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Kun Li[a], Fereydoun Aghazadeh[a], Selen Hatipkarasulu[a] & Thomas G. Ray[a]

[a] Department of Industrial and Manufacturing Systems Engineering, Louisiana State University, Baton Rouge, USA

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Health Risks From Exposure to Metal-Working Fluids in Machining and Grinding Operations

Kun Li
Fereydoun Aghazadeh
Selen Hatipkarasulu
Thomas G. Ray

Department of Industrial and Manufacturing Systems Engineering, Louisiana State University, Baton Rouge, USA,

Metal-working fluids (MWFs) are used in machining and grinding operations to cool the tool and work, reduce the friction between the tool and work, improve the surface integrity of the work piece, and increase tool life and productivity. Health problems have been reported among workers exposed to MWFs, including incidences of respiratory, digestive and skin cancers, and increased rates of cough and phlegm. This paper reviews and discusses issues concerning health risks from exposure to MWFs in machining and grinding operations, the various factors that influence the degree of exposure, and control methods to reduce exposure to metal-working fluids.

machining safety   cutting fluid hazards
occupational illnesses   occupational cancer   metal-working

1. INTRODUCTION

Machining and grinding operations play a very important role in the manufacture of products. Metal parts that require high dimensional accuracy and good surface finish usually have to go through these operations. In these operations, metal-working fluids (MWFs) are used to cool the tool and work, reduce the friction between the tool and work, improve the surface integrity

Correspondence and requests for offprints should be sent to Fereydoun Aghazadeh, 3128 CEBA Building, Department of Industrial and Manufacturing Systems Engineering, Louisiana State University, Baton Rouge, LA 70803-6409, USA. E-mail: <aghazadeh@lsu.edu>.

of the workpiece, and increase tool life and productivity. More than 1 million workers in the USA are exposed to cutting oils, and many others use soluble and synthetic coolants in machining and grinding operations (National Institute for Occupational Safety and Health, 1977).

Health problems have been reported among workers exposed to MWFs, and methodologies used to assess health risks from exposure to MWFs have been discussed (National Safety Council, 2002). Previous investigations have shown elevated respiratory, digestive, and skin cancers in exposed populations and increased rates of cough and phlegm. There are also case studies that indicate that these exposures may cause occupational asthma.

This paper intends to review issues concerning health risks from exposure to MWFs in machining and grinding operations. The various factors that influence the degree of exposure, and control measures to reduce exposure are also discussed.

2. METAL-WORKING FLUIDS

Practically all MWFs (coolants and lubricants) in use today fall into four classes: (a) oil, (b) soluble oil, (c) semisynthetic, and (d) synthetic (Bienkowski, 1993). Each category is defined by its oil content. Furthermore oils are divided into two groups: mineral or synthetic. Mineral oils are naphthenic and paraffinic hydrocarbons refined from natural crude oil. Their major function is to provide a base for blends and additives. Synthetic oils, on the other hand, are manufactured polyalphaolefins, which are hydrocarbon-based, polyglycols, or ester oils. Various ingredients, such as emulsifiers, corrosion inhibitors (alkaline and alkanolamine salts of organic acids, sulfonates, amines, amides, and organic boric compounds), polar additives (animal and vegetable oils, caster oils, and esters of organic acids), extreme-pressure (EP) additives (chlorine, phosphorus, or sulfur compounds), biocides, solvents (such as long-chain alcohols), color and fragrance additives, antioxidants, and antifoaming agents are combined to form a fluid with specific properties. The major components, properties, and applications of the four classes of MWFs are listed in Table 1.

Straight oils can build up heat quickly, create a mist that can cause unsafe and unclean work conditions, and are a fire risk. Like straight oils, soluble or emulsifiable, oils generate mists that can dirty work areas and make them unsafe. The water content also has its drawbacks, such as rust problems, bacterial growth and rancidity, tramp oil contamination, and evaporation

TABLE 1. The Major Components, Properties, and Applications of the Four Classes of MWFs

Class	Major Components	Properties	Applications
Straight oils	mineral oil, EP additives, fatty-oil-based wetting agents	excellent lubrication, good rust control	light-duty machining of ferrous and nonferrous metals
Soluble oils	60–90% mineral oil, water, emulsifiers, corrosion inhibitors, biocides, EP additives	good lubrication, better cooling capacity	general-purpose for a variety of ferrous and nonferrous operations
Semisynthetic fluids	2–30% mineral oil, water, emulsifiers, wetting agents, corrosion inhibitors, biocides	good lubricity, better cooling, wetting, settling, and cleaning properties	moderate to heavy-duty applications (higher speeds and feeds)
Synthetic fluids	no mineral oil, organic and inorganic salts, water, synthetic lubricants, water-soluble organic compounds (esters)	excellent microbial control, settling, and cleaning properties, good corrosion control, better cooling capacity	grinding, moderate to heavy-duty machining operations

Notes. EP—extreme-pressure.

losses. On the other hand, semisynthetic fluids, having less oil content, generate less smoke and oil mist, and can control rancidity and bacteria growth better. Synthetic fluids can be classified into three types: simple, complex, and emulsifiable. Simple synthetic concentrates are organic and inorganic salts dissolved in water, and are mainly for light-duty grinding. In addition to organic and inorganic salts and water, complex synthetics contain synthetic lubricants, and can work in moderate to heavy-duty machining operations. Emulsifiable synthetics contain water-soluble organic compounds in addition to the ingredients found in complex synthetics, and serve as lubricants and coolants during grinding or heavy cutting.

