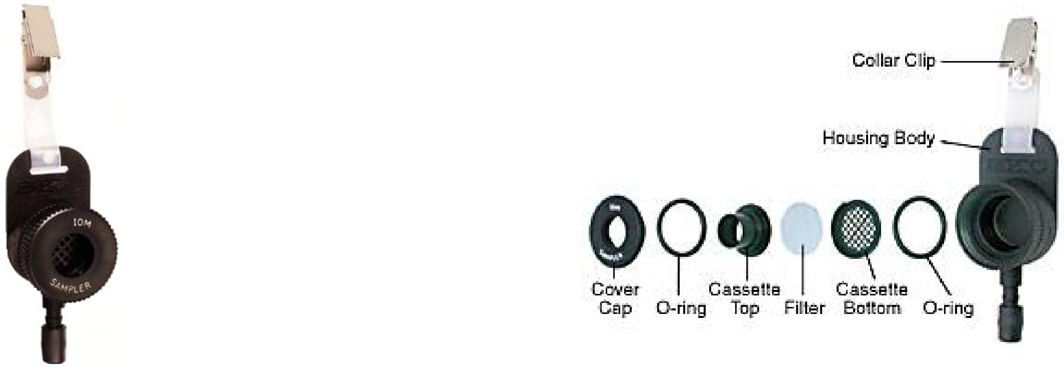
Respirable dust samples were collected using SKC aluminum cyclones (part no. 225-01-02, SKC Inc., Eighty Four, PA) with open-faced, three-piece cassettes with a PVC filters. Using NIOSH 0500, this method provides a 50% cut point of 4 microns (µm) when operating at a flowrate of 2.5 liters per minute. Filters were pre-weighed by an AIHA-certified laboratory (DataChem Laboratory, Salt Lake City, UT). The same laboratory was used for analysis following air sampling. See Figure 3 below.

(a) (b)

Figure 3 Aluminum cyclone (a) and when in holder with open-faced cassette mounted (b) (courtesy of SKC Inc., Eighty Four, PA)

The IOM Sampler (part no. 225-70, SKC Inc., Eighty Four, PA) was used to determine inhalable and respirable dust fractions for comparison to the 37-mm cassette and aluminum cyclone results. This sampler was developed by Mark and Vincent at the Institute of Occupational Medicine (IOM), in Scotland.[24] It was the first fully validated personal inhalable sampler for airborne particulate sampling, since it closely matches the 50% cutpoint requirement of 100 μm.[25] It has a reusable filter/cassette assembly with a large, 15-mm diameter inlet with a thin lip protruding outwards through which aerosol is aspirated. It was designed to closely simulate the dust particle collection behavior of the nose and mouth.[26] Particles collect either on the filter paper or inside surfaces of the internal two-piece cassette assembly. Since the entire cassette assembly is analyzed, there is no wall loss as is possible when using 37-mm cassettes.

A MultiDust Foam Disc (part no. 225-772, SKC Inc., Eighty Four, PA) was inserted into the inlet in order to sample inhalable and respirable dust fractions simultaneously. With the foam disc in the inlet of the IOM, respirable particles are collected on the filter. The entire cassette assembly is weighed to first determine the inhalable fraction. The foam plug is then removed and the cassette and filter are weighed to then determine the respirable mass fraction. The IOM sampler provides a 50% cutpoint of 4 μm for respirable dust and 100 μm for inhalable dust, when running at a flowrate of 2 liters per minute. See Figure 4 below.



(a) (b)

Figure 4 Sampler (a) and with an expanded view (b) (courtesy of SKC Inc., Eighty Four, PA)

Total, inhalable, and respirable dust samples were also analyzed for crystalline forms of silica (quartz, cristobalite, and tridymite) using x-ray diffraction (XRD). Note that NIOSH Method 7500, which uses XRD analysis, applies to only specific methods using respirable samples. For this study, XRD was conducted on all dust samples (i.e., respirable, inhalable, and total dusts). XRD is advantageous in that it avoids interferences that occur in infrared (IR) and visible spectrometry methods, which can bias sample results. It is able to speciate and quantify the three different types of crystalline forms of silica.

