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Investigation of Changes in Physical Properties and Microstructure and Mathematical Modeling of Shrinkage of Onion during Hot Air Drying

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Abstract

The effect of air drying temperature on shrinkage, rehydration ratio and microstructure of dried onion slices (3±0.2 mm thickness and 30 mm diameter) was studied. The different drying conditions led to distinctive structural changes in the samples, affecting the shrinkage and rehydration ratio. Experiments showed that the intensity of structural changes depends on temperature and drying times. A higher temperature and time caused greater damage to the microstructure of onion slices, resulting in the formation of a highly porous structure. The results also indicated that increasing time and temperature increased the shrinkage and rehydration ratio of samples. In mathematical modeling of shrinkage, the model proposed in this study, which had R^2 values higher than 0.978 and SSE values pretty low, predicted accurately the experimental data.

Keywords: Shrinkage, Rehydration, Microstructure, Onion, Drying, Modeling

Introduction

Onion (Allium cepa L.) has been widely used even in ancient times as seasonings, for medical uses and as foods. In current times, onion is an important vegetable to serve as ingredients in dishes, toppings on burgers, in seasonings, chip coatings, and in a variety of other food products including ramen noodles and canned foods. Onion ranks third highest in world vegetable production with an annual production of 47 million tons (17). Iran is the sixth largest producer of onion with 1.5 million tones production per annum (1). Onion finds widespread usage in both fresh and dried forms. Dried onions are a product of considerable importance in world trade and are made in several forms: flaked, minced, chopped and powdered. It is used as flavor additives in wide variety of food formulations such as comminuted meats, sauces, soups, salad dressings, pickle and pickle relishes (16).

Dehydration of foods is aimed at producing a high density product, when adequately packaged has a long shelf life, after which the food can be rapidly and simply reconstituted without substantial loss of flavour, colour, taste and aroma.

Hot air-drying is the most commonly employed commercial technique for drying of biological products (14). The processing temperature mainly influences the quality changes during drying. Drying is a complex process involving simultaneous heat and mass transfer and it can result in significant changes in the chemical composition, structure, and physical properties of food material. Loss of water and heating cause stresses in the cellular structure of the food leading to change in microstructure (e.g. formation of pores) and shrinkage. The development of pores and shrinkage depends upon the variation in moisture transport mechanisms and the external pressure. The strength of the solid matrix can also be affected (e.g. ice formation, case hardening, permeability of crust, and matrix reinforcement) (18). Thus, the drying conditions applied have a significant effect on product characteristics affected by shrinkage.

Porosity is one of the most important physical properties that characterize the quality of dried, crispy foods. The loss of water that occurs during drying causes a reduction in cell tissue size, which is usually referred to as shrinkage. These two properties have been studied in many dehydrated food products (10, 20). Experimental data reported in previous studies showed that shrinkage and porosity could be related mainly as a function of moisture content for a wide variety of food products (11). General empirical shrinkage models have been

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proposed for fruits and vegetables. One of these models described the shrinkage behaviour of apples as a function of moisture content during conventional drying with a linear model (10). However, it was concluded that non-linear empirical models could describe the shrinkage behaviour more adequately for fruits and vegetables in most studies (11, 13).

In food systems, shrinkage is rarely negligible and it is necessary to take it into account when predicting moisture content profiles in the material undergoing dehydration. Modeling, design, and control of drying operations require and consider changes in physical dimensions of the product, moisture content, shrinkage, porosity, bulk density, and volume. For such purposes, attempts at modeling shrinkage during drying have been made by several researches for different fruits and vegetables like apple, banana, carrot, potato and garlic (11, 13, 19). However, no information has been reported on modeling shrinkage of onion during drying.

In previous researches, effect of drying conditions on the quality of vacuum-microwave dried potato cubes was studied and results showed the extent of changes was depended on the method and pretreatments on drying (6).

Although onion drying has been investigated by many researchers, the effect of drying conditions on microstructure of dried samples has never been reported so far. Thus the objective of this study is to examine the effect of drying conditions on shrinkage, rehydration ratio and microstructure (e.g. formation of pores) of onion slices during hot air drying and propose a simple mathematical model to accurately predict shrinkage as a function of moisture content.