The earliest MWFs in widespread use were straight oils, which are still commonly used for their excellent lubricating properties. Soluble oils and some synthetic types were introduced in the 1940s and because of their cooling properties, are well suited to grinding operations. Widespread use of synthetic types of coolants began in the mid-1970s (Eisen, Tolbert, Monson, & Smith, 1992).

Whereas all types of MWFs are used in machining operations, straight oils are rarely used for high speed grinding due to high viscosity. In the turning departments acid-refined mineral oils were used from 1927 to 1975. Before 1950, fatty oils in concentrations of about 10% were added to cutting oil. Since 1975, solvent-refined mineral oils have been used. Sulfur has also been added in concentrations of between 0.1 and 0.9%. The cutting fluids used in the grinding departments since 1940 are described in Table 2 (Jarvholm & Lavenius, 1987).

TABLE 2. Cutting Fluids Used in Grinding Departments Since 1940

Component	Period	Remarks
Acid-refined mineral oils	1940–1975	
Solvent-refined mineral oils	1975–	
Sodium carbonate (0.5–1%)	1940–1960	
Sodium nitrite (0.2–0.6%)	1940–	Successively removed 1972–1976, but may still occur in a few places
Amines	mid-1950s–	Mostly alkanolamines
Emulsifiers	mid-1950s–	
Bactericides	mid-1950s–	Mostly formaldehyde releasers
Antifoaming agents, colors, antioxidants	mid-1950s–	

A 5-year study to investigate changes in the chemical, physical, and biological properties of a neat cutting oil during prolonged use in a large manufacturing facility revealed that the generation of individual 4–6 ring polycyclic aromatic hydrocarbons during the use of cutting oil was slow and the dilution effect of oil additions prevented their excessive build-up. No evidence of any increase in irritancy, sensitizing, or carcinogenic potential was found in the course of the study (Evans, Hooper, Ingram, Pullen, & Aston, 1989).

Metals are found as trace contaminants in the refining of most mineral oils (International Agency for Research on Cancer, 1987). In addition, the machining process generates metal particles, which can dissolve in the MWFs (Mosher, Peterson, & Skold, 1986). Recent studies have demonstrated that metals tend to leach into MWFs and increase in concentration as the coolant ages (Stebbins, 1989). Chromium, nickel, cobalt, lead, and molybdenum have all been found in bulk MWF samples (Oxhoj, Andreasen, & Henius, 1982).

Grinding and turning machines are equipped with hydraulic systems, which leak oil to the cutting fluid. Thus, hydraulic fluid and lubricating oil may be found in small amounts in the cutting fluid. We have adequate information about cutting fluids and lubricating oils, but less is known about hydraulic fluids, which were based on mineral oils with a few additives (Jarvholm & Lavenius, 1987).

3. HEALTH PROBLEMS FROM EXPOSURE TO METAL-WORKING FLUIDS

3.1. Mortality Patterns

Three auto parts manufacturing facilities in the USA, Plant I producing gears and axles for rear-wheel drive vehicles; Plant II, transmissions; and Plant III, steering gears, were selected to evaluate potential health risks associated with all the major types of machining fluids currently in widespread use in the automobile industry (Eisen et al., 1992). The study included more than 45,000 workers, over 20 years of follow-up, more than 10,000 deaths, and an extensive exposure assessment component. Using the U.S. population as the reference group, the standardized mortality ratio (SMR) for all causes of death was 0.96. One fifth of the total number of deaths was due to cancer. For all cancers, the SMR was 1.01. The SMR was 0.92 for all circulatory diseases and 0.78 for all external causes of death.

Straight and soluble oils were the predominant fluids used in Plant I; all three types, straight, soluble, and synthetic oils, were used at Plant II; and straight oils were most common at Plant III. Cause-specific SMRs were estimated separately for white males at each of the three facilities (Table 3). White workers at Plant I had higher risks of leukemia, brain cancer, and esophageal cancer. The SMR among black males at Plant I was 1.60 for liver cancer, 1.63 for laryngeal cancer, and 1.70 for pancreatic cancer. Elevated SMRs were found for stomach cancer, lung and laryngeal cancer among white males at Plant II. In Plant III, the top killer was liver cancer, and there was an elevated SMR for all digestive cancers. McMichael (1976) came to the same conclusion, the total mortality of workers exposed to MWFs was not found to increase when compared with that of the general population.

