FRACTURE AND FATIGUE BEHAVIOR OF TOUGHENED DRA, Al-Be, AND BULK METALLIC GLASS COMPOSITES

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ABSTRACT

The fracture and fatigue behavior of discontinuously reinforced aluminum (DRA) composites, Al-Be composites, and toughened bulk metallic glass systems are presented. Data on the effects of particulate reinforcement additions to an aluminum matrix are presented first and illustrate the decrease in toughness typically observed with reinforcement additions in such systems. The effects of incorporating extrinsic toughening regions on the fracture and fatigue crack growth are subsequently presented and show that both the fracture and fatigue crack growth performance can be improved with such additions. Additional work is presented on the behavior of Al-Be composites produced by powder metallurgy techniques. The fracture and fatigue behavior of the constituents are presented in addition to that of the behavior of the Al-Be composites containing, by volume, 70% Be and 30% Al. The addition of Al to produce the Al-Be composite provides improvements to the toughness and some aspects of the fatigue crack growth behavior in comparison to the monolithic Be. Finally, the effects of the addition of a refractory metal containing toughening phase on the fracture behavior of a bulk amorphous material based on the Zr-Ti-Ni-Cu-Be system is presented

KEYWORDS: ***Discontinuously Reinforced Al (DRA), Ultra-light Al-Be composites, bulk metallic glass/composites.***

1. INTRODUCTION

There is a continuing need for high performance affordable materials with high specific strength and stiffness. The modified Ashby plot shown in Figure 1 illustrates that composites based on a variety of lightweight materials (e.g. Al, Mg, Ti, Be) provide combinations of high specific stiffness and strength which are attractive to the automotive, aerospace, and electronic packaging communities. Recent reviews have illustrated some of the material sources and balance of properties present in the DRA systems [1-3]. While discontinuous reinforcement additions increase the modulus, Figure 2 [1] illustrates the significant decrease in fracture toughness resulting from such additions. The fatigue crack growth characteristics of DRA (Figure 3 – closed symbols) in comparison to the monolithic matrices (Figure 3 – open symbols) are summarized in Figure 3 [1]. The DRA generally exhibits similar/increased fatigue thresholds and higher Paris Law slopes in comparison to the monolithic matrices upon which they are based [1].

Ultra-light materials based on Be also present some interesting combinations of properties. While Figure 1 illustrates that extra-ordinary combinations of specific stiffness and strength are possible with monolithic

Be, these materials often possess relatively low ambient ductility and fracture properties [4]. Compositing with Al and the production of Al-Be composites potentially provides extrinsic toughening approaches [5], which can provide a balance of properties.

Ultra-high strength (e.g. 2 GPa) bulk amorphous materials based on the Zr-Ti-Ni-Cu-Be system have recently been produced [6]. Preliminary fracture toughness [7-10] and ductility [10-13] data have been developed for this system. The bulk amorphous materials possess low ductility in tension [10-13] due to the initiation and propagation of intense localized shear. The addition of a refractory metal containing toughening phase has been shown to provide for multiple initiation and growth of such localized shear regions, thereby increasing the tensile ductility [14]. Little work has been conducted to determine the effectiveness of such regions on the fracture toughness of such systems.

This paper briefly reviews some ongoing work to illustrate the effects of extrinsic [5] toughening approaches on the fracture and fatigue behavior of DRA, Ultra-light materials based on Be, and toughened bulk metallic glass based on the Zr-Ti-Ni-Cu-Be system. In the DRA systems, the incorporation of unreinforced regions of different size/properties have been investigated using powder metallurgy approaches in order to determine the effectiveness of such additions on both the fracture and fatigue crack growth behavior. In the Al-Be system, powder metallurgy approaches have also been utilized to produce Al-Be composites containing 70% by volume Be. In the bulk metallic glass system, the refractory metal containing toughening regions have been produced by controlled devitrification of the metallic glass during solidification processing. The effects of such additions to the fracture and fatigue behavior of these various systems are presented.