## RESULTS

A total of nine samples were collected during dry machining of alloy 6061, which includes three pairs of samples each for IOM:cyclone and IOM:37-mm comparisons. The concentrations of total, inhalable, and respirable dusts, along with crystalline silica were calculated using the following formula:

$$\text{Concentration (mg/m}^3\text{)} = \frac{\text{mass collected (mg)}}{\{[\text{flowrate (L/min)}/1000\ \text{L/m}^3]*[\text{time sampled (min)}]\}}$$

Results showed measurable concentrations of total, respirable, and inhalable dust fractions were detected. However, no definitive correlation could be made to relate total dust results to inhalable results. Likewise, no correlation could be made between the NIOSH Method 0600 (aluminum cyclone) and IOM respirable dust results. Ideally, linear regression would be used to establish a correlation coefficient that could be used to relate total to inhalable dust or to relate respirable results for cyclone sampling versus IOM sampling. In addition, no silica was quantified above the limit of detection reported by the laboratory. See Table II below.

TABLE II

Sample results for total, respirable, and inhalable dusts and silica

| Method | Sample # | Respirable Dust (mg/m$^3$) | Total Dust (mg/m$^3$) | Inhalable Dust (mg/m$^3$) | Silica (mg/m$^3$) |
|---|---|---|---|---|---|
| **Cyclone** | 1 | 0.116 | | | ND |
| | 2 | 0.153 | | | ND |
| | 3 | 0.192 | | | ND |
| **Cassette** | 1 | | 0.141 | | 0.0938* |
| | 2 | | 0.15 | | ND |
| | 3 | | 0.106 | | ND |
| **IOM Sampler** | 1 | ND | | 1.13 | ND |
| | 2 | 0.0948 | | 1.71 | ND |
| | 3 | ND | | 0.755 | ND |

ND: none detected above the analytical limit of detection (LOD)
*: result was above the LOD, but below the limit of quantification

## DISCUSSION

It is not surprising that respirable silica was not detected above the limit of quantification (LOQ) during this study. Alloy 6061 contains only 0.6% silicon, by weight, which is much less than an alloy such as A390, which contains 16-18% silicon. The machining process used for this study, drilling, is not an unusually dusty process, which may have led to the negligible dusts generated. The probability of detecting silica is also dependent on total sampling time. In this study, a limited supply of alloy meant that sampling could only be conducted for approximately 100 minutes. Also, it should be noted that the machining enclosure was opened after each hole was drilled to facilitate the collection of chips for metallurgical analysis, which was part of unrelated research. Drill bits had to be changed periodically, due to breakage at least partially caused by the various speeds and depths of cuts that were required for the unrelated research.

In addition, several issues arose concerning the IOM Sampler. Static electricity problems during the analysis of the multi-foam disc may have affected inhalable dust fractions. With the IOM Sampler being relatively new to the industrial hygiene community, experience continues to build regarding their proper use and analysis techniques. Also, the plastic cassette and body of the IOM Sampler may be susceptible to mass instability, related to the adsorption of moisture while in the field. Another issue that arose, but was not a factor in this pilot study, is the potential susceptibility to rapid overloading during heavily contaminated environments, due to the large 15-mm inlet of the sampler.

It is obvious that dry machining avoids several problems introduced by machining methods relying on metalworking fluids (e.g., costs and health hazards). But, dry machining introduces a new set of challenges. For example, without metalworking fluids to lubricate and transport heat away from the tool/workpiece interface, buildup of heat probably attributed to the increased number of broken drill bits. This led to the conclusion that drill speed and depth of cut used during traditional wet drilling may need to be adjusted when dry drilling is performed. The lack of metalworking fluid also caused restricted chip ejection, buildup on the drill bits, and generation of dust particles instead of mist.[27]

## CONCLUSIONS

This study served as an initial review of potential silica inhalation hazards due to dry machining of Al-Si alloys. Results showed that silica was not detected during the dry machining of alloy 6061. Based on this set of data, potential inhalation of silica does not appear to be a significant hazard during dry machining of alloy 6061.