In a study of 792 workers exposed to cutting fluids in a bearing ring manufacturing firm in Sweden, the total mortality of these workers was in line with “normal” mortality in industrial workers (Jarvholm & Lavenius, 1987). When compared with that of the general population, the total mortality was not found to increase. The mortality in nonmalignant respiratory diseases was not increased. The workers who died of respiratory diseases had different diagnoses including pneumonia, chronic bronchitis, asthma, and emphysema. There was no increased risk of cardiovascular diseases or nephritis.

TABLE 3. Cause-Specific Standardized Mortality Ratios (SMRs) for White Males

Plant I		Plant II		Plant III	
Cause	**SMR**	**Cause**	**SMR**	**Cause**	**SMR**
Leukemia	1.57	Laryngeal cancer	1.85	Liver cancer	2.77
Brain cancer	1.34	Asthma	1.39	Rectal cancer	1.70
Esophageal cancer	1.25	Stomach cancer	1.26	Large intestine cancer	1.47
Stomach cancer	1.08	Lung cancer	1.16	Esophageal cancer	1.38
Liver cancer	1.06	Rectal cancer	1.09	All digestive cancers	1.29
Respiratory cancer	1.03	Skin cancer	1.06	Skin cancer	1.27
Lung cancer	1.02	All cancers	1.03	Leukemia	1.07
Laryngeal cancer	1.02	Liver cancer	0.99	All cancers	0.98
All cancers	1.02	Leukemia	0.94	Lung cancer	0.91
Rectal cancer	1.01				
Digestive cancer	0.97				
Skin cancer	0.61				

In another study by Tolbert et al. (1992), involving 30,000 workers employed at two automotive pants in Michigan (USA), mortality patterns were studied in relation to exposure to each of the three major fluid types: straight oils, soluble oils, and synthetic types. The SMRs are listed in Table 4.

For each of the three exposure groups, the all-cause SMR value for white males was 1.0. For black males, the SMR values were between 0.8 and 0.9. A slight increase of esophageal cancer is indicated among white males exposed to straight oils, whereas there was no increase among black males. Stomach cancer was slightly elevated in each of the three exposure groups for white males; black males showed no increase. There was no indication of excessive colon cancer in any of the SMR analyses. An excessive number of instances of rectal cancer was apparent among white males exposed to straight oils, with a statistically significant SMR of 1.5. Whereas white males showed no excessive number of instances of pancreatic cancer, black males exposed to soluble oils had a statistically significantly elevated SMR of 1.6. Among white males, the SMR value for laryngeal cancer was elevated in each of the exposure groups, but to the greatest degree in the group exposed

TABLE 4. Mortality Patterns in Relation to Exposure to Three Major Fluid Types

Cause of Death	Straight Oil		Soluble Oil		Synthetic Fluids
	W-SMR	B-SMR	W-SMR	B-SMR	W-SMR
All causes	1.02	0.82	1.00	0.81	1.01
All cancers	1.01	0.92	1.02	0.90	0.97
Esophagus	1.18	0.76	1.03	0.72	0.99
Stomach	1.12	1.05	1.19	1.01	1.28
Colon	0.79	0.42	0.85	0.55	0.83
Rectum	1.47	0.45	1.09	0.66	0.92
Pancreas	0.80	1.40	0.77	1.62	1.03
Larynx	1.98	0.50	1.41	1.46	1.57
Lung	1.02	1.06	1.07	0.91	1.01
Prostate	1.16	0.98	1.08	0.98	1.11
Brain	1.08		1.24	0.77	0.61
Leukemia	1.25	0.77	1.33	0.74	1.22
Cirrhosis	1.19	0.55	1.16	0.74	1.04

Notes. W-SMR—standardized mortality ratio for white males, B-SMR—standardized mortality ratio for black males.

to straight oils, with a statistically significant SMR of 2.0. There were too few laryngeal cancer deaths among black males exposed to straight oils to evaluate this association. The SMR for lung cancer among white males exposed to soluble oil was slightly elevated, whereas no increases were observed among black males. Among white males, the SMR values for prostate cancer were slightly elevated for each exposure group. There was a slight excess of brain cancer among white males exposed to soluble oils, the SMR being 1.2. There were too few deaths from brain cancer among black males for the associations with machining fluid types to be assessed. Among white males, leukemia was somewhat elevated in each of the exposure groups; the SMR in the group exposed to soluble oils was 1.3 and statistically significant. Leukemia was too rare an outcome among black males to be statistically evaluated. For cirrhosis, SMR values of 1.2 and borderline significance were obtained in white males exposed to soluble and straight oils. No increases were observed among black males. Suspect carcinogens in straight oils include polyaromatic hydrocarbons, long-chain aliphatics, sulfur additives, and various metals introduced during use. Silverstein, Park, Maizlish, and Mirer (1985) noted excessive cirrhosis among grinders exposed to oil and water-based machining fluid at a ball-bearing plant.