2. MATERIALS

The DRA composite consisted of a 7093 powder metallurgy Al matrix reinforced with 15 volume % SiC particles, denoted 7093/SiC/15p DRA (nominal composition of 9 Zn, 2.2 Mg, 1.5 Cu, 0.14 Zr, 0.1 Ni, bal Al reinforced with 10 μm average size SiC particulates) provides the baseline material for the DRA reviewed in this work. "Toughened" DRA was produced at ALCOA via the addition of aluminum/aluminum alloy particles to the powder metallurgy blend at volume fractions of either 10% or 25%. The final product thus consists of DRA and discrete unreinforced Al regions. The global volume fraction of the reinforcement was kept at 15%, while the strength of the toughening region was varied independently in the manner described elsewhere [15]. The material test matrix is shown in Table 1. The behavior and properties of the "toughened" materials are compared to the materials with a conventional DRA structure (i.e. C1, C2, C3). The consolidated billets were extruded at 22:1 ratio to produce 1" x 3" bars, while Figures 4 (a-c) show the three major classifications of materials studied corresponding to the descriptions provided in Table 1. All materials were heat treated to an overaged condition, T7E92, consisting of 490ºC/4 hrs/CWQ, followed by aging at 120ºC/24hrs + 150ºC/8hrs.

The Al-Be composites were produced by Brush Wellman Inc., Cleveland, Ohio. Prealloyed powders containing 62wt% Be were atomized and filtered to below 74 mesh (i.e. 120 – 150 μm). The powders were then cold isostatically pressed to 80% density, degassed, and extruded at 10:1 ratio at 454ºC, followed by annealing at 593ºC/24 hrs. The microstructure of the extruded Al-Be composite is shown in Figure 5.

Both 4 mm and 7 mm thick bulk metallic glass plates and composites were supplied by Howmet Corporation and were produced by solidification processing. The composition of the bulk amorphous alloy was, in at%, 12.0-12.9Ti, 9.3-9.5Ni, 11.9-12.0Cu, 23.8-26.5Be, and balance Zr. Oxygen contents were in the range 1350 – 1600 ppm, respectively [7,8,12,13]. X-ray diffraction and TEM analyses revealed the structure to be fully amorphous [7,8,12]. The "in-situ" toughened bulk metallic glass composites were obtained via dendritic growth of a beta-phase (Ti-Zr-Nb) grown during partial crystallization of a molten alloy during cooling. The remaining matrix was vitrified during solidification to produce the composite structure shown in Figure 6.

3. EXPERIMENTAL PROCEDURES

Fracture toughness testing was conducted in general accordance with ASTM E-399-90 on single edge notch bend specimens for all of the materials listed above. The DRA and toughened DRA utilized dimensions of 65 mm x 14 mm x 4 mm, the Al-Be composites utilized dimensions of 75 mm x 16 mm x 22 mm, and the bulk metallic glass (BMG) and BMG composites used dimensions of either 85 mm x 12 mm x 4 mm or 95 mm x 14 mm x 7 mm. In addition, the BMG specimens were also tested in the notched condition, with notch root radii varying from 65 μm to 250 μm, as reported elsewhere [7,8,13]. Fatigue precracking was conducted in general accordance with ASTM E-399-90, while toughness testing was conducted on an MTS servo-hydraulic testing machine. Load, load point displacement, and clip gage opening displacement were continuously monitored during the test.

Fatigue crack growth experiments for DRA and Al-Be composites were conducted using the MTS testing machine described above. Crack growth was monitored via the use of a foil gage (KRAK gage) bonded to the outer surface of the specimen. The samples were cycled at 20 Hz with a stress ratio of 0.1.

Fracture surfaces were examined in a Hitachi Field Emission Gun (FEG) scanning electron microscope (SEM) to characterize the predominant fracture mode and the fine-scale features on the fracture surface. Operating voltages were generally in the range 10-12 kV.

4. RESULTS AND DISCUSSION

4.1 *Microstructures*

The microstructures of the DRA/toughened DRA, Al-Be composite, and toughened BMG composite were shown in Figures 4,5,6, respectively. Fracture experiments were performed such that fracture propagated perpendicular to the extrusion direction in the DRA and Al-Be composites. The crack growth direction in the BMG and toughened BMG cast plates was perpendicular to the thickness of the original casting.

