Journal of Alloys and Compounds, 211/212 (1994) 385–389
JALCOM 027

Jet: physical and material aspects*

Manfred Weller
Max-Planck-Institut für Metallforschung, Seestrasse 92, 70174 Stuttgart (Germany)

Charles Wert
Department of MS&E, University of Illinois, Urbana, IL 61801 (USA)

Abstract

We have obtained jet samples (Gagat) from several well-known sources: Whitby in England, Holzmaden in Germany, New Mexico in the USA and mines in southern Poland. Chemical analysis verifies that all have the composition of a sub-bituminous coal. Their specific gravity, 1.2, is the same as that of vitrinite in coal. Their internal friction and dielectric loss spectra are similar to those of the fuel coals. Slight differences, though, show that their macromolecular structure is somewhat different from that of the fuel coals. It has, in fact, similarities to that of amber (Bernstein).

1. Introduction

Jet, a fossilized hydrocarbon, has long been used as a gemstone. Soft enough to carve easily, it also polishes to a mirror-like surface. It is extremely durable because of few mineral impurities – clay, sulphides and quartz. In spite of extensive use and world-wide occurrence, its physical and chemical properties have not been studied extensively. We first describe briefly the history of the use of jet and then cite some of its coal-like properties. We then describe measurements of mechanical and dielectric loss which show differences in polymeric character of several jets and differences from that of the coals.

2. History of its use for jewellery

The most famous modern jet comes from the Yorkshire moors in England. It was used at least as early as Roman times, was traded around Europe and was further spread by the Vikings. An excellent history of its use in that period may be found in the book by Helen Muller [1]. She also cites the extensive history of its use for jewellery worldwide.

Jet is also found in Germany (often called Gagat). An early example of its use for ornamentation was found in southern Germany. A carving of a larva of a damsel fly was found in a grave-site near Heubach in Baden-Württemberg. This ornament dates back to Stone Age times; it and others may be seen in the Württembergisches Landesmuseum in Stuttgart. This jet probably had its origin in the Posidonia shale layer of the black Jura formation (called Lias) which outcrops on the north-west edge of the Schwäbische Alb east of Stuttgart. Such jet has been found in later excavations and samples can be seen in the Urwelt Museum Hauff in Holzmaden. Muller cites many examples of ancient carvings and jewellery from southern German sites all the way down to Bodensee.

Jet was used in Germany in later times, especially by the Romans and Celts. Examples may be seen in the collection of the Landesmuseum in Stuttgart and also in the Römisch-Germanisches Museum in Köln. Other examples of jewellery from this period may be seen in museums in London, York, Edinburgh, Bergen and many other cities.

This long period of use of jet has not been accompanied by much research on its coal-like features. Perhaps this is a result of its scarcity relative to other commercial coals and perhaps because its historical role as a gem material is not much known to coal scientists. We present in this paper new measurements of its coal-like qualities.

3. Physical and chemical properties

Several physical and chemical properties make jet a desirable material for jewellery and small sculpture. Importantly, it is a hydrocarbon; its chemical composition is that of a sub-bituminous coal. Thus it is not readily attacked by chemical reagents. It is also soft in comparison with most mineral gemstones, so it

---

*Invited paper.

SSDI 0925-8388(93)00027-V

TABLE 1. Density and colour streak of several jets and other coals

Material	Density (g cm^{-3})	Colour	Comment
Yorkshire #1	1.17	Yellow–brown	Whitby jet
Yorkshire #2	1.20	Yellow–brown	Whitby jet
Poland block	1.24	Grey	Origin unknown
Acoma (USA)	1.20	Brown	New Mexico
Holzmaden	1.24	Brown	Posidonia shale
Coals			
Gem slab	1.28	Grey–brown	Origin unknown
Cannel	1.11	Brown	Origin unknown
Anthracite	1.36	Black	Pennsylvania
Carvings			
Coyote	1.19	Brown	Zuni
Bear	1.24	None	Fake
Bear (China)	1.24	Brown	Fushun coal field
Pendant	1.37	None	Fake
Button	2.44	None	Fake (glass)

carves easily (it has hardness of 4 or less on the Mohs scale). Lack of mineral inclusions means that it does not develop cracks, as often happens with the fuel coals as they weather. Thus it is durable.