Although the total mortality showed no increase, slight excess risks for several specific digestive and respiratory cancers were identified. In addition, elevated risks for leukemia and for asthma were noted. None of the elevated risks for specific causes was entirely consistent across all plants and all gender-race groups.

3.2. Cancer Risks

The International Agency for Research on Cancer has concluded that hydrocarbon mineral oils used in metal machining are carcinogenic (International Agency for Research on Carcinogens, 1987). Toxicity tests show that some fluid additives cause cancer in laboratory animals. For example, nitrates (corrosion inhibitors) or nitrosating agents in combination with amines, which are antioxidant and corrosion inhibitors, can help form nitrosamines, a liver carcinogen. In 1984, the U.S. Environmental Protection Agency passed a rule prohibiting the use of nitrites in MWFs containing alkanolamines.

Although MWFs have generally been treated as a single material in the epidemiological literature, they are in fact a complex and variable mixture of many substances, some of which are known or suspected carcinogens, tumor promoters, or co-carcinogens. Among the groups of toxicologically suspect classes of chemicals associated with the use of machining fluids are polycyclic aromatic hydrocarbons (including benz(a)pyrene), N-nitroso compounds (including nitrosamines), and abrasives (Eisen et al., 1992). Among suspect cancer initiators and promoters contained in one or another type of machining fluid as additives or contaminants are the following: long-chain aliphatics, polyaromatic hydrocarbons (PAHs), nitrosamines, sulfur-containing compounds, formaldehyde-releasing biocides, and certain metals (Tolbert et al., 1992).

Crude mineral oils contain PAHs. Through refining, PAH content can be reduced but acid-refined mineral oils still contain PAHs in such amounts that they cause skin cancer in animals. Today most mineral oils are solvent-refined with much less PAHs and would constitute an even smaller risk. However, commercial fluids and lubrication oils contain a variety of additives, and therefore the risk of cancer can vary between different products (Jarvholm & Lavenius, 1987).

3.2.1. Respiratory cancer risk

With the introduction of high-speed machinery, substantial exposures to machining fluids now also occur via inhalation of the mist. This change in technology, and the resultant change in the route of entry, have turned public health attention toward potential effects on digestive and respiratory systems associated with machining fluid use.

The existing literature on the association between respiratory cancer and oil mist exposure is less consistent. Jarvholm, Lillienburg, Sallsten, Thiringer, and Axelson's (1981) and Jarvholm and Lavenius's (1987) studies of Swedish workers in a bearing manufacturing facility make it improbable that exposure of these workers caused any substantially increased risk of lung cancer (99% confidence interval of risk ratio 0.1–1.1). No excessive risk of lung cancer was found in the bearing factory studied by Silverstein et al. (1985). Whereas Vena, Sultz, Fiedler, and Barnes (1985) list mineral oil mist as a possible cause of increased risk of lung cancer in workers in the automobile industry, other studies do not show an increase in the risk of lung cancer as a result of exposure to oil mist (Decoufle, 1978).

In a study by Eisen et al. (1992), the SMRs for lung cancer and laryngeal cancer were both 1.02 among white males at the gear and axle plant; and the SMR among black males was 1.05 for lung cancer and 1.63 for laryngeal cancer at the same plant. At the transmissions plant, elevated SMRs were found for lung cancer (1.16) and laryngeal cancer (1.85). The SMR for lung cancer and laryngeal cancer among workers at the steering gears plant were 0.91 and 0.77, respectively. When studying the relation between cancer and specific fluid types (Tolbert et al., 1992), the SMR for lung cancer among white males exposed to soluble machining fluid was slightly elevated, whereas no excess was observed among black males. Among white males, the SMR value for laryngeal cancer was elevated in each of the exposure groups, and to the greatest degree in the group exposed to straight mineral oils, with almost a twofold increase (Eisen et al., 1994; Tolbert et al., 1992). There were too few laryngeal cancer deaths among black males exposed to straight oils to evaluate this association, but black males exposed to soluble oils exhibited unstable excess.

Water-based fluids are subject to high levels of microbial contamination, including endotoxin-producing gram-negative bacteria, and the inhalation of endotoxin has been hypothesized to exert a protective effect against lung cancer. Gram-negative bacteria (Pseudomonas) have been reported in machining fluids at concentrations as high as 108 colony-forming units per milliliter of fluid (Bill & Zubaidy, 1979).

There is also evidence of an association with elemental sulfur, commonly added to straight machining fluids (MF) to improve the integrity of the materials under extreme pressure and heat. It is not clear whether sulfur is causally related to an excessive risk of laryngeal cancer or whether the observed association is the result of unmeasured confounding by another contaminant or process feature. For example, the high stress operations that require MF enriched with sulfur are also more likely to produce polycyclic aromatic hydrocarbons (PAHs) during the process. Thus, the observed association with sulfur may be due to an association with PAHs (Eisen et al., 1994).

