Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

LA-UR 94-1730

Conf-940598--1

TITLE: Mechanical Behavior of $MoSi_2$ and $MoSi_2$ Composites

AUTHOR(S): John J. Petrovic, MST-4

SUBMITTED TO: 3rd International Conference on High-Temperature Intermetallics
May 16-19, 1994
Hyatt Islandia
San Diego, California

MECHANICAL BEHAVIOR OF $MoSi_2$ AND $MoSi_2$ COMPOSITES

John J. Petrovic
Ceramic Science & Technology Group
Materials Science & Technology Division
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ABSTRACT:

$MoSi_2$ is a key member of the new class of high temperature structural silicide materials. Important features of the mechanical behavior of $MoSi_2$ and $MoSi_2$ composites are reviewed. The mechanical properties of $MoSi_2$ single crystals, polycrystalline $MoSi_2$, and $MoSi_2$-based composites are discussed in association with properties such as elevated temperature deformation and low temperature fracture toughness. Interrelationships between single crystal, polycrystal, and composite mechanical behavior are identified.

INTRODUCTION:

Materials based on the silicide $MoSi_2$ hold considerable promise for a wide variety of elevated temperature structural applications at temperatures above 1000 °C [1-3]. Industrial applications include furnace elements and components, power generation components, high-temperature heat exchangers, gas burners, lances for liquid metals and glasses, igniters, and high-temperature filters. Aerospace applications include turbine aircraft engine hot-section components such as blades, vanes, combustors, nozzles, and seals. Automotive applications involve components such as turbocharger rotors, valves, glow plugs, and advanced turbine engine parts.

$MoSi_2$ possesses a combination of properties which make it attractive as a high temperature material. It has a high melting point of 2030 °C, with excellent high temperature oxidation resistance, essentially equivalent to the oxidation resistance of the silicon-based structural ceramics SiC and Si_3N_4. It exhibits a brittle-to-ductile transition in the vicinity of 900 °C, as determined by the compression of single crystals. $MoSi_2$ is thermodynamically stable with a wide variety of potential ceramic reinforcements for composites, including ceramics such as SiC, Si_3N_4, ZrO_2, Al_2O_3, mullite, YAG, Y_2O_3, TiB_2, and TiC. Its stability extends essentially to the full range of important structural ceramic materials. $MoSi_2$ can be alloyed with other high melting point silicides as another potential avenue to improve its properties. Possible silicide alloying species are WSi_2, $NbSi_2$, $CoSi_2$, Mo_5Si_3, and Ti_5Si_3. $MoSi_2$ is an abundant, relatively low cost material which is non-toxic and environmentally benign. Because of its relatively high electrical conductivity, $MoSi_2$ and $MoSi_2$-based materials can be electro-discharge machined (EDM).

There are four general aspects to the structural use of $MoSi_2$ materials. The first is as a matrix for $MoSi_2$-based composites. This aspect has seen the most activity to date. However, a second aspect is the use of $MoSi_2$ as a reinforcement for structural ceramic matrix composites. Very little work has been done to date in this area. Third, $MoSi_2$ is a potential high temperature joining material for structural ceramics, due to its oxidation resistance and high melting point. Finally, $MoSi_2$-based materials can serve as oxidation-resistant coatings for refractory metals and carbon-based materials.

The silicide $MoSi_2$ can best be described as a borderline ceramic-intermetallic compound. A generic definition of a ceramic is that a ceramic is a solid, iono-covalent, inorganic compound. Applying this definition to $MoSi_2$ indicates its borderline nature, since it differs from a ceramic only because its atomic bonding is a mixture of covalent and metallic. $MoSi_2$ possesses ceramic-like high temperature oxidation resistance, and metal-like electrical conductivity. This material exhibits ceramic-like brittleness at room temperature, and hence fracture toughness is a major issue. It also shows metal-like plasticity at elevated temperatures, with the result that creep resistance is a major issue.

For $MoSi_2$-based materials to be successful in elevated temperature structural applications, it is necessary to improve both high temperature strength and creep resistance, as well as low temperature fracture toughness. In this paper, important aspects of the mechanical behavior of $MoSi_2$ and $MoSi_2$ composites are reviewed. This is best accomplished by considering the behavior of single crystals, polycrystals, and composites based on this material.

SINGLE CRYSTAL $MoSi_2$:

The crystal structure of $MoSi_2$ is the $C11_b$ type, as shown in Figure 1. It can be viewed as the stacking of three body centered sub-unit cells. Unal et.al. [4] and Maloy et.al. [5] have analyzed the possible slip systems in $MoSi_2$. Potential slip systems are shown in Table 1. Important burgers vectors for slip are shown in Figure 2. In general, the Peierls stress for a given slip system is expected to decrease with increasing ratio of slip plane spacing/Burgers vector, d/b. Thus, in Table 1, the slip systems with the highest values of d/b might be expected to be favored in the deformation of $MoSi_2$. However, as will be shown, this is not necessarily always the case for this material.

The mechanical behavior of $MoSi_2$ single crystals has been studied to a limited extent [5,6-10]. Umakoshi et.al. [7] were the first to determine the compressive deformation of $MoSi_2$ single crystals as a function of temperature and crystallographic orientation. They determined that the onset of plastic deformation in single crystals began at a temperature of approximately 900 °C. They also showed that crystallographic orientation had a significant effect on yield stress. Specifically, the yield stress of crystals in the [001] orientation was observed to be very much higher than the yield stress in other crystallographic orientations.

Yield stresses of $MoSi_2$ single crystals as determined by Maloy [5,10] are shown in Figure 3. As with previous work, the onset of plastic deformation appears to occur at 900 °C in $MoSi_2$ single crystals. Yield strengths in the [001] orientation were observed to be significantly higher than those reported by Umakoshi et.al. [7], with a yield stress value of 600 MPa at 1600 °C observed. Yield stress values in the [001] direction were noted to be sensitive to the applied strain rate, and increased significantly with increasing strain rate. Strengths in other crystallographic orientations were much lower than those in the [001] direction.

Slip systems which have been observed to operate in elevated temperature deformation of $MoSi_2$ single crystals are shown in Table 2 [5,10]. At the lower temperatures, the {013}1/2<331> slip system is observed to be active, as well as the slip systems {011}<100> and {110}1/2<111>. At higher temperatures, the {110}, {011}, and {001} slip planes have been observed, with <100>, <110>, and 1/2<111> Burgers vectors.

Nakamura et.al. [9] have determined the elastic stiffnesses and compliance constants for $MoSi_2$ single crystals. These values are shown in Table 3. From these values, they have estimated the following values for polycrystalline $MoSi_2$: Bulk modulus K = 210 GPa, Young's modulus E = 440 GPa, Shear modulus G = 191 GPa, Poisson's ratio $\nu = 0.151$.

POLYCRYSTALLINE $MoSi_2$:

The strength of polycrystalline $MoSi_2$ generally depends on the silica content and the grain size of the material. High silica contents and small grain sizes tend to promote grain boundary sliding as a deformation mechanism, which can operate at lower stress levels than dislocation plasticity. The yield stress behavior of low silica content, relatively large grained $MoSi_2$ polycrystalline material has been studied by Aikin [11], and is shown in Figure 4. Under compressive deformation, polycrystalline $MoSi_2$ can exhibit significant plastic deformation at temperatures as low as 900 °C. However, in bending deformation, the brittle-to-ductile transition temperature has been observed to be between 1300-1400 °C. As shown in Figure 4, the yield stress of polycrystalline $MoSi_2$ is in the vicinity of 200 MPa at 1400 °C for both compression and bending modes of mechanical loading.

Gibala et.al. [12] have shown that prestraining polycrystalline $MoSi_2$ at an elevated temperature of 1300 °C can significantly lower the brittle-to-ductile transition temperature of the material as measured in compression. The prestraining has been observed to lower the transition temperature to as low as 750 °C. This transition temperature lowering is attributed to the introduction of mobile dislocations into the material as a result of the elevated temperature prestrain. The presence of greater numbers of mobile dislocations then promotes increased plastic deformation at the lower temperatures.