To examine the characteristics of several jets, we have secured samples from well-known sites: from Whitby (courtesy of Helen Muller), from the Posidonia shale of southern Germany (courtesy of Rolf B. Hauff of the Urwelt Museum Hauff in Holzmaden), from Poland (precise source unknown) and from the Acoma deposit of New Mexico, USA. We have measured their density, their colour streak and their mechanical and dielectric loss spectroscopy (by means of which we are able to infer their polymeric character). We have also examined the sulphur distribution of a sample of Whitby jet.

The external appearance of unpolished jet shows longitudinal surface streaks characteristic of wood. The reader may see this pattern in photographs from Muller's book and from the paper of Weller and Wert [2]. Thus it is commonly believed that jet has its origin in wood and that it was altered to a coal-like material through the fossilization process characteristic of the fuel coals. However, it was protected from exposure to the usual minerals found in coal during fossilization, so it is more nearly a "pure" hydrocarbon. This feature apparently aids its durability.

3.1. Density and colour streak

We have measured the density of several raw jets and carvings using water immersion methods. The results are given in Table 1. The jets have a density of about 1.20 g cm^{-3}, close to that of the phase in coal called vitrinite, a phase derived from wood. Traverse and Kolvoord [3] cite a specific gravity of 1.2 for a piece of Utah jet, which they identify by coal science techniques as a vitrinite. Teichmüller also describes the coal-like features of several German jets and European coals [4].

A second measurement is the "colour streak", the colour of the trail of debris left on an unglazed porcelain plate when a mineral is scratched along the surface. Our measurements are listed in Table 1 as well. The jets leave a brown or brownish-black colour streak. Muller, in fact, claims that this colour is a defining characteristic of Whitby jet. However, a brown or brownish-black colour streak also occurs for some "ordinary" sub-bituminous coals which have a specific gravity near 1.2. Thus, enough variability exists that colour streak alone does not uniquely differentiate jet.

Fake materials are often substituted for jet by makers of jewellery – inferior coals, glass and plastic, among others. Density, colour streak and surface texture, among other properties, may be used to determine fakes. However, positive detection of fakes is difficult.

3.2. Chemical composition

We have measured the chemical composition of several jets. The results are given in Table 2. The carbon content is proper for the sub-bituminous class. The hydrogen, oxygen and nitrogen contents, though variable among the samples, are appropriate for such coals. The sulphur content is high – Muller reports that Whitby residents were mindful of the sulphurous smell of burning jet. She also reports seeing no pyrite, although she observed X-ray lines of sulphur using a scanning electron microscope.

We have examined the sulphur distribution of one of the jets, Yorkshire #1, using scanning electron microscopy. We also find no pyrite; all the sulphur is organic, *i.e.* it is distributed atom by atom through the hydrocarbon matter as a solid solution. If this is true of all jets, it may help to explain the remarkable chemical stability of polished jet in a moist oxidizing atmosphere. In fact, few mineral inclusions of any kind were seen in the jet, using the scanning electron microscope.

4. Mechanical and dielectric loss spectroscopy

The major part of our work was a study of the macromolecular structure of the various jets using internal friction and dielectric loss. The mechanical energy loss results from the rearrangement, under a mechanical stress, of specific segments of a macromolecular solid. The internal friction is a maximum for an oscillating stress at appropriate values of frequency and temperature. These phenomena have long been observed for synthetic polymers [5–7]. We have also observed such

TABLE 2. Chemical composition of several jets

Element (wt.%)	Yorkshire #1	Yorkshire #2	Yorkshire #3	Acoma (USA)	Holzmaden	Poland	Utah	Whitby
Carbon	82.48	81.96	80.77	79.40	80.50	83.50	76.21	75.2
Hydrogen	11.28	7.88	7.94	6.85	7.65	6.49	6.33	7.0
Nitrogen	0.48	1.26	1.31	0.88	1.35	1.20	0.63	0.7
Oxygen	3.78	6.8	7.9	10.9	8.15	8.4	11.84	12.5
Sulphur	1.83	1.64	2.19	1.96	2.38	0.54	3.10	4.6

losses for natural macromolecular solids (wood, coal, oil shale, amber and cork) [8–11].