3.2.2. Cancer of the digestive system

The findings of a modest excess in digestive cancers are consistent with several studies of machining fluid exposed populations. Stomach cancer, often in combination with large intestine and pancreatic cancer, has been the most frequently reported cancer type in association with cutting oils.

A slight excess risk of 12% was reported for all digestive cancers for white males exposed to oil mist for at least 1 year at a U.S. engine plant (Decoufle, 1978). A twofold risk for stomach and large intestine (combined) was reported for males with more than 20 years of follow-up who had more than 5 years of exposure to oil mists prior to 1938 (Decoufle, 1978). In an engine plant in Sweden, a twofold excess was reported in digestive cancers among a subgroup of grinders with more than 5 years of exposure to soluble oils and more than 20 years of latency (Jarvholm et al., 1981). A significantly increased risk of stomach cancer was observed among grinders in a ball-bearing factory (Silverstein et al., 1985). An elevated proportional mortality ratio (PMR) of 2.0 was reported for stomach cancer as well as a statistically significant association between stomach cancer and grinding exposure. The pattern of stomach cancer suggested an association with water-based (soluble) cutting fluids. A significant number of digestive cancers, particularly pancreatic, was indicated among grinders and machinists. Jarvholm and Lavenius (1987) reported an increased risk of esophageal and gastrointestinal cancer in grinders in a bearing ring firm. A PMR of 1.9 was reported for excess pancreatic cancer among white male auto workers at a machining and assembly plant. Among those employed more than 20 years, the PMR increased to 2.30 (Vena et al., 1985).

In a study by Eisen et al. (1992), the SMRs for stomach cancer, large intestine cancer, and pancreatic cancer were 1.08, 0.92, and 0.76, respectively, among white males at the gear and axle plant; the three SMRs among black males were, respectively, 0.96, 0.59, and 1.70. At the transmissions plant, an elevated SMR was found for stomach cancer (1.26). Among white males at the steering gear plant, the SMR was 1.29 for digestive cancers, with 0.59, 1.47, and 0.87 for stomach cancer, large intestine cancer, and pancreatic cancer, respectively. In the exposure-response analysis by Tolbert et al. (1992), stomach cancer was slightly elevated in each of the three exposure groups among white males; and black males showed no excess. Whereas white males showed no excess of pancreatic cancer, black males exposed to soluble oils had a statistically significantly elevated SMR of 1.6 (95% CI 1.0–2.5).

An excessive number of esophageal cancers was found among white males at the gear and axle plant and the steering gear plant (Eisen et al., 1992). An increased risk of rectal cancer was observed for workers at the steering gear plant. The SMR values for white males suggested a slight excess of esophageal cancer and rectal cancer among those exposed to straight oils (Tolbert et al., 1992). A slight excess of rectal cancer was reported among workers exposed primarily to straight and soluble machining fluids (Decoufle, 1978). A statistically significant threefold excess of rectal cancer in a proportionate mortality study of bearing plant workers exposed to machining fluid was reported, but an association with specific fluid types was not observed (Silverstein et al., 1985). Vena et al. (1985) observed a statistically significant threefold excess among workers employed more than 20 years in an engine plant but lacked any information on personal exposure to specific machining fluid types.

3.2.3. Other cancers

Until the middle of the 20th century, the primary route of exposure to machining fluids was through the skin. The association between exposure to mineral oils and squamous cell cancer of the skin, particularly scrotum, has been well known since the 1800s (Cruickshank & Squire, 1950; Eisen et al., 1992; Waterhouse, 1971).

In a study of cancer morbidity in male turners exposed to oil mist during the 1958–1983 period, there was an increased risk of squamous cell cancer on the skin of the scrotum (Jarvholm & Lavenius, 1987). Studies by Eisen et al. (1992) and Tolbert et al. (1992) reported that an excess of leukemia was observed among white males at a gear and axle plant, and in each of the exposure groups: straight, soluble, and synthetic. Leukemia was also reported in association with machining fluids among machinists employed in a shipyard (Tola, Kalliomaki, Pukkala, Asp, & Korkala, 1988). Leukemia is known to be caused by benzene and has recently been suggested to be related to electromagnetic fields (Savitz & Calle, 1987). There was a slight excess of brain cancer among white males exposed to straight oils at the gear and axle plant (Eisen et al., 1992; Tolbert et al., 1992).

3.3. Nonmalignant Respiratory Disease

As indicated in the studies by Jarvholm and Lavenius (1987) and Eisen et al. (1992), mortality in nonmalignant respiratory diseases was not increased. In the latter analysis, an elevated risk for asthma was found at the transmissions plant and the gear and axle plant. Case studies have been reported in which occupational asthma was thought to be caused by exposure to cutting fluids (Hendy et al., 1985; Robertson, Wier, & Burge, 1988). Reports have also suggested that ethanolamines, agents commonly found in synthetic machining fluids, may be a cause of occupational asthma.