Theory

Shrinkage is usually expressed by the volume ratio of sample before and after drying. A few researchers have expressed shrinkage as a function of the change of selected dimensions of the samples, measured with vernier or digital callipers (5, 7, and 13). Mostly, it was expressed in terms of the apparent volume (Eq. 1). This volume can be measured by the Archimedes principle or by a number of displacement techniques.

$$S = \frac{V_0 - V_d}{V_0} \times 100 \qquad (1)$$

Where, S (%) is shrinkage, V_d is the apparent volume of the sample after drying, cm^3 and V_0 is the apparent volume of the raw sample, cm^3. An organic solvent was always selected to displace sample in order to estimate sample volume gravimetrically. The sample volume is calculated as follows:

$$V = V_f - \frac{M_{sf}}{\rho_s} \qquad (2)$$

Where, V is the volume of sample, cm^3; V_f is the volume of the volumetric flask, cm^3; M_{sf} is the weight of solvent added to fill the flask,g and ρ_s is the density of solvent, g/ cm^3 (21).

Materials and methods

The local variety (Texas early grano) of white onion (50-68 mm diameter), having initial moisture content around 92 ± 0.7% was used for experiments. It was stored for approximately two weeks in dark room at a temperature of 4˚C and relative humidity of 17%, prior to the experiments. Onions were manually sorted, peeled and cut into ring slices 3 ± 0.2 mm thick and 30 mm diameter using a manual slicing machine. The initial moisture content of fresh onion and the moisture content of the dried products were determined using the oven-drying method (2).

A laboratory scale hot air dryer, shown in Fig.1, equipped with a centrifugal fan (Soroush Medical Company) contain 3 trays with dimensions 35×30 cm was developed for the present study wherein air temperature could be varied within the range of 60-90˚C and air velocity is constant at 1.5m/s.

Fig. 1- Hot air dryer

Onion slices were uniformly distributed on the metal trays in a single layer. Trays were then put in the drying section of the dryer. Air conditions throughout the experiment were measured continuously. The weight loss and total volume during drying was determined using an electronic balance.

The drying experiments were performed at four different air temperatures (60, 70, 80 and 90˚C) for 12 time intervals (30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330 and 360 min). The changes of relative humidity were negligible during experiments. Samples dried at different conditions were removed from the dryer at specific times and their moisture contents and total volume were measured.

Measurements of volume and shrinkage of fresh and dried onion slices

A flask was calibrated using distilled water and the volume was determined to be 49.8708 ml. The density of toluene, determined by weighing the flask full with toluene, was found to be 0.8687 g/cm^3. The samples were weighed precisely and then transferred into a flask half filled with toluene. The flask was then filled with toluene, the level of solvent being carefully adjusted to ensure consistency, and weighed. The volume of sample was calculated using Eq. (3):

$$V = V_f - \frac{M_{t+s} - M_f - M}{\rho_s} \quad (3)$$

Where V_f is the flask volume, cm^3; M_{t+s} is the flask weight plus the sample and solvent, g; M_f is the flask weight, g; M is the sample weight, g; and ρ_s is the density of toluene, g/cm^3 (21).

To obtain the percentage of shrinkage, three samples were used for each shrinkage measurement. Shrinkage is expressed in terms of the percentage change of the sample volume as compared with its original volume with respect to Eq. (1). Each experimental point was the average value of the three samples.

Rehydration ratio

The rehydration ratio (R) of the dried sample was determined by immersing the dried sample in hot water at 100˚C for 10 min. The sample was then drained and its mass, both before and after immersion, was measured by using an electronic balance (accurate to 0.001 g). The rehydration ratio of the sample was calculated by Eq. (4) (8):

$$R = \frac{M}{M_0} \quad (4)$$

where M_0 and Mare the weights of sample before and after immersion in hot water, g, respectively. The average values of three samples were reported and all measurements were performed in duplicate.

