Experimental Verification for Improving Dielectric Strength of Polymers by Using Clay Nanoparticles

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Abstract. *Nanoparticles are a considerable attention due to very interesting properties have been accepted to base matrix materials during the nanostructure incorporation. Therefore, this paper has been presented an experimental study for the dielectric strength of several new industrial polymer nanocomposites specimens. It has been studied the effects of clay nanoparticles incorporation into polypropylene (PP), polyvinyl chloride (PVC), low density polyethylene (LDPE), and high density polyethylene (HDPE) on electric properties, dielectric properties, dielectric strength and voltage endurance significantly for variant polymers by a simplified breakdown model. Experimental results have been compared with respect to unfilled industrial materials under AC electric field (uniform and non-uniform) and variant thermal temperatures.*

Keywords

Clay nanoparticles, dielectric strength, insulation, nanocomposite, nanoparticles, polymers.

1. Introduction

Nanodielectrics, which are concentrated in polymer matrix incorporating nanofillers, have received considerable attention due to their potential benefits as dielectrics. Nanoparticle-filled polymers provide advantages over un-filled polymers because they provide resistance to degradation, and improvement in thermo-mechanical properties without causing a reduction in dielectric strength [1], [2], [3] and [4]. Recently published results for electrical voltage endurance in these new materials indicate that very substantial (3 orders of magnitude) improvements in voltage endurance can be demonstrated. These improvements in dielectric properties observed for nano-filled polymers could be due to several factors:

- the large surface area of nanoparticles which creates a large 'interaction zone' or region of altered polymer behavior,
- changes in the polymer morphology due to the surfaces of particles,
- a reduction in the internal field caused by the decrease in size of the particles,
- changes in the space charge distribution,
- a scattering mechanism.

It should also be recognized that this technology also results in characteristic changes in non-electrical properties that have been found beneficial as detailed in references from a recent review paper [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11] and [12]. In most papers devoted to the research of polymeric dielectric behavior in a high electric field the aging of polymers have been related to macroscopic inhomogeneities of structure. The majority of authors suppose that the damage of dielectrics with inhomogeneous sub-microscopic structure under long-term voltage application can be caused by different processes. It is obvious that both these processes can be observed during ageing of semi-crystalline polymers, such as low-density polyethylene (LDPE), in a high electric field. Nanocomposites present a series of unique properties, such as electrics, mechanics, optics and magnetics, due to nanoparticles with a giant specific surface area, quantum size effect and the special interface between particles and polymer matrix. Nanodielectrics have attracted a great attention since the first experimental data were reported [13], [14] and [15].

The homogeneous distribution of nanoparticles in polymer matrix is another problem of the interface research. Nanoparticles are dispersed in matrix chiefly by shear force diffusion and chemical modification in the majority of experiments. The viscosity of the matrix is an important factor for shear force diffusion. Chemical modification will alter the surface states of nanoparticles (such as silane couplings pretreatment) in order to increase the electrostatic force between fillers and matrix. In different production processes, the interface is in various thickness and layer numbers. In this way, the results of nanodielectric properties have little comparability and poor reproducibility, which has been confirmed by the reported data. It has been discussed that Dielectric material performance, whether conventional or nanocomposite dielectric, its aging, degradation and breakdown present a strong spatio-temporal hierarchy relationship [16], [17], [18], [19], [20], [21], [22], [23] and [24].

The current research has been concentrated on the effects of uniform and non-uniform electric fields on the new nanocomposite specimen's insulation materials (Polypropylene, Polyvinyl Chloride, Low density polyethylene and High density polyethylene). Also, it has been monitored the changing in dielectric properties of the new nanocomposite with respect to unfilled materials, therefore, a comparative study discussed the effects of under uniform and non-uniform electric fields on pure and nanocomposites also, measured the thermal effects on the dielectric strength of the new nanocomposite specimen's insulation materials.

2. Experimental Setup

2.1. Specification of Selected Nanoparticles

Spherical nanoparticles shape (Diameters: 10 nm) have been used in our research and in the most polymer applications. Cost less of clay catalyst is the best filler among nanofillers industrial materials.