Several studies are recommended for future consideration, including sampling during blow-down/cleanup processes, comparisons of dry- vs. wet machining methods, and comparisons of sampling during machining of alloys with different silica contents. It may also be beneficial to compare performance of the different sampling media and analyze whether a conversion factor can be determined in order to use total dust samplers as a surrogate, in lieu of respirable dust samplers. This would provide an easier, less expensive means to collect personal air samples for compliance with standards that are stated in terms of respirable mass fractions.

In addition, future research would ideally collect larger data sets to help clarify inconsistencies seen in this pilot study and to provide statistical significance. However, it should be noted that larger data sets would require the purchase of much more alloy, some of which is very expensive and difficult to obtain.

Other studies might also address the electrostatic instability of the IOM multi-dust foam plugs, used to simultaneously collect two dust fractions, and how to reduce such instability. Li, Lundgren, et al.[28], noted that area sampling performances of IOM and closed-face 37-mm cassettes are highly dependent on wind orientation, wind speed, and particle size. Therefore, future research may be warranted in order to investigate such variables.

Another consideration for future efforts would be to swab interior surfaces of the 37-mm cassettes, in order to collect particulate matter deposited on the walls of the cassettes. Particles deposited onto the inner wall of the cassette are considered inside losses and may underestimate actual contaminant captured during sampling. Analyses on 37-mm cassettes used in this study did not account for such wall losses, since it is not part of the NIOSH Methods that were incorporated into the study design.

Future studies might address the issue of mass stability. The standard IOM plastic cassette assembly is prone to mass stability problems, due to the tendency of the plastic to adsorb moisture. The use of stainless steel IOM cassette assembly, instead of the commonly used and less expensive conductive plastic assembly, will tend to minimize bias due to adsorption of moisture and may improve air sampling data.[29]

## ACKNOWLEDGMENTS

The authors would like to thank Dr. A.K. Balaji and Mr. Anshu Dhar Jayal of the Department of Mechanical Engineering for providing technical expertise, lab space, cutting machine time, and supplies.

## REFERENCES

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[1] Sutherland, J.W.; Kulur, V.N.; King, N.C.: An Experimental Investigation of Air Quality in Wet and Dry Turning. Annals of the CIRP 49:61-64 (2000).

[2] National Institute for Occupational Safety and Health (NIOSH): What You Need to Know About Occupational Exposure to Metalworking Fluids, DHHS (NIOSH) Pub. No. 98-116, p.1. NIOSH, Cincinnati, OH (1998).

[3] Sutherland, J.W.; Kulur, V.N.; King, N.C.: An Experimental Investigation of Air Quality in Wet and Dry Turning. Annals of the CIRP 49:61-64 (2000).

[4] Machado, A.R.; Wallbank, J.: The Effect of Extremely Low Lubricant Volumes in Machining. WEAR 210:76-82 (1997).

[5] Cozzens II, D.A.; Rao, P.D.; Olson, W.W.; Sutherland, J.W.; Panetta, J.M.: An Experimental Investigation Into the Effect of Cutting Fluid Conditions on Boring of Aluminum Alloys. Transactions of ASME 121:434-439 (1999).

[6] Cozzens II, D.A.; Rao, P.D.; Olson, W.W.; et al.: An Experimental Investigation Into the Effect of Cutting Fluid Conditions on the Boring of Aluminum Alloys. Transactions of the ASME 121:434-439 (1999).

[7] National Institute for Occupational Safety and Health (NIOSH): What You Need to Know About Occupational Exposure to Metalworking Fluids, DHHS (NIOSH) Pub. No. 98-116, pp.8-10. NIOSH, Cincinnati, OH (1998).