Microstructural analysis

The microstructural changes of dried onion slices were observed by a scanning electron microscope (SEM). The process of microstructural imaging consists of fixation. The objective of the fixation step is to immobilize cellular components in order to ensure that the structure and tissue shown in the microstructural images reflect as closely as possible the living state of the sample. In fixation step, the sample was flushed with a series of ethanol solutions at different concentrations starting with 30%, 50%, 60%, 70%, 80%, 90%, 95% and 100%, respectively. The sample was flushed with ethanol from the lower to higher concentrations to prevent the damage of the cell structure, which might occur from the sudden loss of moisture. The time used for flushing the sample with each concentration of ethanol was approximately 20 min per solution. Finally, the sample surface was covered with gold and then the sample was put in the SEM.

Modeling

The experimental data of the samples for each drying conditions was fitted to the equations proposed in the literature for shrinkage as shown in Tables 1. The model of number 11 was proposed in this study.

The coefficients of the shrinkage models were estimated from the experimental data using the non-linear regression analysis (DataFit 9) which minimizes the residual sum of squares. Best fitting equations were evaluated with the correlation coefficient (R^2) and the sum of square error (SSE), which is defined as:

$$SSE = \frac{1}{N}\sum_{i=1}^{N}\left(X_{exp} - X_{pre}\right)^2 \quad (5)$$

Where, X_{pre} is the estimated value through fitting of the models and X_{exp} is the measured value of data, and N is number of data. A model is considered acceptable if the SSE value is small and the R^2 value is higher than 0.90.

Results and discussion

Physical changes of onion slices

Physical changes of onion slices undergoing hot air drying are shown in Figs. 2 and 3. With respect to Fig. 2, shrinkage is increased with increasing drying time. In addition, at the same sampling time, the samples undergoing drying at higher temperatures suffer more shrinkage than those undergoing drying at lower temperatures. This is because the drying temperature directly affects the product shrinkage (or deformation); larger moisture gradients within the samples develop in higher drying temperatures and these larger gradients lead to increased internal stresses, which in turn lead to larger degrees of shrinkage (3). Moreover, the shape of the dried samples was not uniform indicating that the deformation of the samples was not symmetrical (15). However, the samples dried at air velocity of 1.5 m/s and different temperatures at end of drying time were not much different in terms of the percentage of shrinkage. This is because case-hardening occurred more at the surface and limited the shrinkage of the samples (17).

Following the trend of each curve shows that initially, the percentage of shrinkage increases rapidly. This is followed by a period of slow increase until reaching the final values at the time corresponding to the points where the samples reach their equilibrium moisture contents. The drying time divides the periods of shrinkage variation into the rapid increase and slow increase (followed by a constant value) periods. Towards the end of drying, case hardened skin develops which inhibits further shrinkage of the samples. It can be seen in Fig. 2 that the samples undergoing hot air drying at higher temperatures possess higher rates of shrinkage than those of samples undergoing drying at lower temperatures.