2.2. Specification of Selected Base Polymers Matrix

Polypropylene is one of the most common and versatile thermoplastics in the plastics industry. PPs are perhaps the only thermoplastic surpassing all others in combined electrical properties, heat resistance, toughness, chemical resistance, dimensional stability, and surface gloss at a lower cost than most others. Polyvinyl Chloride is the most widely used of any of the thermoplasts, polymerized vinyl chloride, and which is produced from ethylene and anhydrous hydrochloric acid. PVC is stronger and more rigid than other general purpose thermoplastic materials. Polyethylene is divided to low-density polyethylene (LDPE) and high-density polyethylene (HDPE), LDPE is a thermoplastic made from petroleum and it contains the chemical elements carbon and hydrogen. LDPE has more branching than HDPE, its tensile strength is lower, and its resilience is higher [25], [26], [27], [28] and [29].

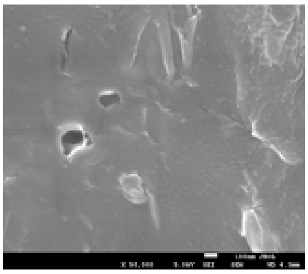
Nanocomposite Polymer: Preparation of studied nanocomposites polymers has been used SOL-GEL method fabrication. The sol-gel processing of the nanoparticles inside the polymer dissolved in non-aqueous or aqueous solution is the ideal procedure for the formation of interpenetrating networks between inorganic and organic moieties at the milder temperature in improving good compatibility and building strong interfacial interaction between two phases. This process has been used successfully to prepare nanocomposites with nanoparticles in a range of polymer matrices. Several strategies for the sol-gel process are applied for formation of the hybrid materials [30]. TEM photos illustrate penetration of nanoparticles polyethylene for LDPE nanocomposites and HDPE nanocomposites as shown in Fig. 1. The sol-gel processing of the nanoparticles inside the polymer dissolved in non-aqueous or aqueous solution is the ideal procedure for the formation of interpenetrating networks between inorganic and organic moieties at the milder temperature in improving good compatibility and building strong interfacial interaction between two phases. This process has been used successfully to prepare nanocomposites with nanoparticles in a range of polymer matrices. Several strategies for the sol-gel process are applied for formation of the hybrid materials [30].

Tab. 1: Electric and dielectric properties of pure and nanocomposite materials.

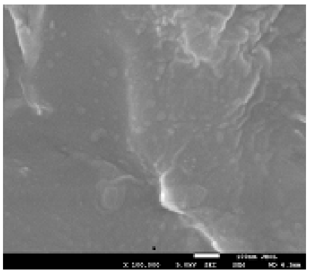
Materials	Dielectric Constant at 1 kHz	Resistivity at [Ω m]
Pure PP	2.28	10^{8}
PP + 1 %wt Clay	2.21	10^{9}
PP + 5 %wt Clay	1.97	10^{9}–10^{10}
PP + 10 %wt Clay	1.75	10^{10}–10^{12}
Pure PVC	3.3	10^{13}
PVC + 1 %wt Clay	3.20	10^{14}
PVC + 5 %wt Clay	2.83	10^{14}–10^{17}
PVC + 10 %wt Clay	2.49	10^{17}–10^{20}
Pure LDPE	2.3	10^{14}
LDPE + 1 %wt Clay	2.23	10^{15}
LDPE + 5 %wt Clay	1.99	10^{15}–10^{18}
LDPE + 10 %wt Clay	1.76	10^{18}–10^{20}
LDPE + 10 %wt Clay	2.3	10^{15}
HDPE + 1 %wt Clay	2.27	10^{16}
HDPE + 5 %wt Clay	2.21	10^{16}–10^{19}
HDPE + 10 %wt Clay	2.16	10^{19}–10^{21}

All polymer materials which studied in this research are available in manufacturing of High-Voltage (HV) industrial products. HIOKI 3522–50 LCR Hi-tester device used for measuring characterization of pure and nanocomposite insulation industrial materials and showed in Tab. 1.