Sadananda et.al. [13] have shown that the elevated temperature creep behavior of polycrystalline $MoSi_2$ is sensitive to grain size, as shown in Figure 5. This sensitivity of creep rate to grain size in $MoSi_2$ is higher than expected, since elevated temperature creep appears to be controlled primarily by dislocation glide/climb processes, as well as grain boundary sliding accommodated by dislocation plasticity. The grain size exponent observed for $MoSi_2$ is in the range of 5-8. For Nabarro-Herring creep one expects a grain size exponent of 2, while for Coble creep a grain size exponent of 3 is expected. These grain size effects on the elevated temperature deformation of polycrystalline $MoSi_2$ are unusual and not fully understood at the present time. However, they also occur in other intermetallic systems as well [13].

At low temperatures, polycrystalline $MoSi_2$ is a brittle material that is similar to ceramics in this characteristic. Wade and Petrovic have determined that at room temperature, the fracture mode of $MoSi_2$ is 75% transgranular and 25% intergranular [14]. The room temperature fracture toughness of $MoSi_2$ is 3 Mpa $m^{1/2}$ [14,15]. This fracture toughness value is similar to that of a polycrystalline, equiaxed Si_3N_4 ceramic material which is densified without the use of densification aids.

The presence of a silica phase in polycrystalline $MoSi_2$ has been observed to have a detrimental effect on the fracture toughness of this material, particularly at elevated temperatures [16]. Figure 6 shows fracture toughness as a function of temperature, for polycrystalline $MoSi_2$ both without and with carbon additions. Without a carbon addition, silica in the $MoSi_2$ microstructure causes the toughness to decrease with increasing temperature, due to grain boundary fracture effects. However, with carbon additions, the toughness increases, due to the operation of dislocation plasticity. A fracture toughness of nearly 12 Mpa $m^{1/2}$ is observed at 1400 °C for polycrystalline $MoSi_2$ with added carbon to remove the silica phase. A transition from intergranular to transgranular fracture in polycrystalline $MoSi_2$ at elevated temperatures has been observed as a result of these carbon additions [16].

$MoSi_2$-BASED COMPOSITES:

Creep Behavior:

The creep behavior of $MoSi_2$-based materials has recently been reviewed by Sadananda and Feng [17]. A number of factors have been observed to improve the elevated temperature creep resistance of these materials. The introduction of SiC whiskers significantly improves high temperature creep resistance. Creep rates of material containing 20 vol.% SiC whiskers have been reported to be approximately two orders of magnitude lower than those of polycrystalline $MoSi_2$. Alloying with WSi_2 has also been observed to improve creep rates, but to a lesser extent than SiC whisker additions. Effects of whisker additions and alloying have been seen to be additive. SiC whiskers have generally been observed to be more effective than SiC particles in terms of improving creep resistance, indicating an importance of reinforcement shape morphology on creep behavior of these composites.

An important observation which has been made is related to the competing effects of SiC reinforcing addition volume fraction and associated grain size of the $MoSi_2$ matrix on the creep resistance of SiC-$MoSi_2$ composites. As SiC is added, the grain size of the $MoSi_2$ is reduced. This leads to a maximum in the composite creep rate with volume fraction of SiC addition, as shown in Figure 7. Creep rates for 5,10, and 20 vol.% SiC particle reinforced composites are higher than those of unreinforced $MoSi_2$, while creep rates of a 40 vol.% SiC particle composite are substantially lower. This behavior is related to the fact that, with increasing SiC addition, the grain size of the $MoSi_2$ matrix is reduced. The reduced matrix grain size then promotes the operation of grain boundary sliding creep mechanisms.

The creep mechanisms in $MoSi_2$-based composites appear to be a combination of dislocation glide/climb processes, as well as grain boundary sliding. The extent of grain boundary sliding depends on the amount of silica phase present in the composite microstructure, as well as the grain size of the $MoSi_2$ matrix. Wiederhorn et.al. [18] have shown that creep rates in tension are higher than creep rates in compression, due to the operation of these grain boundary sliding processes. Stress exponents for the creep of $MoSi_2$ and many $MoSi_2$ composites are in the vicinity of 2-5, while creep activation energies are in the range of 300-600 kJ/mole. The stress exponents suggest dislocation glide/climb processes and/or grain boundary sliding accommodated by dislocation plasticity. Although self-diffusion values for $MoSi_2$ have not been extensively established, published values are 250 kJ/mole for Si in $MoSi_2$ and 350-540 kJ/mole for Mo in $MoSi_2$ [19]. These self-diffusion values are in the range of observed creep activation energies.

Figure 8 shows a comparison of $MoSi_2$ composite creep rates to those of other metals and intermetallics [17]. It is clear that $MoSi_2$ materials are significantly more creep resistant at elevated temperatures than these other materials. Although $MoSi_2$-based materials are not yet as creep resistant as silicon-based structural silicides such as Si_3N_4 and SiC, with continued materials development, the creep resistance of these structural silicide materials may match or even surpass that of the structural ceramics.

Crack Growth Behavior:

The elevated temperature crack growth behavior of $MoSi_2$ materials under static and fatigue conditions has been studied by Ramamurty et.al. [20,21]. Crack growth occurs by grain boundary controlled mechanisms. Crack growth behavior has been observed to be significantly affected by additions of carbon to the microstructure [21]. Crack growth rates at 1300 °C are reduced by approximately two orders of magnitude and the ΔK for initial crack growth increased by a factor of two with the addition of carbon. This reflects a reduction in the amount of microstructural silica present, due to reactions between the silica phase and the carbon to form in-situ SiC. Figure 9 compares cyclic fatigue crack growth rates of $MoSi_2$ materials to a number of other high temperature materials [20]. The $MoSi_2$ materials compare quite favorably, both in terms of initial crack growth and the sensitivity of crack growth rate to the applied cyclic stresses.

Fracture Toughness:

Evans has nicely summarized the results of years of research on the toughening of structural ceramic materials [22]. The toughest ceramics have been composites incorporating continuous fiber reinforcements. The next toughest ceramics are those with ductile metal second phase dispersions. This is followed by ceramic materials incorporating zirconia transformation toughening effects. Second phase whiskers/particles/platelets fall next in the heirarchy of toughening mechanisms. Finally, matrix microcracking constitutes the least effective, although still significant, toughening approach.

In the work performed on $MoSi_2$ composites to date, the fracture toughness heirarchy which has been observed for ceramics has also been observed for $MoSi_2$ materials, as shown in Table 4. The toughest materials have incorporated refractory metal wires. These materials exhibit the "graceful failure" fracture morphology observed in continuous fiber ceramic matrix composites [23]. Composites containing Ta particles have shown the ductile phase toughening effects associated with the plastic deformation of ductile particles bridging the crack opening [24]. However, it is important to note that refractory metal reinforcements in $MoSi_2$ composites can exhibit significant reaction and oxidation problems.

ZrO_2 transformation toughening effects have been employed to toughen ZrO_2 particle-$MoSi_2$ matrix composites [25]. Figure 10 shows the fracture toughness of these composites as a function of the amount of Y_2O_3 stabilizer in the ZrO_2 phase. Unstabilized ZrO_2 is observed to produce the maximum toughening effects in these types of composites. The unstabilized ZrO_2 tetragonal-to-monoclinic martensitic phase transformation occurs spontaneously upon cooling in the vicinity of 1100 °C. Thus, this transformation occurs above the brittle-to-ductile transition temperature of the $MoSi_2$ phase, where the $MoSi_2$ is still ductile. Since the ZrO_2 tetragonal-to-monoclinic phase transformation produces an approximately 4% expansional volumetric strain, this transformation effectively "pumps" dislocations into the $MoSi_2$ matrix, with potentially beneficial effects on the brittle-to-ductile transition temperature of ZrO_2-$MoSi_2$ composites, as well as on improvements to the fracture toughness.