A: *Fracture and Fatigue Behavior of DRA/Toughened DRA*

Both the size and chemistry of the toughening phase affect the increase in toughness over that of the control DRA. The control DRA (i.e. C1, C2, C3) exhibited toughness in the range 19.0-20.8 MPa-m$^{1/2}$, while that of the SDP1 and SDP2 composites were 19.4 and 20.8 MPa-m$^{1/2}$, respectively. The peak toughness of the LDP1, LDP2, and LDP3 composites were 33.1, 30.4, and 23.3 MPa-m$^{1/2}$, respectively. The toughened DRA containing the small ductile phase reinforcements (i.e. SDP1 and SDP2) provided negligible toughening in comparison to that of the large ductile phases (i.e. LDP1, LDP2). Increasing the alloy content of the toughening phase (i.e. LDP3 vs. LDP1 or LDP2), while increasing the strength of the toughened composite [15,16] in comparison to that obtained in the material toughened with pure Al (i.e. LDP1, LDP2), did not produce as significant increases to the toughness as did the weaker, but more ductile large Al additions. Some of these differences in fracture behavior are related to the constrained flow and fracture behavior of the toughening phases, as demonstrated in other work [17,18].

The fatigue behavior of the DRA and toughened DRA were all similar except for the toughened DRA containing the large Al toughening regions. Figure 7 plots the fatigue crack growth behavior at R=0.1 for the control DRA in comparison to the DRA toughened with the large Al regions, Figure 4c. Although the fatigue threshold of all of the materials tested was similar, the fatigue crack growth characteristics of the toughened DRA shown in Figure 7 are significantly different. Comparison of the crack growth data to the microstructure encountered during fatigue (c.f. Figure 4c) revealed that significant crack deceleration occurred as the fatigue crack approached and entered the large ductile Al regions. Upon exiting these regions, the crack growth rate in the DRA regions was similar to that of the control material, until the next toughened region was encountered, as shown in Figure 7. The higher strength toughening regions did not significantly change the fatigue crack growth characteristics from that exhibited by the control DRA, although fracture of the high strength toughening regions was often along grain boundaries [16] and this may have compromised the fatigue behavior of the toughening phases in those specimens.

B: *Fracture and Fatigue Behavior of Al-Be Composites*

The toughness of monolithic polycrystalline Be is in the range 8-13 MPa-$m^{1/2}$ [4] on both cast/extruded as well as powder metallurgy produced material. The addition of 30 volume % Al in the extruded powder metallurgy product tested presently significantly increases the fracture toughness, as shown by Table 2. Fracture surface analyses revealed a combination of ductile rupture of the Al with brittle fracture of the Be. The fracture toughness values were relatively unaffected by changes in test temperature over the range -125ºC to 225ºC at the testing rates specified by ASTM E-399-90.

The fatigue behavior of the extruded Al-Be composites is also summarized in Table 2 and is accompanied by literature data on both pure Al [19] as well as monolithic Be [4, 20]. Although the monolithic Be has a lower toughness than any of the materials tested, it exhibits a somewhat higher fatigue threshold. The fatigue crack growth rate accelerates rapidly as static modes of fracture intervene near the toughness of Be. In this regard, the fatigue behavior of the Al-Be composites represents an improvement over that of the monolithic Be. Paris law slopes less than 2 were observed for the composite, in comparison to that of 3.8 for the pure Al and 9 – 21 for the pure Be. Fatigue crack growth in the composite extends over a much wider range of ΔK in comparison to both the pure Al and Be. This is due to the higher toughness of the composite in comparison to that of the Be in the latter case, and due to the early onset of net section yielding in the pure Al due to its very low strength, in the former case.

C: *Fracture Behavior of Bulk Metallic Glass and Toughened Bulk Metallic Glass*

The effects of changes in notch root radius on the toughness of the bulk metallic glass are shown in Figure 8. The values for toughness for fatigue precracked bulk metallic glass specimens are in the range 18 MPa-$m^{1/2}$ and no stable cracking was observed in these specimens. The toughness increases dramatically with an increase in notch root radius, as shown in Figure 8 [7,8,13]. As reviewed elsewhere [8], this increase in toughness with increase in notch root radius exhibited by the bulk metallic glass specimens reported presently far exceeds that exhibited by other structural materials. The potential sources of this large increase in toughness with increase in notch root radius are covered elsewhere [7,8,13]. Despite the general lack of tensile ductility in the bulk metallic glass, the presence of extensive shear banding at the notch significantly increases the toughness of the notched specimens, in contrast to that of the planar fracture surface exhibited by the fatigue precracked specimens. The fracture toughness of the fatigue precracked specimens is in general agreement with a model provided by Argon [21], which predicts toughness values in the range of those obtained presently.