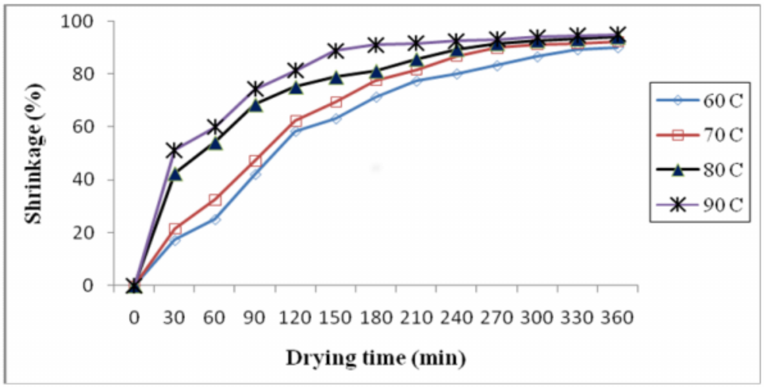


Fig. 2- Percentage of shrinkage of onion slices undergoing hot air drying

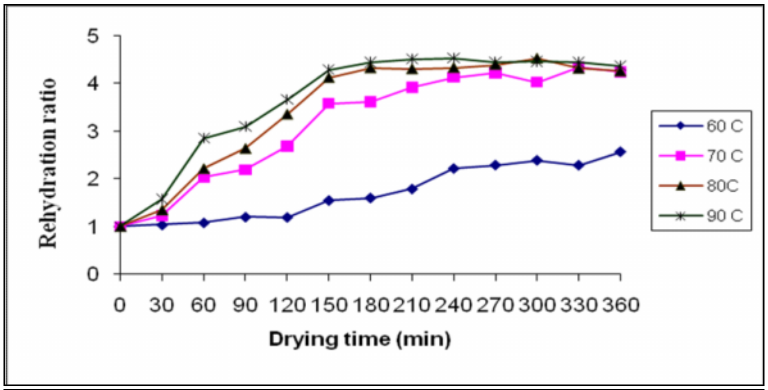


Fig. 3- Rehydration ratio of onion slices undergoing hot air drying

Higher drying temperatures lead to products with higher rehydration ratios. Higher rehydration ratios are observed in onion slices dried using hot air drying at 90˚C as compared to those dried at lower temperatures (Fig. 3). This is because the samples, which were dried at lower temperatures, needed more time to achieve their equilibrium moisture contents than those dried at higher temperatures. Thus the samples suffered more structural damage (e.g., collapse of porous structure) at higher temperatures. As a result, the reconstitution capability of the sample undergoing high-temperature drying was higher than those undergoing low-temperature drying.

Microstructure

Microstructural observation of the surface of dried onion slices was performed to explore the effects of drying conditions (temperature and time) on the microstructural changes of the samples. The SEM photographs (Fig. 4) show the effect of the drying time on the surface morphology of dried onion slices at air temperatures of 70˚C. Fig. 4 shows the formation of pores is increased with increase the drying time. So that long time process (Fig. 4a) causes more serious changes in the microstructure of dried onion slices in comparison with short time process (Fig. 4b). In long time process, excessive loss of water and heating caused the stresses in the cellular structure of the food leading to the serious change in the microstructure (e.g. formation of pores).

A higher drying temperature can cause more violent evaporation of water. During the violent evaporation of water in the cells, the vapor pressure is high which can cause the destruction observed in the microstructure of hot air dried material. Therefore with respect to Fig. 5, the formation of the pores in the dried samples at low temperature (Fig. 5a) is lower as compared with it of the dried samples at high temperature (Fig. 5b).

Modeling

The comparison between the experimental data and predicted values using Eq. (11) for shrinkage in Fig. 6 shows that the fitting is very good.

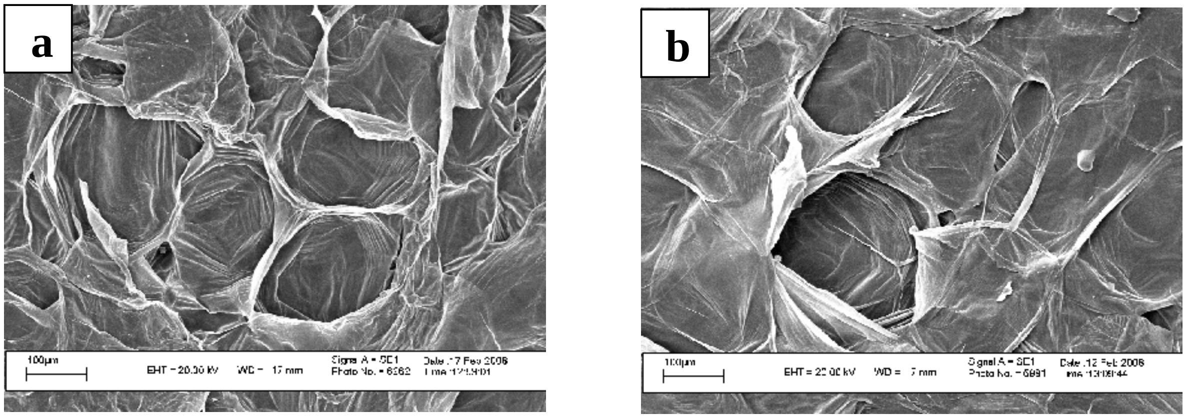


Fig. 4- SEM images of onion slices at 70 °C in different drying times.
(a) after 6 h; (b) after 4 h