4.1. Loss spectra

The internal friction spectra of two natural hydrocarbons (Fig. 1) form the basis for our analysis. The spectrum for a typical bituminous coal (coal from the Fushun field of north-east China) shows three loss peaks. That at lowest temperature, the γ peak, occurs near 120 K for a frequency near 1 Hz. This peak (observed in a great many synthetic polymers) is attributed (by polymer scientists) to the rearrangement, under a stress, of main-chain units of the macromolecular structure. The peak near 200 K, the β peak, is attributed to the motion of side-units. The peak at highest temperature, the α peak, is attributed to the glass transition temperature. Similar plots are reported for synthetic polymers, many of which show these three peaks at roughly the same temperatures.

We have made similar measurements for coals of rank from lignite to anthracite. All three peaks exist for all coals, although the amplitudes vary with rank. For wood the γ peak is absent, as is seen for a measurement on a specimen of spruce (Fig. 1). This absence implies that wood lacks the main-chain units responsible for the γ peak. The peak for side-unit motion, the β peak, is present. All woods seem to have such a spectrum.

We now report similar measurements for several jets. First we show data in Fig. 2 for three jets from Yorkshire. They show similar loss peaks, nearly at the same temperatures as for the coals, but not exactly so. Indeed, the polymeric character of #1 is rather different from that of #2 and #3. Whether these differences in peak position and peak height are related to a variation in chemistry is not clear. Certainly the differences in peak position are larger than we have found for the bituminous coals of the same compositions.

A second set of measurements (Fig. 3) is for jets from Germany, Poland and the USA. They have quite different loss spectra from those of the Yorkshire jets. The low temperature peak, the γ peak, is absent. This implies the absence of the main-chain structures present in the usual bituminous coals. The β peak is present

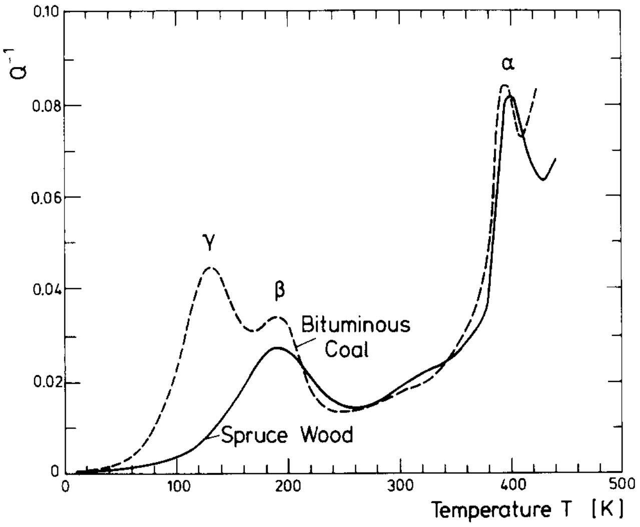

Fig. 1. Internal friction spectrum for a sample of bituminous coal and a sample of spruce wood. Coal (in common with many synthetic polymers) has three prominent peaks: a peak at 120 K (for this frequency of 1 Hz), another at 200 K and a high, sharp peak at 400 K. Wood lacks the peak at 120 K.