The introduction of the toughening phase shown in Figure 6 produces R-curve behavior in the composite. The peak toughness measured on fatigue precracked specimens of the toughened bulk metallic glass was in the range 29.7 – 35.6 MPa-$m^{1/2}$ for tests conducted at room temperature. Analyses of the fracture surfaces revealed ductile behavior of the toughening ligaments. Work is continuing on this system to determine the effects of such toughening phases on the fatigue crack growth characteristics.

5. CONCLUSIONS

1. Significant toughness increases may be obtained in DRA materials via the use of extrinsic toughening approaches. The size and chemistry of the toughening regions are important considerations in the toughness attained. The fatigue crack growth behavior is also affected by the size and chemistry of the toughening regions. In this work, the use of large regions of relatively low strength Al was very effective in improving the fatigue performance, although this will reduce the strength of the material.

2. The Al-Be composites tested presently exhibited toughness values in excess of that of monolithic Be. Fracture occurred via ductile rupture of the Al with brittle fracture of the Be. The improved toughness exhibited by the Al-Be composites enabled the composites to be tested over a wider range of ΔK than that of the more brittle Be. Fatigue thresholds were greater than that exhibited by the pure Al, although slightly lower than that reported for pure Be.

3. The fracture toughness of bulk metallic glass is dramatically affected by changes in the notch root radius. Fatigue precracked specimens exhibited values in the range 18 MPa-m$^{1/2}$, while increasing the notch root radius increased the toughness to values in excess of 100 MPa-m$^{1/2}$. The incorporation of toughening phases in the bulk metallic glass produced R-curve behavior in the fatigue precracked specimens, and increases in toughness to 29.7 – 35.6 MPa-m$^{1/2}$.

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TABLE 1
MATERIAL TEST MATRIX FOR DRA AND TOUGHENED DRA

	Material ID	Type of Ductile Phase Addition	Quantity (vol. %)	Discrete Ductile Phase in Product?
"Control DRA"	C1	None	N/A	No
	C2	commercial purity Al powder	10%	No
	C3	commercial purity Al powder	25%	No
"Small Ductile Phase"	SDP1	small c.p. Al - low strength	10%	Yes
	SDP2	small c.p. Al - low strength	25%	Yes
"Large Ductile Phase"	LDP1	large c.p. Al -low strength	10%	Yes
	LDP2	large c.p. Al - low strength	25%	Yes
	LDP3	large alloyed Al - high strength	10%	Yes

TABLE 2
FRACTURE AND FATIGUE BEHAVIOR OF Al-Be COMPOSITES, PURE Al, PURE Be

Material	K_{Ic} (MPa√m)	ΔK_{th} (MPa√m)	Paris slope
Al [19]	> 45	< 2.5	3.8
Be [4, 20]	8-13	< 8.8	9-21
Al-Be	20.3	5	< 2