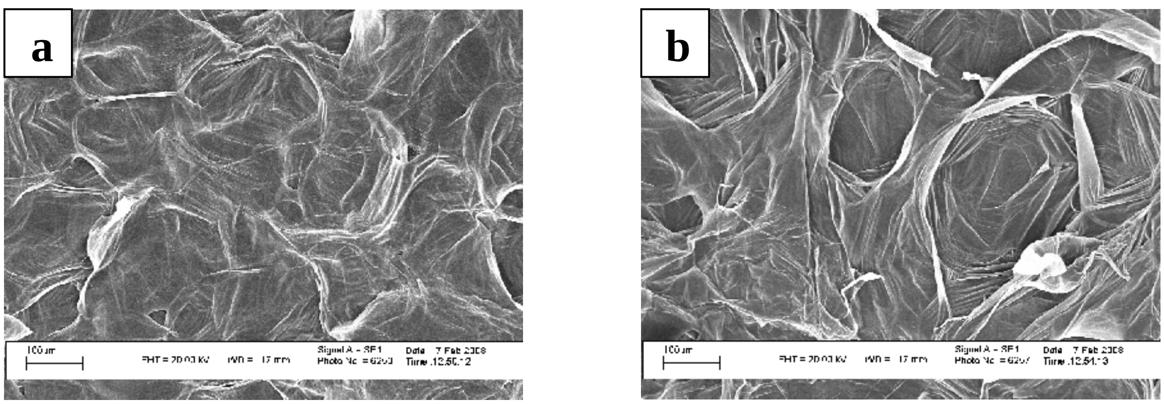
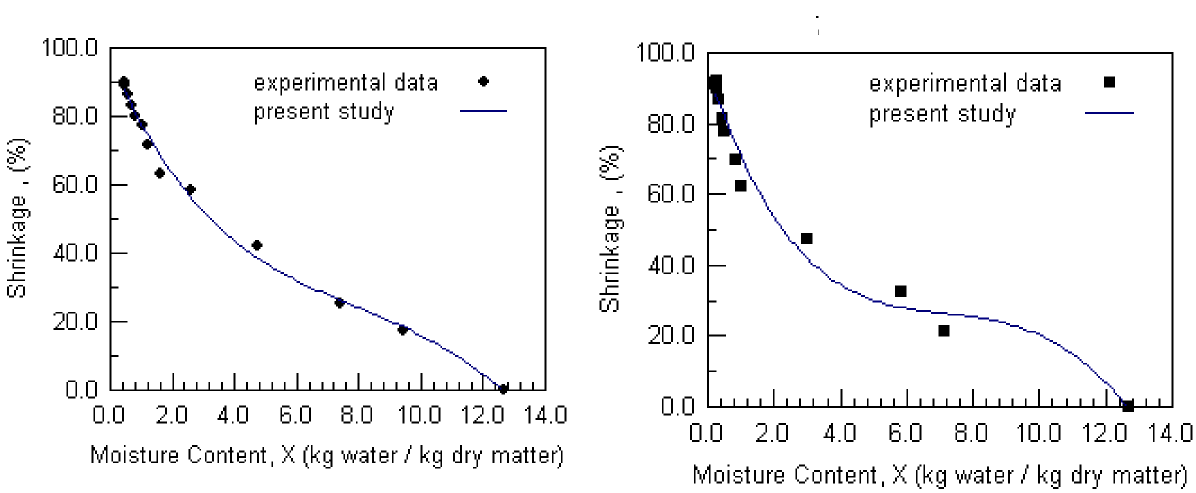


Fig. 5- SEM images of onion slices after 2 h in different drying temperatures.
(a) at 60°C; (b) at 70°C