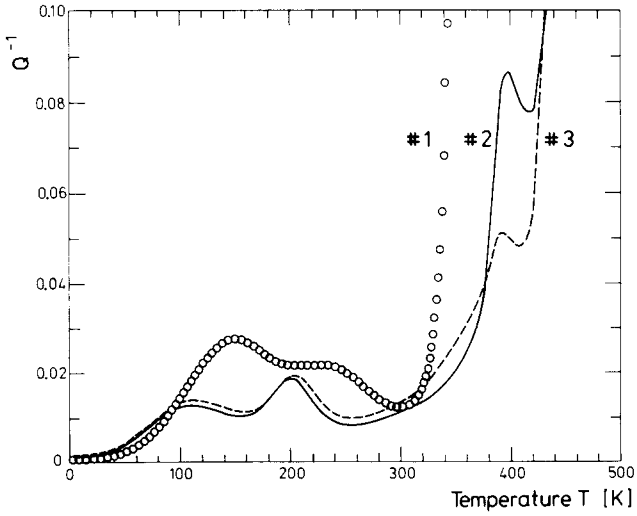

Fig. 2. Measurements for three specimens of Yorkshire jet. Three peaks are present, but they are not the same for the three specimens, implying differences in polymeric character among the three.

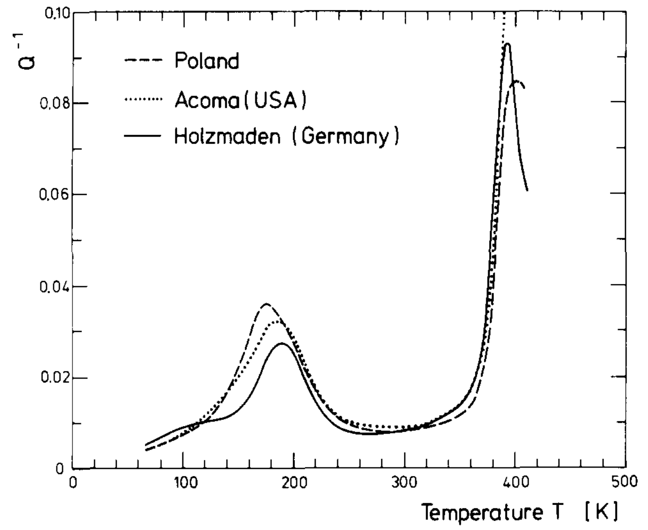

Fig. 3. Measurements for specimens from Poland, southern Germany and the south-western desert of the USA. These are similar to each other, but the low temperature peak (near 180 K) is dissimilar from the peaks of coal, wood and the Yorkshire jets.

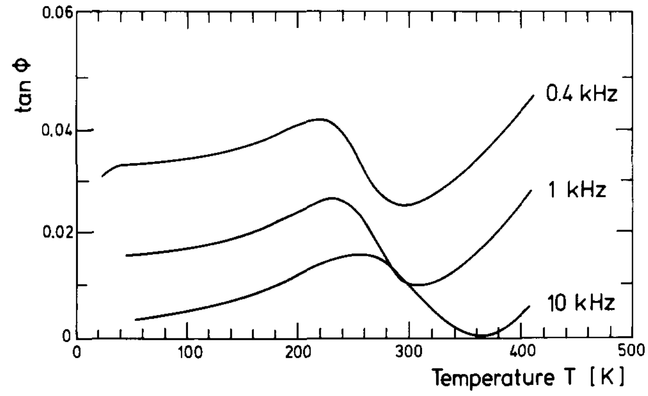

Fig. 4. Dielectric loss of a wafer of Holzmaden jet. Measurements were made at three widely spaced frequencies, allowing the rate constants to be measured accurately.

for all three, although at a slightly lower temperature than that of wood and amber.

The measurements show that the jets are generally similar to the coals, yet they show sufficient differences from the bituminous coals to indicate that their polymeric nature is not identical to that of the fuel coals.

We have measured the dielectric loss of a wafer of the Holzmaden jet. Measurements of the tangent of the phase angle (θ) between P and E at three widely spaced frequencies are shown in Fig. 4. The prominent peak between 200 and 250 K is the analogue of the mechanical loss peak of Fig. 3. Its presence in dielectric loss shows that the mechanical dipole responsible for the internal friction peak is also an electric dipole.

4.2. *Activation energies and rate constants of the peaks*

We have reported earlier the activation energies of the two low temperature peaks for coal. Using the temperature-shift-with-frequency technique, we have measured the activation energy for the Holzmaden jet. The pertinent numbers are listed in Table 3 for both internal friction and dielectric loss. Clearly the activation energy for the loss peaks around 200 K for the Holzmaden jet corresponds to that of the β peak for coal.