SUMMARY:

The above discourse has been an attempt to review the current salient features of the mechanical behavior of $MoSi_2$ and $MoSi_2$ composites. The mechanical behavior of $MoSi_2$ single crystals was discussed, and possible and observed slip systems described. A most interesting feature of single crystal behavior is the extremely high strengths seen in the [001] orientation at elevated temperatures. The elevated temperature mechanical properties of polycrystalline $MoSi_2$ improve with decreasing silica content and increasing grain size. The brittle-to-ductile transition temperature of polycrystalline $MoSi_2$ can be reduced by the introduction of mobile dislocations as a result of high temperature prestraining. Transgranular fracture is the primary fracture mode of polycrystalline $MoSi_2$ at room temperature. Carbon additions improve elevated temperature fracture toughness by removing deleterious silica phases.

Creep, crack growth, and fracture toughness can be substantially improved by the development of $MoSi_2$-based composites. An important feature associated with creep resistance is the balance between reinforcement strengthening and matrix grain size reduction due to the reinforcing phase. Creep mechanisms involve dislocation glide/climb and grain boundary sliding accommodated by plastic deformation. Good elevated temperature crack growth behavior is exhibited by $MoSi_2$-based composites, and is further improved by carbon additions. Toughening mechanisms for $MoSi_2$-based composites parallel those for structural ceramics. Continuous fiber reinforcement, ductile phase toughening, transformation toughening, second phase whiskers and particles, and matrix microcracking are all mechanisms operative in $MoSi_2$-based composites.

ACKNOWLEDGEMENTS:

The author gratefully acknowledges the DOE Advanced Industrial Materials Program, the Office of Naval Research, and the DOE Office of Basic Energy Sciences for supporting various aspects of the research at the Los Alamos National Laboratory on $MoSi_2$-based structural silicides, which are associated with the content of the present review paper.

REFERENCES:

1. J.J. Petrovic, "$MoSi_2$-Based High-Temperature Structural Silicides", *MRS Bulletin*, XVIII (1993), 35.

2. J.J. Petrovic and A.K. Vasudevan, "Overview of High Temperature Structural Silicides", *Mat. Res. Soc. Symp. Proc.*, 322 (1994), 3.

3. A.K. Vasudevan and J.J. Petrovic, "A Comparative Overview of Molybdenum Disilicide Composites", *Mat. Sci. Eng.*, A155 (1992), 1.

4. O. Unal, J.J. Petrovic, D.H. Carter, and T.E. Mitchell, "Dislocations and Plastic Deformation in Molybdenum Disilicide", *J. Am Ceram. Soc.*, 73 (1990), 1752.

5. S.A. Maloy, T.E. Mitchell, J.J. Petrovic, A.H. Heuer, and J.J. Lewandowski, "The Temperature and Strain Rate Dependence of the Flow Stress in $MoSi_2$ Single Crystals", *Mat. Res. Soc. Symp. Proc.*, 322 (1994), 21.

6. Y. Umakoshi, T. Hirano, T. Sakagami, and T. Yamane, "Slip Systems and Hardness of $MoSi_2$ Single Crystals", *Scripta Met.*, 23 (1989), 87.

7. Y. Umakoshi, T. Sakagami, T. Hirano, and T. Yamane, "High Temperature Deformation of $MoSi_2$ Single Crystals with the $C11_b$ Structure", *Acta Metall. Mater.*, 38 (1990), 909.

8. K. Kimura, M. Nakamura, and T. Hirano, "High Temperature Deformation Behaviour of $MoSi_2$ and Wsi_2 Single Crystals", *J. Mat. Sci.*, 25 (1990), 2487.

9. M. Nakamura, S. Matsumoto, and T. Hirano, "Elastic Constants of $MoSi_2$ and Wsi_2 Single Crystals", *J. Mat. Sci.*, 25 (1990), 3309.

10. S.A. Maloy, "Dislocations and Mechanical Properties of Single Crystal $MoSi_2$", Ph.D Thesis, Department of Materials Science & Engineering, Case Western Reserve University, Cleveland, Ohio (1994).

11. R.M. Aikin, Jr., "On the Ductile-to-Brittle Transition Temperature in $MoSi_2$", *Scripta Met.*, 26 (1992), 1025.

12. R. Gibala, H. Chang, and C.M. Czarnik, "Plasticity Enhancement Processes in $MoSi_2$-Base Materials", *Mat. Res. Soc. Symp. Proc.*, 322 (1994), 175.

13. K. Sadananda, C.R. Feng, H.N. Jones, and J.J. Petrovic, "Creep of Intermetallic Composites", Proceedings, Int. Symp. on Structural Intermetallics, Seven Springs, September 26-30, 1993, in press (1993).

14. R.K. Wade and J.J. Petrovic, "Fracture Modes in $MoSi_2$", *J. Am. Ceram. Soc.*, 75 (1992), 1682.

15. R.K. Wade and J.J. Petrovic, "Processing Temperature Effects on Molybdenum Disilicide", *J. Am. Ceram. Soc.*, 75 (1992), 3160.

16. S.A. Maloy, J.J. Lewandowski, A.H. Heuer, and J.J. Petrovic, "Effects of Carbon Additions on High Temperature Mechanical Properties of Molybdenum Disilicide", *Mat. Sci. Eng.*, A155 (1992), 159.

17. K. Sadananda and C.R. Feng, "A Review of Creep of Silicides and Composites", *Mat. Res. Soc. Symp. Proc.*, 322 (1994), 157.

18. S.M. Wiederhorn, R.J. Gettings, D.E. Roberts, C. Ostertag, and J.J. Petrovic, "Tensile Creep of Silicide Composites", *Mat. Sci. Eng.*, A155 (1992), 217.

19. J.J. Petrovic and J.S. Idasetima, "Sintering of $MoSi_2$", *Mat. Res. Soc. Symp. Proc.*, 322 (1994), 107.

20. U. Ramamurty, A.S. Kim, S. Suresh, and J.J. Petrovic, "Micromechanisms of Creep-Fatigue Crack Growth in a Silicide-Matrix Composite with SiC Particles", *J. Am. Ceram. Soc.*, 76 (1993), 1953.

21. U. Ramamurty, S. Suresh, and J.J. Petrovic, "The Effect of Carbon Addition on Elevated Temperature Crack Growth Resistance in $(Mo,W)Si_2$-SiC_p Composite", submitted for publication, 1994.

22. A.G. Evans, "Perspective on the Development of High-Toughness Ceramics", *J. Am. Ceram. Soc.*, 73 (1990), 187.

23. M.J. Maloney and R.J. Hecht, "Development of Continuous-Fiber-Reinforced $MoSi_2$-Base Composites", *Mat. Sci. Eng.*, A155 (1992), 19.

24. R.G. Castro, R.W. Smith, A.D. Rollett, and P.W. Stanek, "Ductile Phase Toughening of Molybdenum Disilicide by Low Pressure Plasma Spraying", *Mat. Sci. Eng.*, A155 (1992), 101.

25. J.J. Petrovic, A.K. Bhattacharya, R.E. Honnell, T.E. Mitchell, R.K. Wade, and K.J. McClellan, "ZrO_2 and ZrO_2-SiC Particle Reinforced $MoSi_2$ Matrix Composites", *Mat. Sci. Eng.*, A155 (1992), 259.

Table 1: Possible Slip Systems in $MoSi_2$ [5].