Cough and phlegm appear to be related to exposure to oil aerosol (Jarvholm, Bake, Lavenius, Thiringer, & Vokmann, 1982; Oxhoj et al., 1982). The lack of association between symptoms and concentration of oil vapor might suggest that the causative agent may be not the oil itself, but something in or on the oil droplets.

In an epidemiological study that examined acute responses to aerosols of machining fluids, Kennedy et al. (1989) reported that machine operators exposed to aerosols of various cutting oils and coolant fluids are significantly more likely to have an acute drop in FEV_1 (Forced Expiratory Volume in 1 s) over a workshift than comparable unexposed workers. The data further indicate that the likelihood of a cross-shift decrease in FEV_1 increases with increasing exposure levels above approximately 0.20 mg/m^3 of inhalable aerosol. The observation that 25–30% of workers exposed to straight mineral oils or oil emulsions had an FEV_1 response, also suggests that mild airway narrowing is a common response to such exposures. The decrement was associated with exposure to straight soluble, as well as synthetic fluids. After adjusting statistically for a history of childhood asthma, for smoking prior to lung function testing, and for race, odds ratios for an FEV_1 response of 4.4 among workers exposed to aerosols of straight mineral oils, 5.8 for oil emulsions, and 6.9 for synthetic fluids were found.

Bacterial antigens have been recognized as important causes of hypersensitivity pneumonitis. Six auto parts manufacturing workers with work related pneumonitis in association with exposure to aerosolized coolant fluid were studied (Santilli, Herd, Bernstein, & Siskosky, 1994). All workers worked near a large machine tooling area in which an aerosol was produced by recirculation of a machinery coolant under high pressure. They presented a 6-week history of work related dyspnea, cough, chest discomfort, and fatigue. Other symptoms reported were fever (2/6) and weight loss (2/6). Chest radiographic studies revealed infiltrative changes in 4 workers. Lung function tests showed that 4 workers had restrictive changes; 3 workers had decreased pulmonary diffusing capacity for carbon monoxide and the coefficient with alveolar volume, DL_{CO}/V_A (range: 55–63% predicted). After removal from their work area, all 6 workers recovered; 3 were treated with prednisone. The machining coolant was classified as a nonhazardous fluid, and contained synthetic chemicals, including high molecular weight polybutene and triazine as a microbicidal agent. Microbiological analysis indicated that the coolant contained a negligible fungal count (10/ml) and a high bacterial count ($>10^6$/ml). The predominant antigenic stimulus in the coolant was an antigen from Pseudomonas, but other microbial antigens elicited an immune response in these patients.

3.4. Skin Disorders

Skin disorders are common acute health effects from exposure to metal-working fluids (MWFs). Cutting fluids cause both allergic and irritant contact dermatitis. They often cause a cumulative insult type of irritant contact dermatitis. The exact pathogenic mechanism of cutting fluid dermatitis remains speculative. There have been conflicting opinions in regards to whether water-soluble cutting fluids or neat mineral oils are the more common cause of irritant contact dermatitis. The exact incidence of cutting fluid dermatitis among metal-workers is unknown. Predisposing risk factors for cutting fluid dermatitis are also unknown (Goh & Gan, 1994).

Several components of MWFs may be irritants, such as mineral oils, organic acids, amines, emulsifiers, preservatives, biocides, antifoams, and system cleaners (De Boer, Van Ketel, & Bruynzeel, 1989a). MWFs are also alkaline, with a pH of between 9.5 and 11.0, and this augments their irritant potential (Rycroft, 1981). Irritations are generally due to the fluid's alkalinity (high pH) or contact with a specific constituent. For example, oils may cause dermatitis or inflame hair follicles. Additives such as amines, petroleum sulfonates, and some biocides also can cause contact dermatitis, inflammation and reddening, and eventual cracking (Bienkowski, 1993).

Biocides such as formaldehyde and formaldehyde releasers, isothialinones, phenols, morpholines, ethylenediamine; and biostatic agents such as alkanolamine-borate complexes are among the common sensitizers in MWFs (De Boer, Van Ketel, & Bruynzeel, 1989b). Dissolved metal ions from the work being machined can also cause metal allergy dermatitis. Nickel (Samitz & Katz, 1975), chrome (Fregert & Gruvberger, 1976), and cobalt (Einarsson, Eriksson, Lindstedt, & Wahlberg, 1979) are three of the most common metal skin sensitizers.

The use of neat oils is associated with oil acne, folliculitis, furunculosis, occasionally irritant reactions, and rarely allergic eczematous eruptions. Prolonged contact with neat oils can result in hyperpigmentation, keratoses of the skin, epitheliomas, and skin cancers (Rycroft, 1987; Zugerman, 1986). However, oil acne does not seem to occur with the use of soluble oils, and the development of keratoses and epitheliomas is very rare. In its early stages, soluble oil dermatitis often represents as a fine follicular erythema, which may progress on to a patchy or even discoid papular eczema over the back of the hands and the forearms. Vesicular palmar and finger eczemas are rarely noted in soluble-oil dermatitis. When such findings are noted, they may be associated with allergy sensitization or with an underlying endogenous eczema (Rycroft, 1981, 1987).