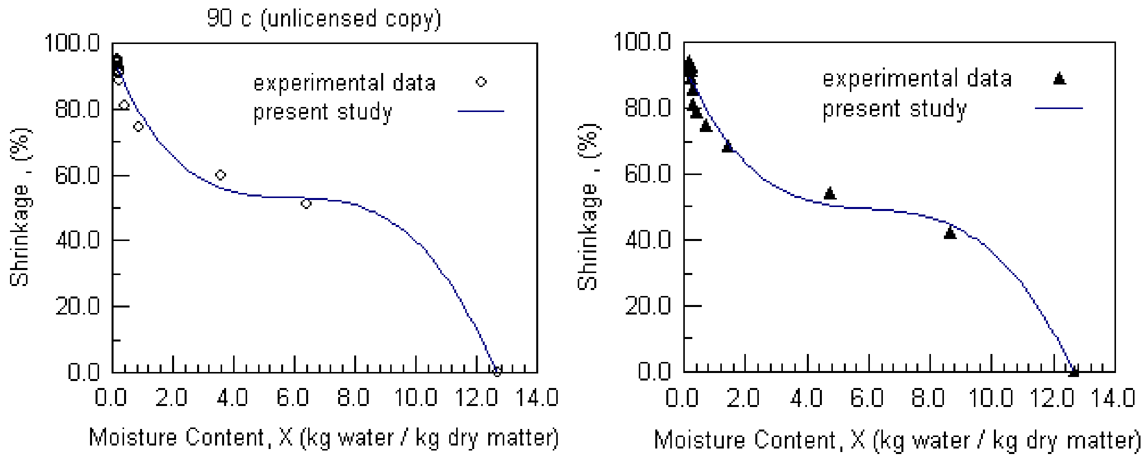


Fig. 6. Comparison of experimental data and values predicted using the present study model of onion slices shrinkage as a function of moisture content at different air temperatures (●,60 °C; ■, 70 °C; ▲, 80 °C; ○, 90 °C)

The statistical results of the fitting of the shrinkage models or equations to the experimental data are shown in Table 2. The non-linear models (Eqs. (7) – (11)) predict the changes in the shrinkage of the onion slices significantly better than the linear model (Eq. (6)) for all drying conditions. The model proposed in this study (Eq. 11), which has R^2 values higher than 0.978 and pretty excellent SSE values, predicts accurately the experimental data.

Conclusion

The effects of drying conditions on the shrinkage and microstructure of the dried onions were examined in this study. Drying conditions significantly affected shrinkage, rehydration ratio and microstructure of the dried onions. In terms of the shrinkage, the drying conditions were found to have an obvious effect on the rates of shrinkage of the samples. The samples undergoing hot air drying at higher temperatures possessed higher rates of shrinkage than those of samples undergoing drying at lower temperatures. Higher drying temperatures led to products with higher shrinkage and rehydration ratio. In terms of microstructure, it was found that formation of pores in dried samples at low temperature and short time are lower in comparison with those dried samples at high temperature and long time. The model proposed in this study (Eq. 11) satisfactorily demonstrated the changes in shrinkage as a function of moisture content.

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Table 1- Empirical equations describing the shrinkage

Name of equation or model	Equation	Eq.no.
Lozano (1980)	$S = b_1.X + b_2$	(6)
Lozano (1983)	$S = b_3 + b_4.\frac{X}{X_0} + b_5.\exp\left(\frac{b_6}{b_7 + X}\right)$	(7)
Ratti	$S = b_8 + b_9.X + b_{10}.X^2 + b_{11}.X^3$	(8)
Va´zquez	$S = b_{12} + b_{13}.X + b_{14}.X^{3/2} + b_{15}\exp(b_{16}.X)$	(9)
Mayor and Sereno	$S = b_{17} + b_{18}.\frac{X}{X_0} + b_{19}.\left(\frac{X}{X_0}\right)^2$	(10)
Present study	$S = b_{20} + b_{21}.\frac{X}{X_0} + b_{22}.\left(\frac{X}{X_0}\right)^3 + b_{23}\exp\left(\frac{X}{X_0}\right)$	(11)

Table 2- Estimated parameters of the shrinkage equations for different drying conditions

Model	Statistical parameter	Air temperature (T) ,˚C			
		60	70	80	90
Lozano (1980)	R^2	0.952	0.90	0.935	0.965
	SSE	515.73	1105.8	561.37	305.99
Lozano (1983)	R^2	0.997	0.997	0.971	0.965
	SSE	22.43	26.70	248.41	305.99
Ratti	R^2	0.993	0.977	0.976	0.988
	SSE	71.10	247.57	204.21	104.63
Va´zquez	R^2	0.993	0.983	0.979	0.992
	SSE	56.21	182.16	178.10	69.68
Mayor and Sereno	R^2	0.981	0.956	0.936	0.965
	SSE	196.46	481.91	559.03	303.19
Present study	R^2	0.994	0.9790	0.978	0.988
	SSE	64.12	233.39	192.45	98.69

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