Slip System	Slip Plane Spacing d(nm)	Burgers Vector b(nm)	d/b ratio
{013}<100>	0.202	0.3204	0.630
{010)<100>	0.160	0.3204	0.499
{110}<110>	0.226	0.4531	0.499
{110}1/2<111>	0.226	0.4531	0.499
{001}<100>	0.131	0.3204	0.409
{011}<100>	0.0989	0.3204	0.309
{110}1/2<331}	0.226	0.7848	0.288
{013}1/2<331>	0.202	0.7848	0.257
{011}1/2<111>	0.0989	0.4531	0.218

Table 2: Slip systems observed in $MoSi_2$ single crystals [5,10].

Crystal Orientation	Temperature (°C)	Strain Rate (s^{-1})	Burgers Vector	Slip Plane
[001]	900-1100	10^{-5}	1/2<331> 1/2<111> <110>	{013}
	1200-1400	10^{-5}	<100> <110> 1/2<111>	{001} {110}
	1400-1600	10^{-4}	<100> <110> 1/2<111>	{001} {110}
[021]	1000-1200	10^{-4} and 10^{-5}	1/2<111>	{110}
	1300-1400	10^{-4} and 10^{-5}	<100>	{001}
[771]	1000-1100	10^{-4}	1/2<331> 1/2<111> <110>	{013}
	1000	10^{-5}	<100>	{011}
	1100-1300	10^{-5}	<100>	{011}
	1200-1300	10^{-4}	<100>	{011}

Table 3: Elastic stiffness and compliance constants for single crystal $MoSi_2$ [9].

Elastic Stiffness C_{ij}	**Elastic Compliance S_{ij}**
C_{11} 4.170	S_{11} 2.611
C_{33} 5.145	S_{33} 2.051
C_{44} 2.042	S_{44} 4.897
C_{66} 1.936	S_{66} 5.165
C_{12} 1.042	S_{12} -0.586
C_{13} 0.838	S_{13} -0.330

Table 4: Room temperature fracture toughness of $MoSi_2$-Based Composites.

Type of Reinforcement	Highest Fracture Toughness (Mpa $m^{1/2}$)
Refractory metal (Nb, W, Mo) wires	Greater than 15
20 vol.% Ta particles	10
20 vol.% ZrO_2 particles	7.8
20 vol.% SiC whiskers	4.4
20 vol.% SiC particles	4.0
Polycrystalline $MoSi_2$	3

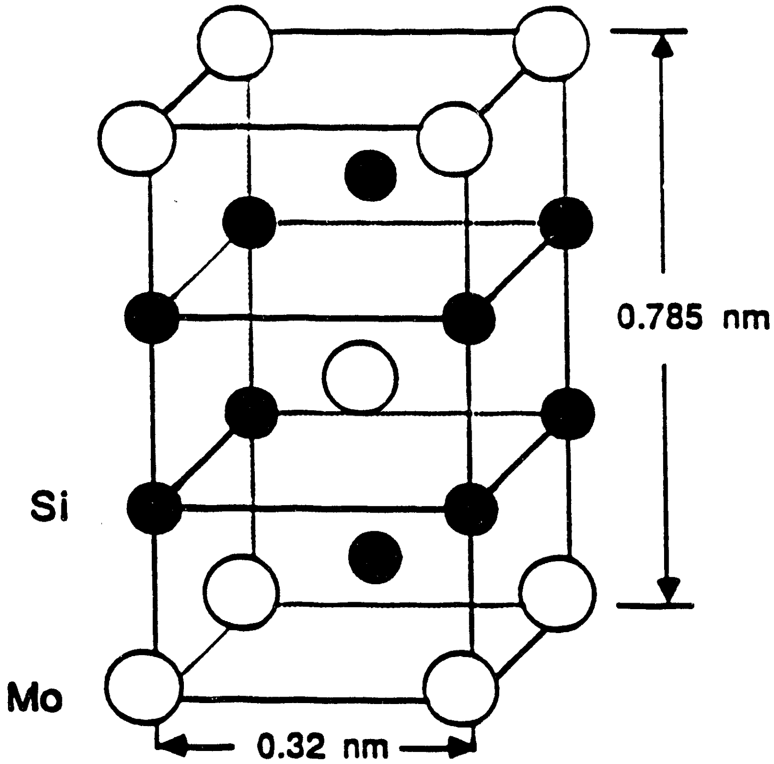

Figure 1: Crystal structure of $MoSi_2$.

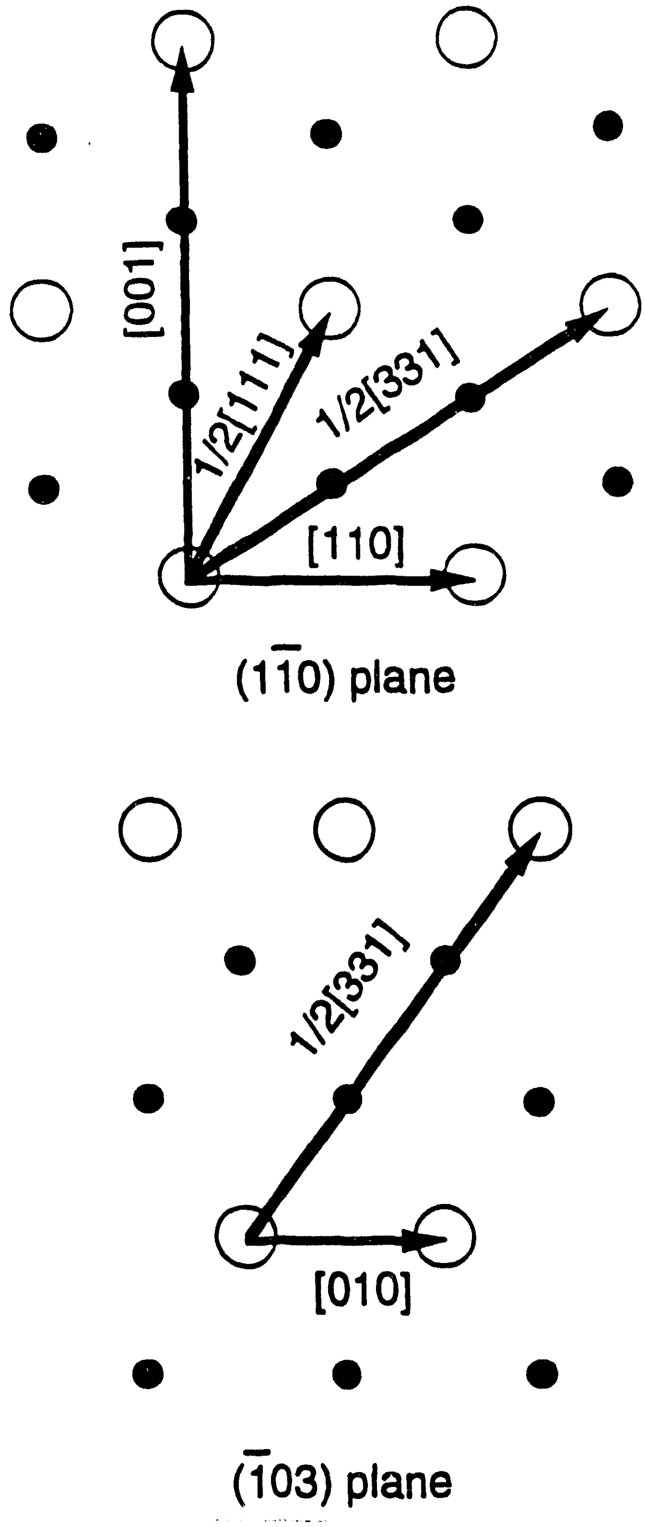

Figure 2: Important Burgers vectors for $MoSi_2$ [10].