[8] Raynor, P.C.; Cooper, S.; Leith, D.: Evaporation of Polydisperse Multicomponent Oil Droplets. Am Indus Hyg Assoc J 57:1128-1136 (1996).

[9] http://www.autoaluminum.org/alloys.htm

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[10] Stern, M.B.; Mansdorf, S.Z.: Applications and Computational Elements of Industrial Hygiene, pp. 103-107. CRC Press, Boca Raton, FL (1999).

[11] Boyer, E.; Gall, T.L.: Metals Handbook, Desk Edition. American Society for Metals, Materials Park, OH (1985).

[12] http://www.autoaluminum.org/alloys.htm

[13] American Conference of Governmental Industrial Hygienists (ACGIH): Particulates (Insoluble) Not Otherwise Specified (PNOS). In: Documentation of the TLV's and BEI's, 7th ed. ACGIH, Cincinnati, OH (2001).

[14] National Institute for Occupational Safety and Health (NIOSH): Health Effects of Occupational Exposure to Respirable Crystalline Silica, DHHS (NIOSH) Pub. No. 2002-129. NIOSH, Cincinnati, OH (2002).

[15] Kent, C.: Basics of Toxicology, p.158. Wiley & Sons, New York (1998).

[16] Plog, B.A.; Niland, J.; Quinlan, P.J.: Fundamentals of Industrial Hygiene, 4th ed., pp. 180-181. National Safety Council, Itasca, IL (1996).

[17] Stern, M.B.; Mansdorf, S.Z.: Applications and Computational Elements of Industrial Hygiene, pp. 103-107. CRC Press, Boca Raton, FL (1999).

[18] International Agency for Research on Cancer (IARC): IARC Monographs of the Evaluation of the Carcinogenic Risk of Chemicals to Humans, Silica and Some Silicates. IARC, Lyon, France (1997).

[19] American Conference of Governmental Industrial Hygienists (ACGIH): Silica, Crystalline - Quartz. In: Documentation of the TLV's and BEI's, 7th ed. ACGIH, Cincinnati, OH (2001).

[20] SKC, Inc.: 2002 Comprehensive Catalog & Air Sampling Guide. SKC, Inc., Eighty Four, PA (2002).

[21] National Institute for Occupational Safety and Health (NIOSH): Particulate Not Otherwise Regulated, Total, Method 0500. In: NIOSH Manual of Analytical Methods, 4th ed. NIOSH, Cincinnati, OH (1994).

[22] DiNardi, S.R.: Calculation Methods for Industrial Hygiene. New York: Van Nostrand Reinhold, 1995.

[23] DiNardi, S.R.: Calculation Methods for Industrial Hygiene. New York: Van Nostrand Reinhold, 1995.

[24] Mark, D.; Vincent, J.H.: A New Personal Sampler for Airborne Total Dust in Workplaces. Ann Occup Hyg 30:89-102 (1986).

[25] SKC: www.skcinc.com/prod/225-70A.html (2003).

[26] Clinkenbeard, R.E.; England, E.C.; et al.: A Field Comparison of the IOM Inhalable Aerosol Sampler and a Modified 37-mm Cassette. Appl Occup Environ Hyg 17(9):622-627 (2002).

[27] Arumugam, P.U.; Malshe, A.P.; Batzer, S.A.; et al.: Study of Airborne Dust Emission and Process Performance During Dry Machining of Aluminum-Silicon Alloy with PCD and CVD Diamond Coated Tools. In: Transactions of the North American Manufacturing Research Institution of SME, Vol. XXX. Society of Manufacturing Engineers, Dearborn, MI (2002).

[28] Li, S.; Lundgren, D.A.; Rovell-Rixx, D.: Evaluation of Six Inhalable Aerosol Samplers. Am Indus Hyg Assoc J 61:506-516 (2000).

[29] Kerr, S.M.; Muranko, H.J.; Vincent, J.H.: Personal Sampling for Inhalable Aerosol Exposures of Carbon Black Manufacturing Industry Workers. Appl Occup Environ Hyg 17(10):681-692 (2002).