Many workers with dermatitis due to contact with soluble oils may also present with a dyshidrotic eczema (De Boer, Bruynzeel, & Van Ketel, 1988). This generally reflects an irritant dermatitis in these affected workers, and is not related to an atopic constitution or nickel contact sensitization in the majority of cases.

In a field study on cutting oil dermatitis among 24 newly recruited machinists in a ball-bearing manufacturing company in Singapore over a 6-month period, the cumulative incidence of occupational dermatitis increased from 38% at week 3 to 77% at week 6. It then decreased to 50% at week 9 and thereafter remained constant at about 50% throughout the remaining study period. All cases of dermatitis were clinically diagnosed as irritant contact dermatitis from cutting fluid (neat mineral oil). However, repeated skin exposure to cutting fluids seemed to be associated with so-called hardening. The majority of machinists had mild dermatitis and was able to continue in their work (Goh & Gan, 1994).

Long-term exposure to mineral oil is a well-known cause of skin cancer on the scrotum (Waldron, 1983). Turners had an increased risk of precancerous skin lesions on the hands and the forearms (Jarvholm, Fast, Lavenius, & Tomsic, 1985). In a study of 682 turners in a bearing ring company, 5 premalignant squamous cell tumors and 8 keratoacanthomas were found between 1960 and 1980. Five of the 13 turners with primary skin tumors had another skin tumor as well. Among the 682 men there were 4 cases of scrotal cancer. No primary skin tumors were found among the turners after 1975, when acid-refined mineral oils were replaced with solvent-refined oils containing a far lower concentration of polyaromatic hydrocarbons, which are probably the cancerogenic agent in oils.

4. FACTORS INFLUENCING EXPOSURE TO METAL-WORKING FLUIDS AND QUANTITATIVE ESTIMATES

Machining fluids are particularly complex due to the wide variety of chemicals that are added to the fluids to improve their physical characteristics and to prolong their usable life. Common additives include biocides, surfactants, and corrosion inhibitors. The types of additives as well as the amount of each additive are generally determined at the plant level. Thus, the composition of the fluids differs from plant to plant. In addition to the components that are deliberately added to the fluids, several contaminants are also produced in the process of fluid use.

A study was conducted on the factors that affect worker exposures to MWFs during automotive component manufacturing: MWF type, machine type, presence of local exhaust, degree of machine enclosure, age of the machine, distance of the worker from the machine, indoor humidity, and outdoor temperature. A two-stage (9.8 and 3.5 μm) personal impactor was used to collect full-shift exposures to MWFs by 403 workers in three automotive component manufacturing facilities (Woskie, Smith, Hammond, & Hallock, 1994b). These workers in machining and grinding operations had an average total particulate exposure of 706 $\mu m/m^3$. Based on the data from a subset of 309 workers, the analysis of covariance was used to investigate which factors contribute most significantly to the variability in exposures to large (>9.8 μm aerodynamic diameter) and small (<3.5 μm) particles. For large particles, the factors of greatest importance were machine type, MWF type, indoor humidity, and outdoor temperature. For small particles, facility or plant, machine type, MWF type, indoor humidity, and degree of enclosure were the most important factors. The greatest aerosol concentrations were produced by high speed operations using a MWF with a high solute/oil content.

A retrospective exposure assessment study in the automotive industry (Hallock, Smith, Woskie, & Hammond, 1994) revealed that the arithmetic mean of machining fluid concentration for all operations was 5.42 mg/m^3 before 1970, and 1.82 mg/m^3 after 1980. Machining fluid levels prior to 1970 were generally 2 to 5 times higher than subsequent measurements. Grinding and machining operations show decreases in aerosol concentration over time; grinding values are considerably higher than machining values prior to 1970.

Personal two-stage, cascade impactor samples were collected on 475 workers at three plants (Woskie et al., 1994a). The air samples taken on workers in the selected machine type and coolant group categories were time averaged, personal, and breathing-zone samples. Some fixed location (area) samples were also collected with the same sampling device placed in close proximity to the operators as they tended their machines. Each sample was collected over a single work period (6–8 hrs). Examination of the data through log and normal probability plots and the use of Shapiro-Wilk's statistic showed the samples from exposed workers fit a log-normal distribution better than a normal distribution. For all MWF exposed workers ($n = 403$) the overall mean exposures to the three impactor size fractions collected were 180 ± 7 (*SE*) μg/m^3 for particles greater than 9.8 μm; 273 ± 10 (*SE*) μg/m^3 for particles between 3.5 and 9.8 μm; and 253 ± 8 (*SE*) μg/m^3 for particles smaller than 3.5 μm. For samples from assemblers, unexposed to machining fluids ($n = 72$), the average exposures to particles in the three size fractions were 60 ± 5 (*SE*) μg/m^3 for particles greater than 9.8 μm; 49 ± 4 (*SE*) μg/m^3 for particles between 3.5 and 9.8 μm; and 77 ± 5 (*SE*) μg/m^3 for particles smaller than 3.5 μm.