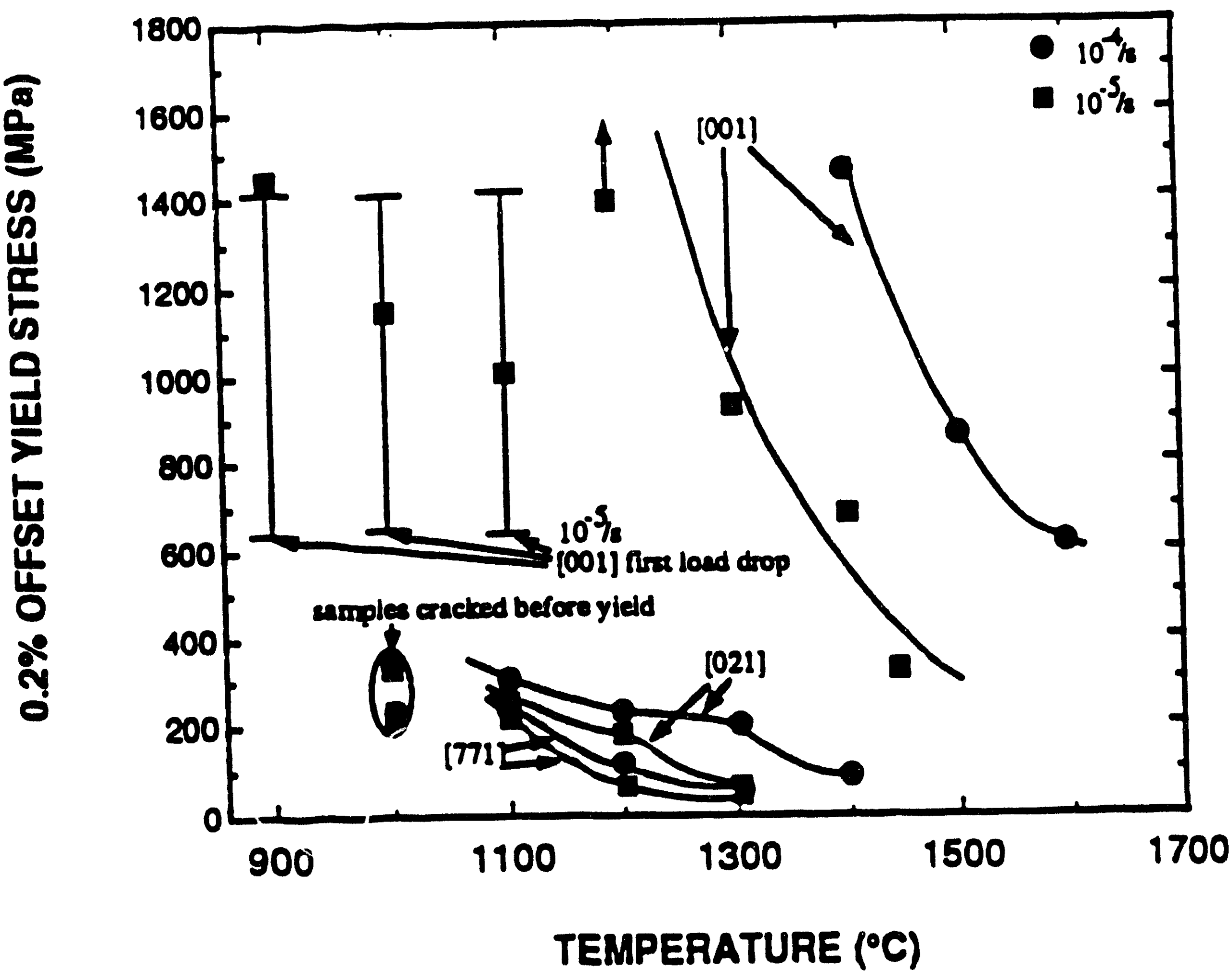

Figure 3: Yield stress of $MoSi_2$ single crystals as a function of temperature and crystallographic orientation [5,10].

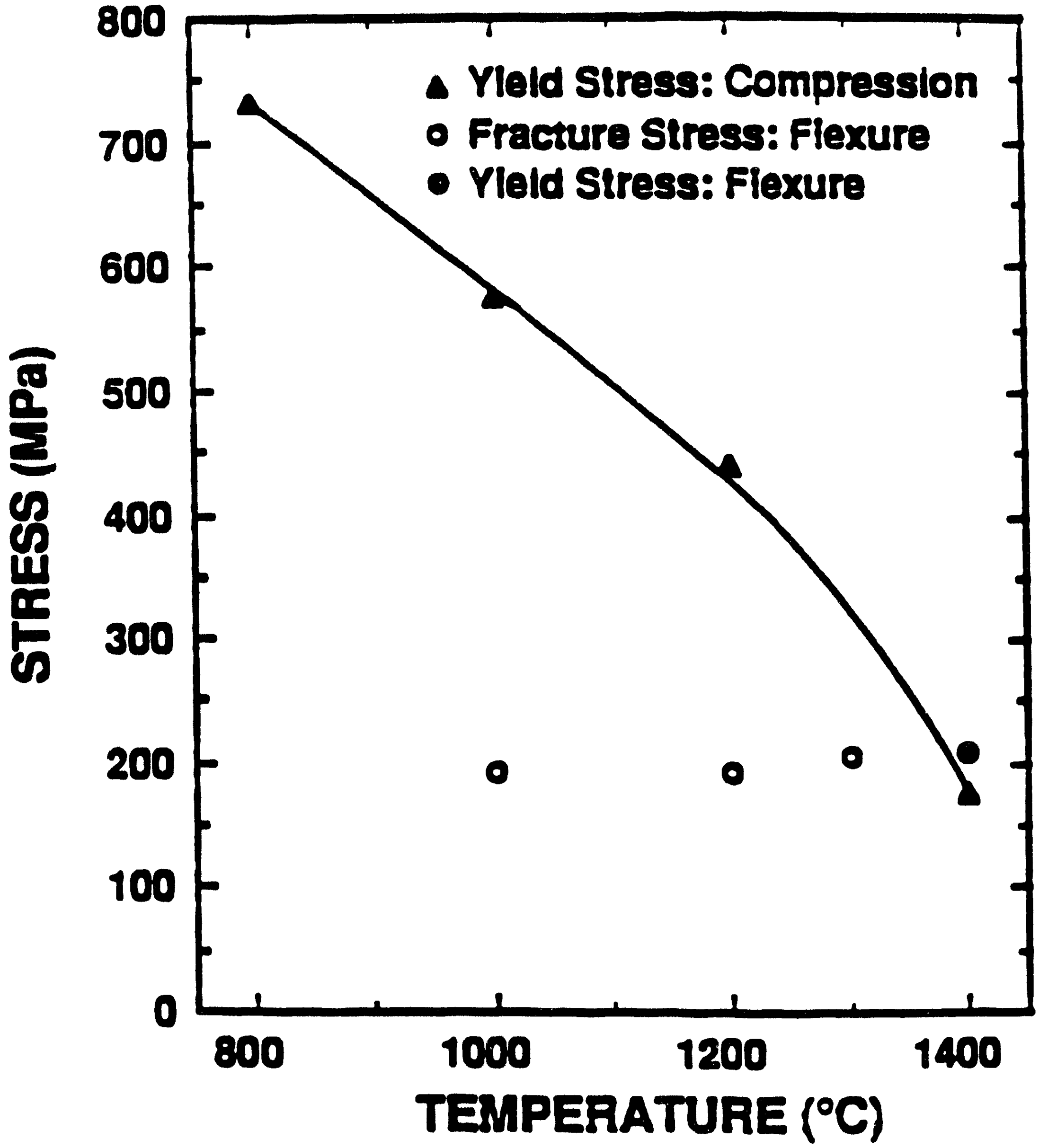

Figure 4: Yield stress versus temperature for low silica content, large grained polycrystalline $MoSi_2$ [11].