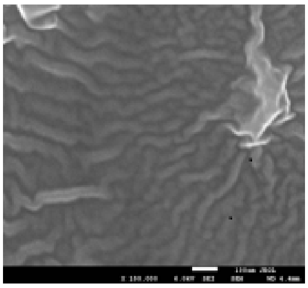
The Scanning Electron Microscope (SEM) has many advantages over traditional microscopes, a large depth of field, much higher resolution, and uses electromagnets rather than lenses. Scanning electron microscope is a type of electron microscope and uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens. Thus, it produces images of a sample by scanning it with a focused beam of electrons. Scanning electron microscope can be achieving resolution better than 1 nanometer. SEM images that illustrate the penetration of nanoparticles polyethylene for LDPE nanocomposites and HDPE nanocomposites have been shown in Fig. 1.



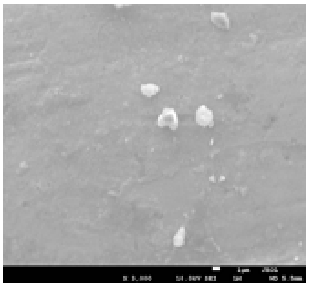
(a) Clay/PP nanocomp.



(b) Clay/PVC nanocomp.



(c) Clay/LDPE nanocomp.



(d) Clay/HDPE nanocomp.

Fig. 1: SEM images for polymers nanocomposites.

2.3. Specification of Measurement Devices

HIOKI 3522–50 LCR Hi-tester device measured characterization of nanocomposite insulation industrial materials. So that, it has been used for measuring electric and dielectric parameters of nanometric solid dielectric insulation specimens at various frequencies as shown in Fig. 2.

Fig. 2: HIOKI 3522-50 LCR Hi-tester device.

On the otherwise, Fig. 3 gives shows HI-POT TESTER Model ZC2674 device for experiment uniform and non-uniform electric field distribution through the thickness of insulation layer with different nanocomposite materials.

The Hi-tester device has been specified as 1 kVA, 20 kV, AC and DC voltages, 10 mA, AC and DC currents. Configuration of both two electrodes of uniform electric field has been made from copper and has 35 mm diameter but configuration of tip electrode of non-uniform electric field has 0.5 mm diameter.

Fig. 3: HIPOT tester model ZC2674 device.

3. Results and Discussion

Dielectric strength of insulation materials is a vital parameter for electrical industrial applications. Thus, the breakdown voltage of new nanocomposite industrial materials has been caused by applying variant AC voltage on the from zero kV until breakdown occurs, also, AC Conduction current was measured through testing the specimen from zero Ampere up to 1 mA.

3.1. Effects of Uniform Electric Fields on Clay/Polymers Nanoparticles

Figure 4 illustrates the effect of uniform electric field on polypropylene nanocomposite materials; it is noticed that increasing clay nanoparticles percentage in the nanocomposite increases dielectric strength of the industrial materials (0 %wt: 5 %wt) whatever the dielectric strength reduces with increasing clay nanofillers (5 %wt: 10 %wt) because of accumulation nanoparticles phenomena due to increasing percentage of clay nanoparticles in polypropylene materials. Figure 5 shows effect of uniform electric field on polyvinyl chloride nanocomposite materials; it has been cleared that increasing percentage of clay nanoparticles up to 10 %wt in polyvinyl chloride decreases dielectric strength of polyvinyl chloride nanocomposite industrial materials and increases conduction current with increasing percentage of clay nanoparticles.

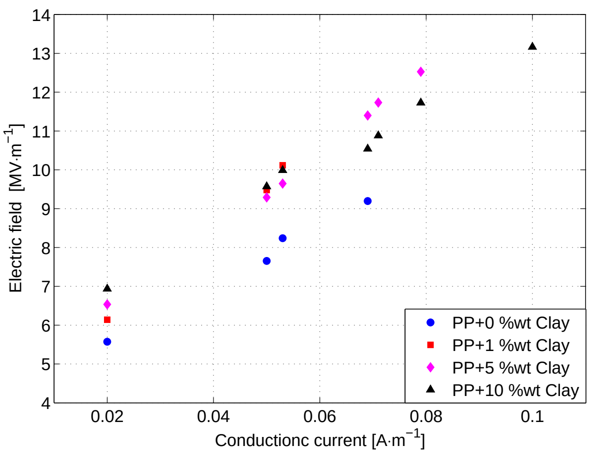


Fig. 4: Effect of clay nanoparticles on polypropylene materials under uniform electric field.