5. CONTROL MEASURES TO REDUCE EXPOSURE

Measures should be taken to limit worker exposure. The main routes of exposure are vapor or mist inhalation and skin contact, but ingestion is also possible. Inhalation potential varies with operation, fluid, and mist particle size. Semisynthetics and synthetics usually generate smaller particles than straight and soluble oils, so workers are more apt to inhale them into their deep respiratory tracts. These mists can irritate the upper respiratory tract, cause bronchitis or nasal irritation.

Exposure to straight oils appears to be associated with modest risk for several cancers. Straight oils are still in widespread use in manufacturing operations. Thus, exposure to this type of fluid may entail a significant public health effect. A general reduction in concentrations of straight mineral oil particulate in occupational environments would be prudent.

Substantial control of exposure to MWFs can be achieved by altering the machining process, changing the MWF type, enclosing the machine, and installing local exhaust. Exposures can also be reduced by increasing fresh air and decreasing recirculation of the general plant ventilation. Several examples of process modifications are the substitution of hard turning with ceramic or cubic boron nitride (CBN) inserts for conventional grinding, substitution of creep feed grinding for conventional grinding (Burke, 1994), and dry machining (Aronson, 1995).

Grinding operations need local exhaust hoods to remove the dust and grindings that otherwise cause poor shop housekeeping. Hoods on grinding wheels serve a dual purpose: (a) they protect the operator from hazards of bursting wheels, and (b) they provide for removal of generated dust and dirt. The exhaust hoods must have sufficient structural strength, and must enclose the wheel sufficiently.

Exposure to cutting fluids in machining operations constitutes one of the major causes of industrial dermatitis. Controls that have virtually eliminated dermatitis have been instituted in many machining operations (National Safety Council, 2002). For example, in one well-controlled plant that produced diesel engines, more than 2,000 workers on two shifts operating approximately 1,000 machines did not have a single case of recordable occupational dermatitis in 1977, in contrast with some poorly controlled operations in which roughly 30% of the work force had skin problems. Control programs put into effect included: (a) careful identification, by generic name, of all ingredients in the cutting fluids used; (b) programs to keep the coolant free of tramp oil, foreign particles, and dirt through the use of effective filters and redesigning the coolant flow system to eliminate "eddies" and "backwaters" of coolant; (c) daily programs to monitor coolant characteristics, such as pH, bacteria count, and so forth; (d) daily programs, such as hosing down, to keep machinery clean; (e) a redesigning of spray application to minimize coolant splash and spray; (f) use of splash goggles and curtains; (g) use of local exhaust systems and oil collectors to reduce airborne oil mist; (h) use of abundant quantities of shop rags; and (i) provision of paid wash time to allow operations to keep clean.

In the prevention of MWF dermatitis, the most important consideration is to reduce or eliminate contact of the skin with the MWF. Automation; machine design incorporating screens, local suction, and ventilation; regular checking and accurate dilution of MWFs; removal of swarf; use of protective equipment such as overalls, aprons, spectacles, sleeves, gauntlets, and gloves; protection against abrasions and injuries from sharp metal chips during cleaning of machines; and the regular use of hand cleaners and emollients are some of the measures which may also help in the prevention of MWF dermatitis (Rycroft, 1987).

The government also regulates MWFs to protect the environment. Not only should manufacturing engineers be aware of potential health hazards, but they must also understand how environmental regulations affect manufacturing operations, as failure to comply may result in severe civil or criminal penalties, or both. Although the U.S. Environmental Protection Agency does not regulate oils and coolants as hazardous wastes, some states, like New Jersey, do consider waste oils hazardous. Other states, such as Connecticut, list waste oils as regulated wastes. Each facility generating a waste oil, coolant, or another fluid should run a toxicity characteristic leachate procedure (TCLP) analysis to determine whether the waste contains listed or characteristic hazardous constituents, cadmium, for example, above regulatory levels.

6. SUMMARY AND CONCLUSIONS

Machining fluids are widely used in a variety of common industrial metalworking operations to lubricate and cool both the tool and the working surfaces. Excess of digestive and respiratory cancers has been reported in association with exposure to machining fluids. Although no significant chronic pulmonary function defects have been reported among workers exposed to oil-based MWFs, excess respiratory symptoms such as cough and phlegm have been reported. An acute cross-shift drop in FEV_1 has also been associated with exposure to all types of MWFs.

Control of exposure to MWFs can be achieved by a variety of methods. Process modification, substitution of processes or materials, isolation and enclosure of the processes, local exhaust system, and so forth, can reduce the exposure by a considerable amount.

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