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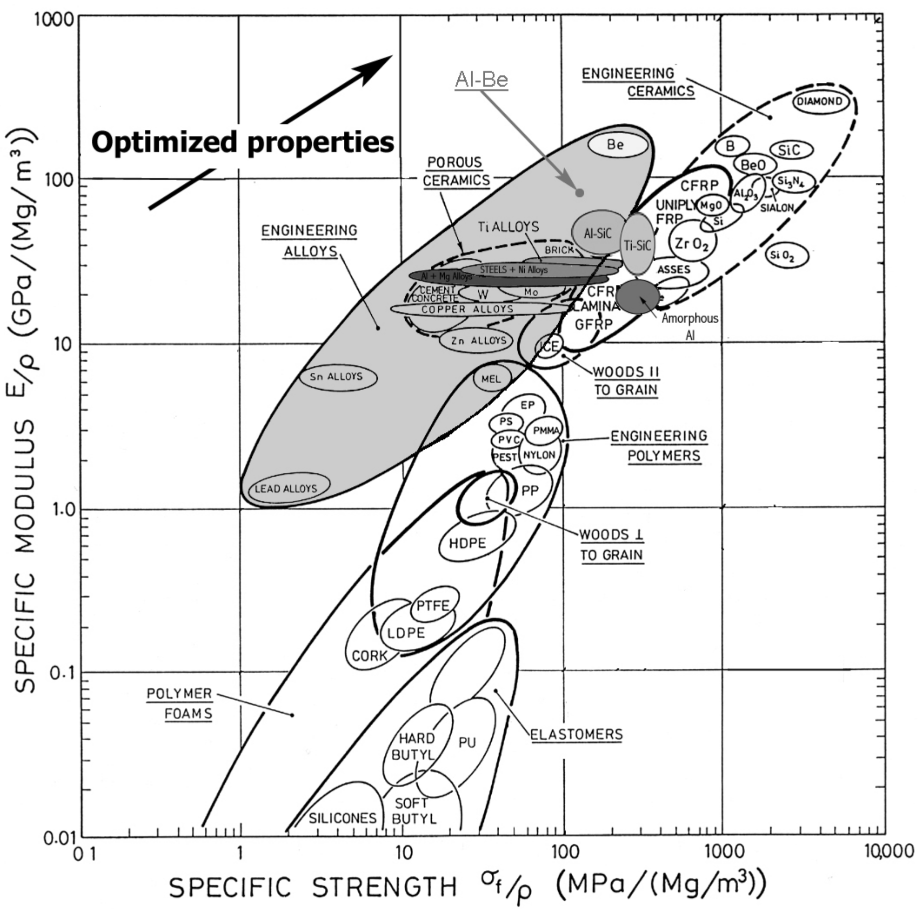


Figure 1: Modified Ashby plot of specific modulus vs. specific strength

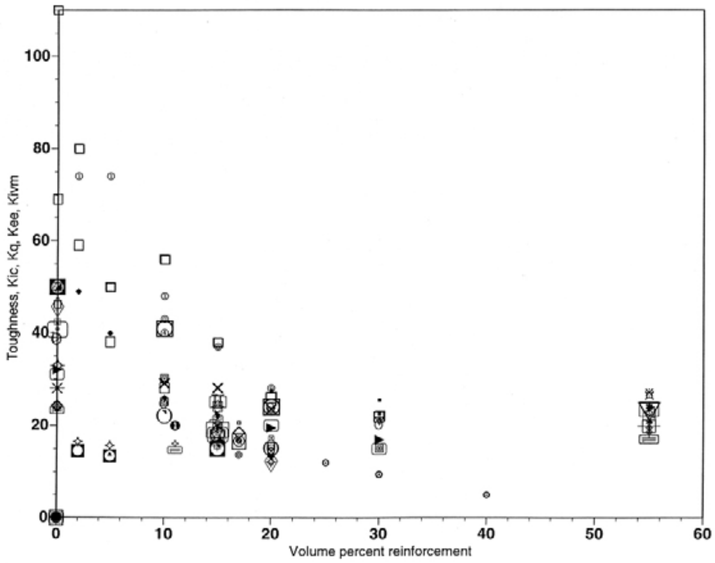


Figure 2: Effects of particulate reinforcement additions on toughness of DRA [1]

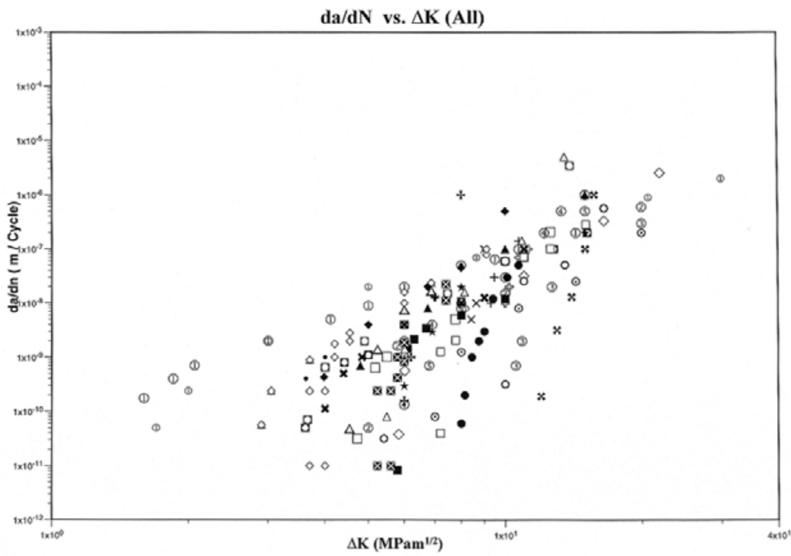
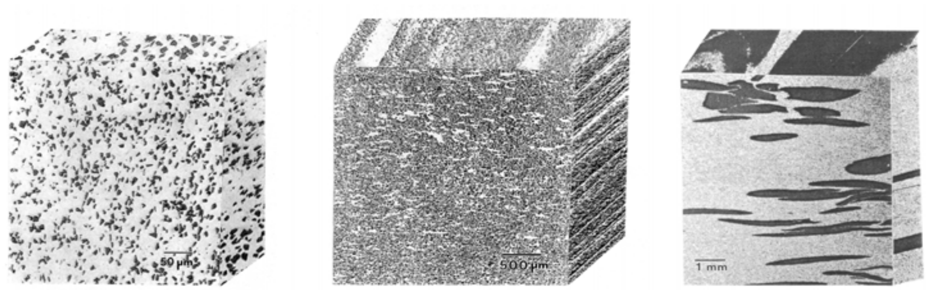