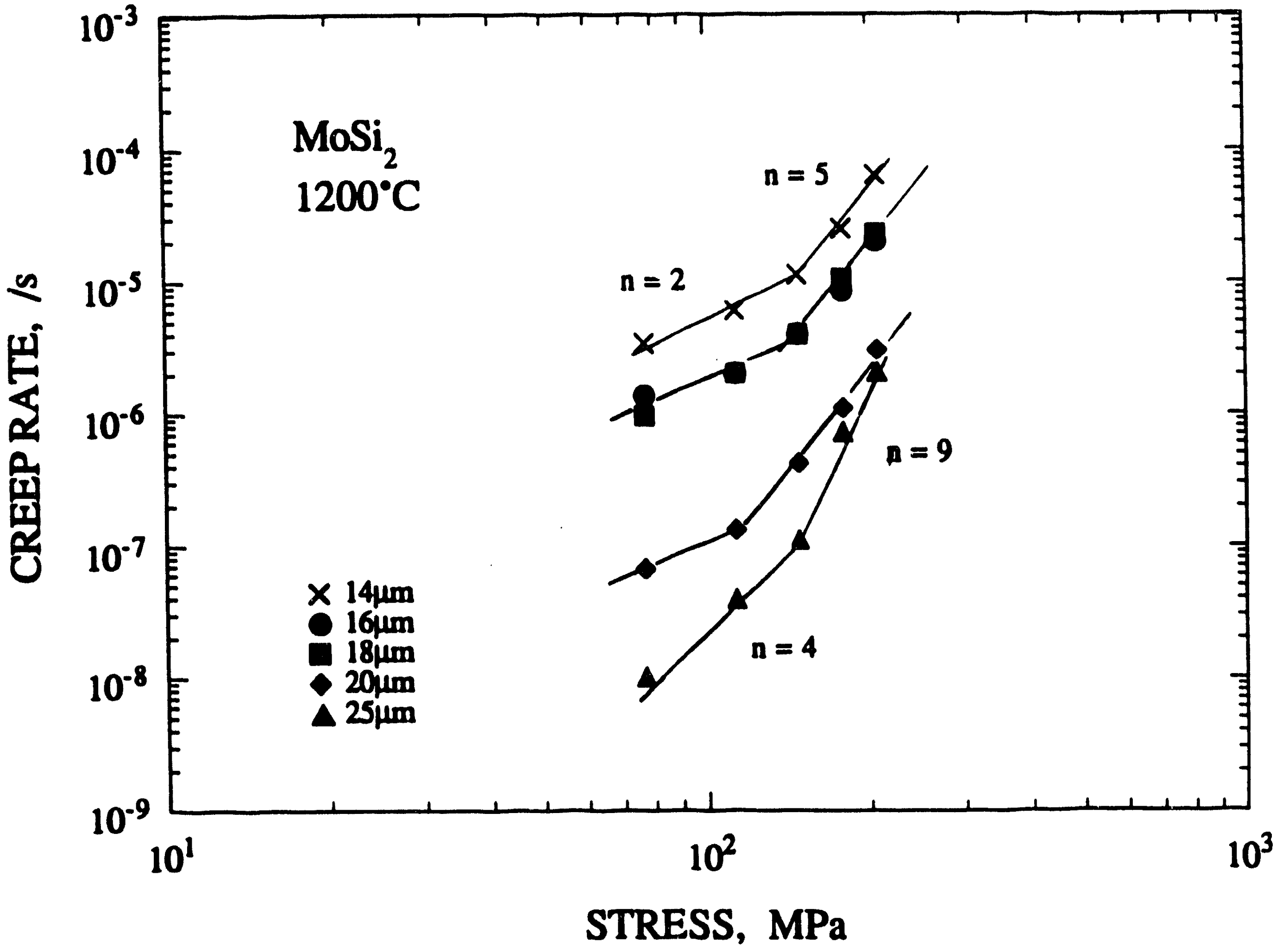

Figure 5: Creep rate of polycrystalline $MoSi_2$ as a function of grain size [13].

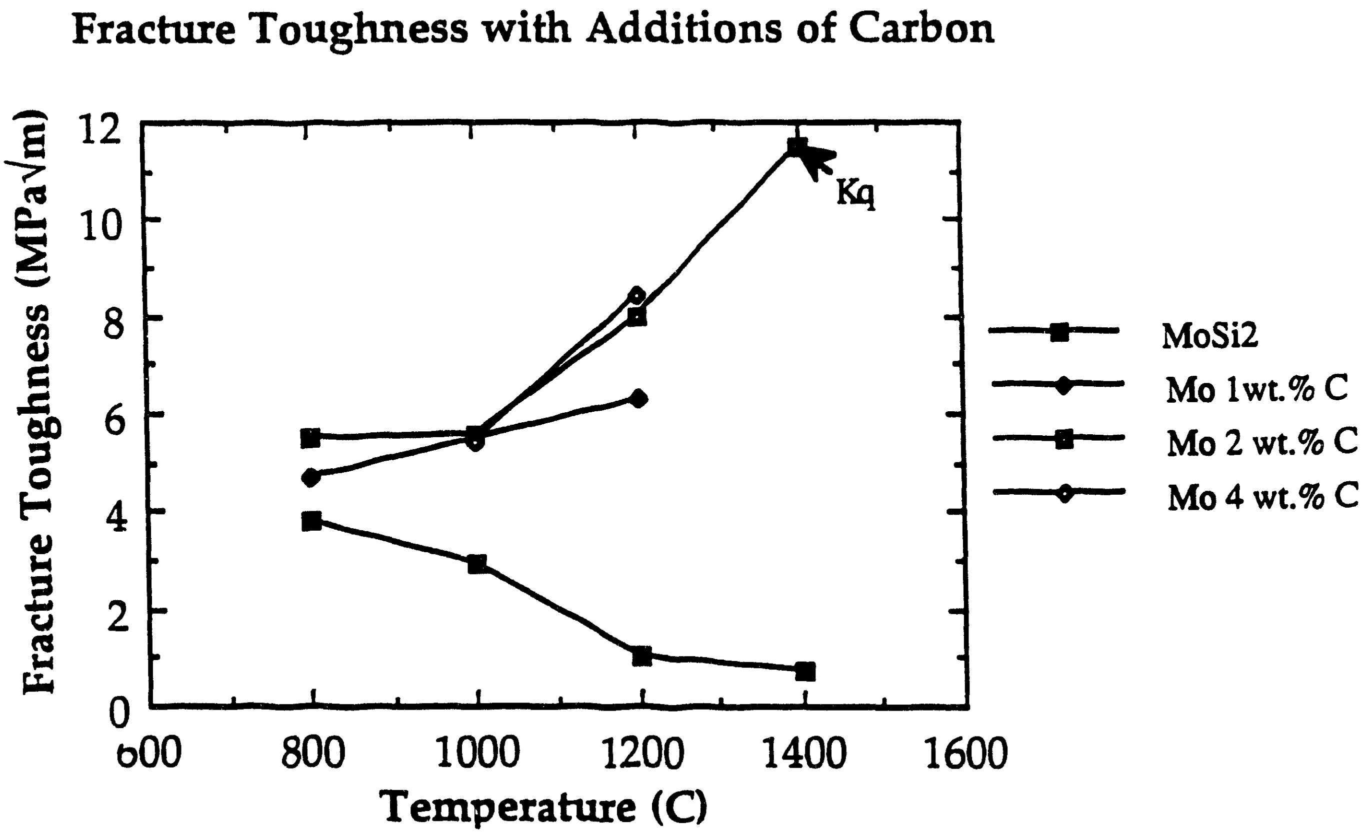

Figure 6: Effects of carbon additions on the elevated temperature fracture toughness of $MoSi_2$ [16].