Figure 6 shows effect of uniform electric field on Low-density polyethylene nanocomposite materials; it has been noticed that increasing clay nanoparticles percentage up to 5 %wt increases dielectric strength of low-density polyethylene nanocomposite insulation specimen. Whatever, accumulation nanoparticles phenomena causes increasing percentage of clay nanoparticles in low-density polyethylene up to 10 %wt.

On the otherwise, Fig. 7 depicts that increasing percentage of clay nanoparticles up to 10 %wt in high-density polyethylene increases conduction current through high-density polyethylene nanocomposite. And so, decreases the dielectric strength slightly with increasing percentage of clay nanoparticles. All these results would impact on AC electrical high voltage breakdown of the tested insulating materials. The performance of the new nanocomposites will be effective on AC electrical power applications.

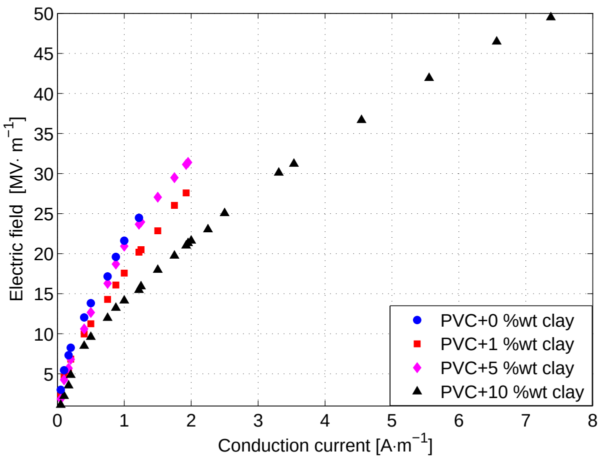


Fig. 5: Effect of clay nanoparticles on polyvinyl Chloride materials under uniform electric field.

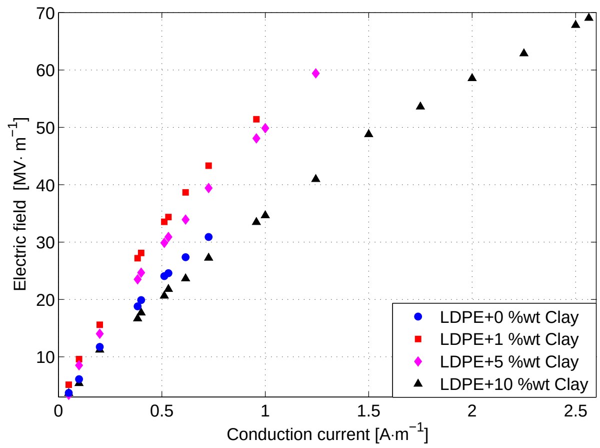


Fig. 6: Effect of clay nanoparticles on low-density polyethylene materials under uniform electric field.

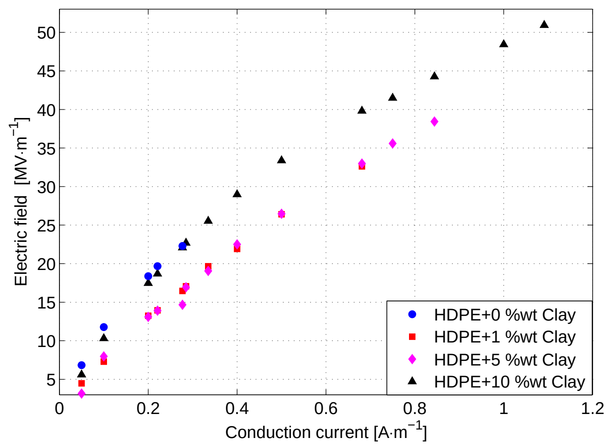


Fig. 7: Effect of clay nanoparticles on high-density polyethylene materials under uniform electric field.

3.2. Effects of Non-uniform Electric Fields on Clay/Polymers Nanoparticles

Figure 8 shows effect of increasing clay nanoparticles on dielectric strength and conduction current of polypropylene materials under non-uniform electric field; so that, increasing percentage of clay nanoparticles in the polypropylene insulation nanocomposite specimen's decreases dielectric strength of polypropylene at the same conduction current, specially, at increasing nanofillers percentage up to 5 %wt. Noting that, because of accumulation phenomena of nanoparticles, the dielectric strength increases slightly with increasing the percentage of clay nanoparticles. And so, Fig. 9 depicts that increasing percentage of clay nanoparticles in polyvinyl chloride insulation nanocomposite specimen's increases dielectric strength of the industrial materials at the same leakage pass current. Specially, adding Nano fillers percentage up to 10 %wt.