TABLE 3. Rate constants for internal friction and dielectric loss in jets and coals

	H (eV)	τ_0 (s)
Coals		
γ peak	0.18	1.1×10^{-8}
β peak	0.45	1.3×10^{-13}
Jets		
β peak	0.47	1.6×10^{-13} (internal friction)
β peak	0.48	1.2×10^{-14} (dielectric loss)

5. Summary

Jet is a coal-like solid with its origin in wood; it is often found in geological strata which have the same age as adjacent coal seams. During coalification, it seems to have been protected (perhaps by overlying shale layers) from massive intrusion of clay and other mineral debris characteristic of the fuel coals. It does contain sulphur, but for good carving jet (termed "hard jet" by Muller) only in organic (*i.e.* solid solution) form. Pyrite is found in widely spaced cleats, but it can be avoided by proper selection of specimens. Because of this lack of mineral content, jet is extremely stable against atmospheric and water attack, so carved objects do not easily degrade.

The specific gravity of jet is about 1.2, the same as for vitrinite in normal bituminous coals. Its carbon content covers the sub-bituminous range. Our internal friction studies show a wide variation in macromolecular structure. Some jets show a spectrum similar to that of wood. Among these are the jets from southern Germany (Holzmaden and Schwäbish Gmünd), from Poland and from New Mexico, USA. The Yorkshire jets, on the other hand, show a spectrum more like that of the fuel coals. We conclude that the jets are a "generic" class of coal with a chemistry and density appropriate for the sub-bituminous rank, but whose coalification processes seem to be at different stages. The Yorkshire jets seem more "mature" and the German jets seem "younger" in terms of development of a long-chain macromolecular structure.

Acknowledgments

We are grateful to many people for assistance. Helen Muller provided us with samples of Yorkshire jet from known localities. She also gave us a great deal of counsel about the nature of jet. Dipl.-Geol. Rolf B. Hauff of the Urwelt Museum Hauff in Holzmaden provided us with excellent samples of Holzmaden Gagat. We thank Professor Haenel of the Max-Planck-Institut für Kohleforschung, Mülheim/Ruhr for analyses. We thank Irena Dumler of the Materials Research Laboratory in Urbana for scanning electron microscopy observations of the sulphur distribution in a jet specimen. Mr. Rahn of the Max-Planck-Institut, Stuttgart prepared the specimens for measurement, Mrs. Wieland made the internal friction measurements and Mrs. Woop made the dielectric loss measurements. Finally, the Alexander von Humboldt Stiftung, Bonn provided fellowship assistance for one of us (C.W.). Without all that help and the steady support and interest of Dr. Jörg Diehl, this work and its predecessor studies would never have been possible.

References

1 H. Muller, *Jet*, Butterworths, London, 1987.

2 M. Weller and C. Wert, *Die Geowissenschaften, 11* (1993) 319.

3 A. Traverse and R.W. Kolvoord, *Science, 159* (1968) 302.

4 M. Teichmüller, *Int. J. Coal Geol., 20* (1992) 1.

5 N.G. McCrum, B.E. Read and G. Williams, *Anelastic and Dielectric Effects in Polymeric Solids*, Wiley, New York, 1967.

6 T. Murayama, *Dynamic Mechanical Analysis of Polymeric Materials*, Elsevier, Amsterdam, 1978.

7 S.A. Bradley and S.H. Carr, *J. Poly. Sci., Poly. Phys. Ed., 14* (1976) 1.

8 C.A. Wert and M. Weller, *J. Appl. Phys., 53* (1982) 6505.

9 M. Weller and C.A. Wert, *J. Phys. (Paris), Colloq. C9, 44* (1982) 191.

10 C.A. Wert, M. Weller and D. Caulfield, *J. Appl. Phys., 56* (1984) 2453.

11 M. Weller and C. Wert, *Fuel, 63* (1984) 891.