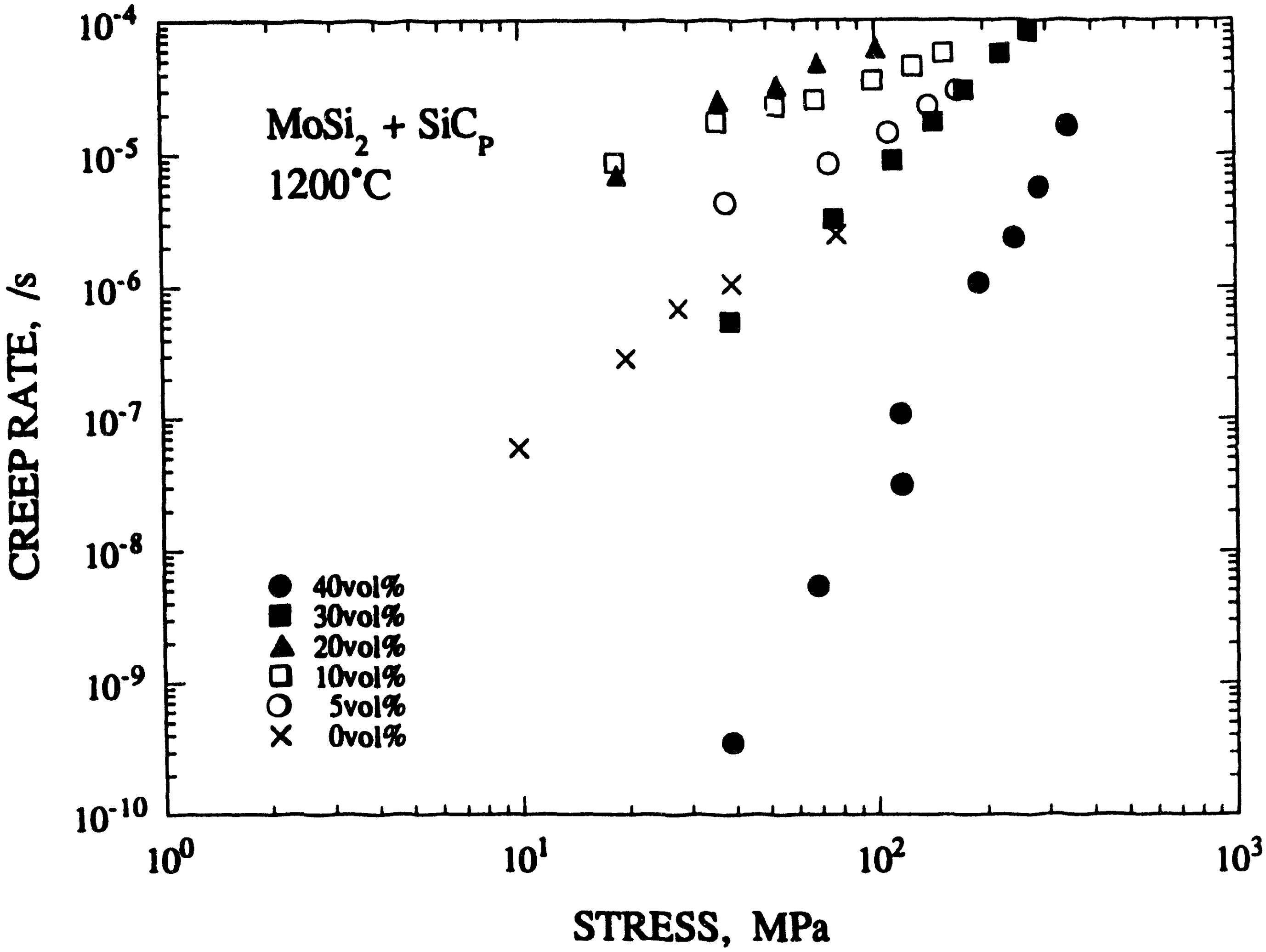

Figure 7: Creep rate of SiC particle-$MoSi_2$ matrix composites with different volume fractions of SiC phase [13].

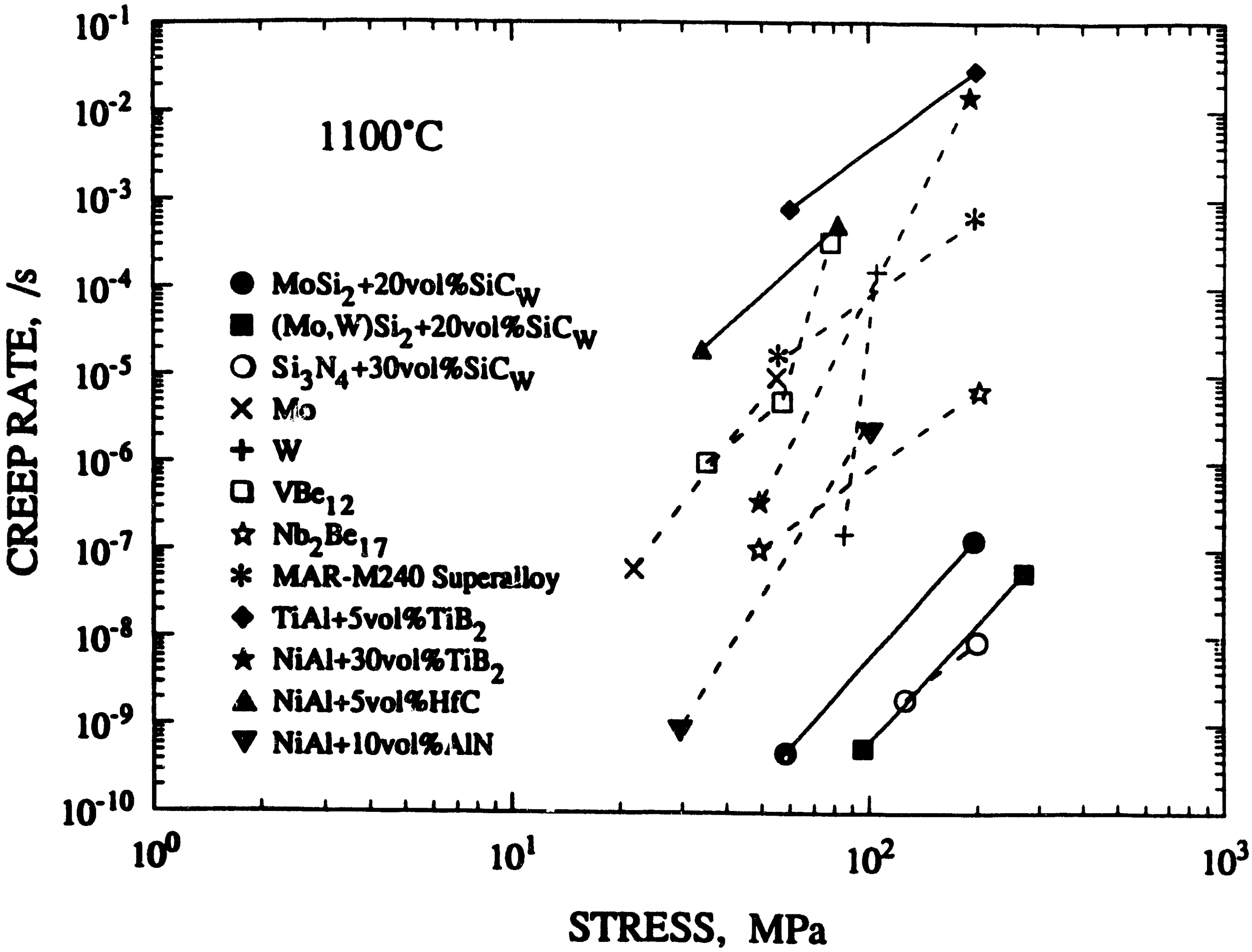

Figure 8: Comparison of the creep resistance of $MoSi_2$-based materials to other metals and intermetallic compounds [17].