Figure 3: Fatigue crack growth behavior of monolithic (open symbols) and DRA (closed symbols) [1]



a) b) c)

Figure 4: 3D structures of DRA / toughened DRA a) "Control" (C1, C2, C3); b) SDP-DRA; c) LDP-DRA [15]

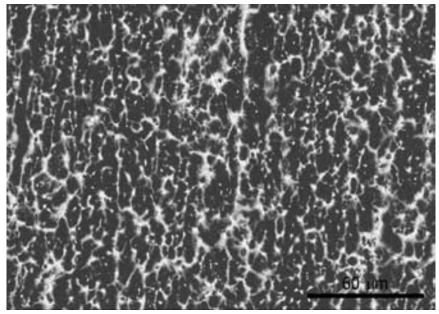


Figure 5: Extruded Al-Be composite

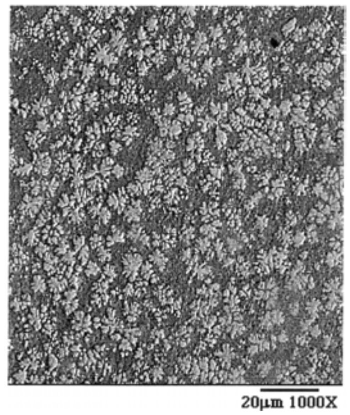


Figure 6: Toughened BMG microstructure [14]

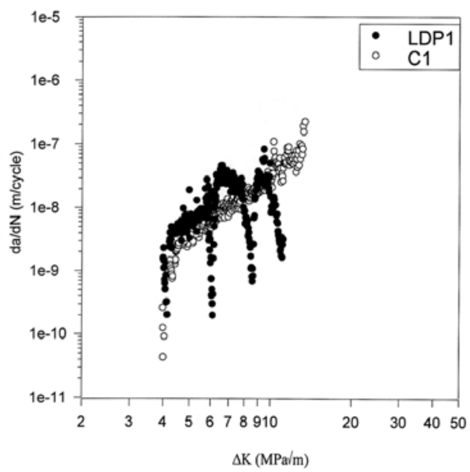


Figure 7: Fatigue crack growth behavior of control (C1) DRA vs. toughened (LDP1) DRA [1,16]

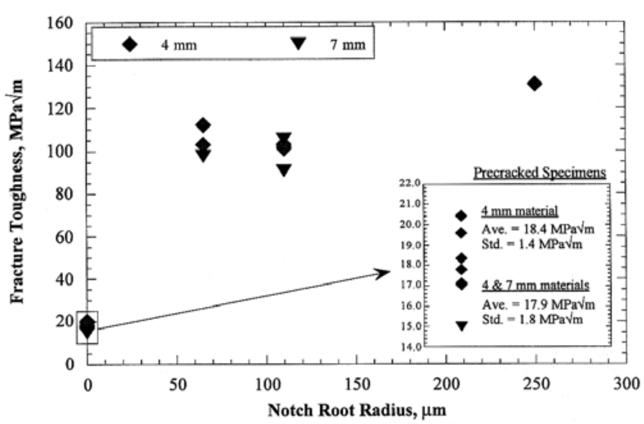


Figure 8: Effects of changes in notch root radius on toughness of bulk metallic glass [7,8,13]