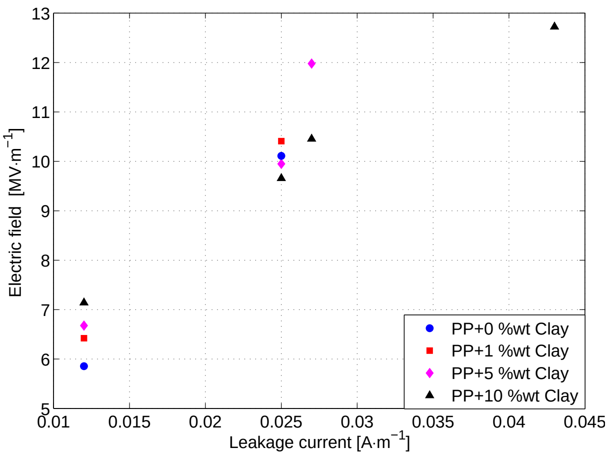


Fig. 8: Effect of clay nanoparticles on polypropylene materials under non-uniform electric field.

Figure 10 shows that effect of clay nanoparticles on dielectric strength and conduction current in Low-density polyethylene materials in non-uniform electric field. Dielectric strength of nanocomposite materials increases with increasing percentage of clay nanoparticles up to 5 %wt in low-density polyethylene at low applied electric field (0: 32 MV·m^{-1}) but due to accumulate clay nanoparticles with increasing their percentage more than 5 %wt in Low-density polyethylene causes decreasing in the dielectric strength of nanocomposite materials.

On the otherwise, Fig. 11 depicts the effect of increasing clay nanoparticles on dielectric strength and conduction current in high-density polyethylene materials in non-uniform electric field. The dielectric strength of high-density polyethylene nanocomposite industrial materials behaved the same behaviour of Low-density polyethylene but different electric field values, specially, at low applied electric field (0: 23 MV·m^{-1}), the dielectric strength of nanocomposite materials increases with increasing percentage of clay nanoparticles up to 5 %wt in high-density polyethylene but it decreases with increasing percentage of clay nanoparticles more than 5 %wt in high-density polyethylene.

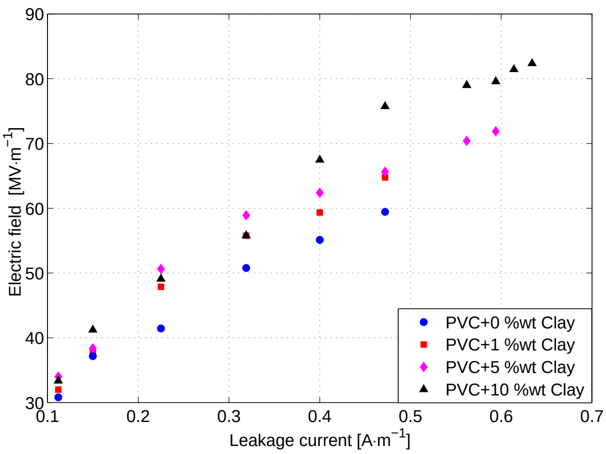


Fig. 9: Effect of clay nanoparticles on polyvinyl Chloride materials under non-uniform electric field.

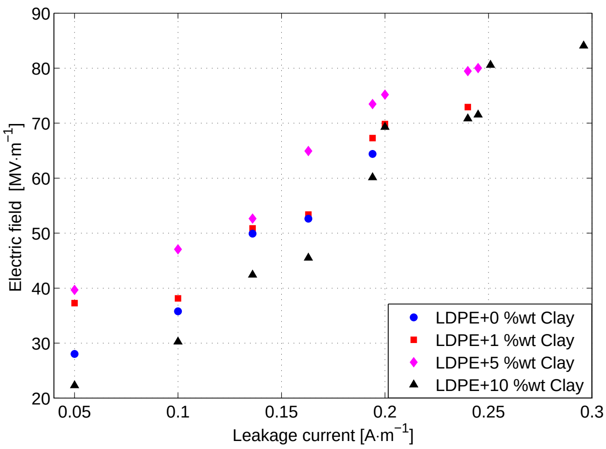


Fig. 10: Effect of clay nanoparticles on low-density polyethylene materials under non-uniform electric field.