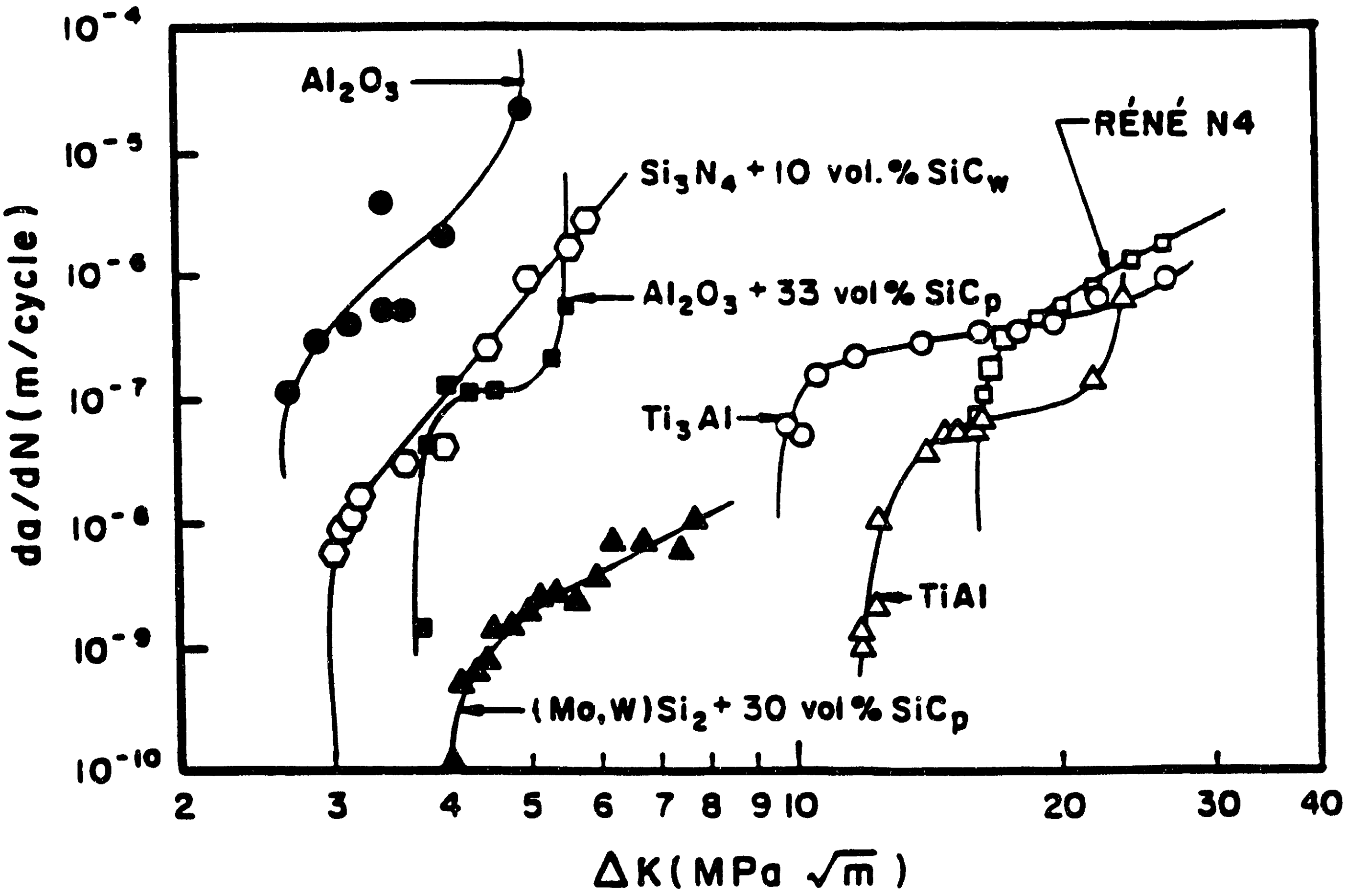

Figure 9: Comparison of high temperature cyclic crack growth of $MoSi_2$ composites to that of other high temperature materials [20].

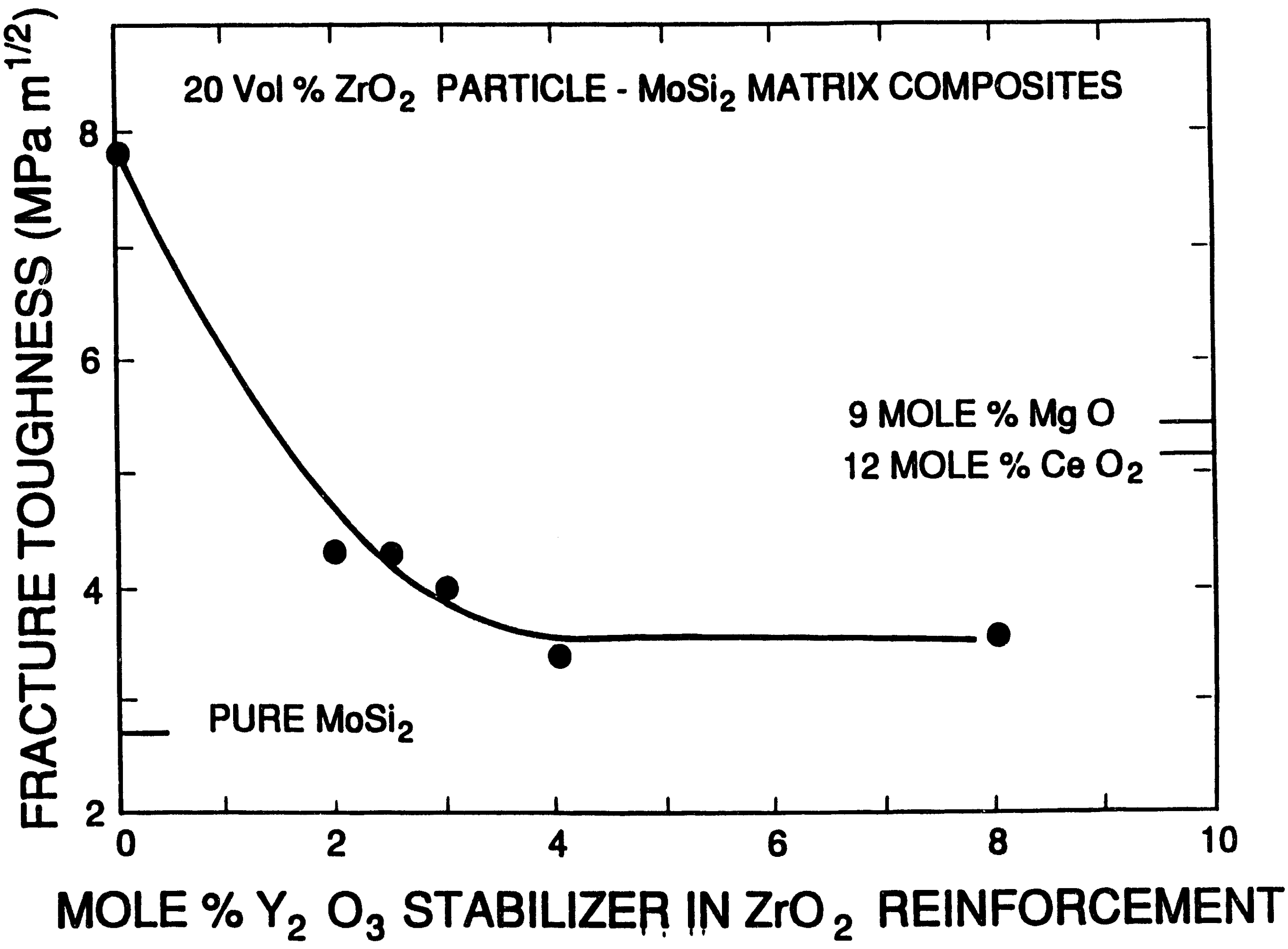

Figure 10: Fracture toughness of ZrO_2 particle-$MoSi_2$ matrix composites as a function of ZrO_2 stabilizer [25].

DATE
FILMED
7/1/94

END