3.3. Thermal Comparative Study for Clay/Polymers Nanocomposites

Adding clay nanoparticles has changed the electric and dielectric nanocomposites industrial materials related to pure original electric and dielectric base materials under room temperature, therefore, this study has interested huge filler-polymer matrix interface which has a major influence on the thermal electric and dielectric properties.

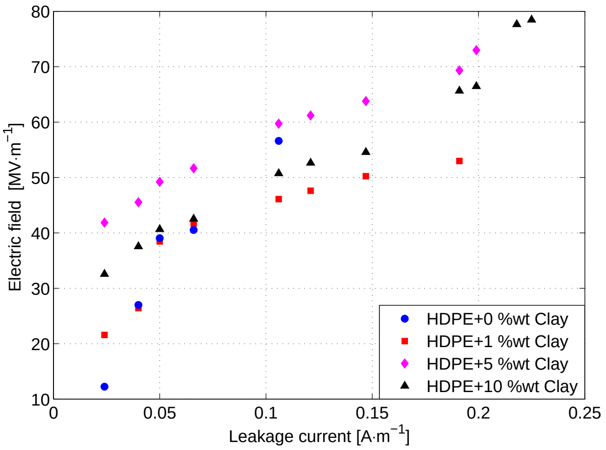


Fig. 11: Effect of clay nanoparticles on high-density polyethylene materials under non-uniform electric field.

Table 2 depicts maximum dielectric strength of pure and nanocomposite materials under uniform and non-uniform electric field with varying cell test temperature from room temperature at 25 °C and 60 °C. It is cleared that there is decreasing in dielectric strength with increasing cell test temperature. Also, this table shows the dielectric strength of pure and nanocomposite materials in non-uniform electric field are higher than dielectric strength of pure and nanocomposite materials in uniform electric field.

Tab. 2: Maximum dielectric strength of pure and nanocomposite materials under uniform and non-uniform electric fields.

Uniform Electric Fields Applied [MV·m^{-1}]		
Materials	**Max. Dielectric Strength at [25 °C]**	**Max. Dielectric Strength at [60 °C]**
Pure PP	9.1953	6.7693
PP + 10 %wt Clay	13.1628	12.3452
PurePVC	24.4715	20.6753
PVC + 10 %wt Clay	49.4949	47.7735
Pure LDPE	30.8939	25.4653
LDPE + 10 %wt Clay	69.0641	67.9765
Pure,HDPE	22.2922	16.8776
HDPE + 10 %wt Clay	50.9394	48.346
Non-Uniform Electric Fields Applied MV·m^{-1}		
Pure PP	10.1107	7.8543
PP + 10 %wt Clay	12.7233	10.5342
Pure PVC	59.4488	50.1874
PVC + 10 %wt Clay	82.3572	751678
Pure LDPE	64.4060	60.448
LDPE + 10 %wt Clay	84.0828	82.6745
Pure HDPE	56.6078	50.5473
HDPE + 10 %wt Clay	78.4624	71.5369

4. Conclusions

This paper proposed new suggested clay/polymers nanocomposites and has been studied the effects of increasing clay nanoparticles:

- Increasing clay nanoparticles to polypropylene and Low density polyethylene nanocomposites increases dielectric strength; noted that, related to accumulation phenomena of clay nanoparticles inside polymer matrix, dielectric strength characterization of nanocomposite may be changed under uniform or non-uniform electric fields according to high percentage of clay nanofillers and polymer molecular type.
- Increasing clay nanoparticles to polyvinyl Chloride, and High density polyethylene decreases dielectric strength; noted that, nature of polymer matrix doesn't accumulate nanoparticles accumulation for changing dielectric strength characterization of the nanocomposite.
- Clay nanoparticles give thermal stability for the suggested nanocomposite materials; therefore, Dielectric strength reduction rate of pure industrial materials is higher than the dielectric strength reduction rate in nanocomposites with respect to increasing temperature environment of industrial polymers.

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